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Chiara Garau · Ana Maria A. C. Rocha ·
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Yeliz Karaca (Eds.)

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# Computational Science and Its Applications – ICCSA 2026 Workshops

Braga, Portugal, June 30 – July 3, 2026
Proceedings, Part VII

7

Part VII




Springer

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Editors

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Proceedings, Part VII

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# Preface

These 9 volumes (LNCS volumes 16758–16766) comprise the peer-reviewed papers from the 57 Workshops of the 2026 International Conference on Computational Science and Its Applications (ICCSA 2026), held between June 30 and July 3, 2026, in Braga, Portugal. The peer-reviewed papers from the six main conference tracks are published in a separate set of 3 volumes (LNCS volumes 16767–16769).

The conference was held in a hybrid format, with the vast majority of participants attending in person, hosted by the University of Minho in Braga, Portugal.

We enabled virtual participation for those who did not attend the event in person due to logistical, political, or economic constraints by adopting a technological infrastructure based on open-source software (Jitsi + Riot) and a commercial Cloud infrastructure. ICCSA 2026 was organized by the University of Minho (Portugal), the University of Perugia (Italy), the University of Basilicata (Italy), the University of Cagliari (Italy), Monash University (Australia), and Kyushu Sangyo University (Japan).

With the 2026 edition, ICCSA celebrated its 26th anniversary, marking a new chapter in its longstanding history after its memorable 25th anniversary celebrated in Istanbul, Türkiye. Hosted in Braga, Portugal, the conference found a particularly meaningful setting in one of Europe's oldest and most vibrant academic cities, a place where historical depth, cultural continuity, and contemporary scientific exchange meet. Braga offers an inspiring European context for renewing the international and intercultural dialogue that has always characterized ICCSA, while giving new visibility to the role of computational science in addressing the complex challenges of cities, territories, technologies, and societies.

ICCSA 2026 marked another fruitful and thought-provoking academic event in the International Conference on Computational Science and Its Applications (ICCSA) conference series, previously held in Istanbul, Türkiye (2025), Hanoi, Vietnam (2024), Athens, Greece (2023), Málaga, Spain (2022), Cagliari, Italy (hybrid with few participants in presence in 2021 and completely online in 2020), Saint Petersburg, Russia (2019), Melbourne, Australia (2018), Trieste, Italy (2017), Beijing, China (2016), Banff, Canada (2015), Guimarães, Portugal (2014), Ho Chi Minh City, Vietnam (2013), Salvador, Brazil (2012), Santander, Spain (2011), Fukuoka, Japan (2010), Suwon, South Korea (2009), Perugia, Italy (2008), Kuala Lumpur, Malaysia (2007), Glasgow, UK (2006), Singapore (2005), Assisi, Italy (2004), Montreal, Canada (2003), and (as ICCS) Amsterdam, the Netherlands (2002) and San Francisco, USA (2001).

Computational Science constitutes the main pillar of most present research, industrial, and commercial applications, and plays a unique role in exploiting innovative ICT technologies, and the ICCSA conference series has, accordingly, provided ample opportunities to researchers and industry practitioners to discuss new ideas, to share complex problems and their solutions, and to shape new trends in Computational Science. As the conference mirrors society from a scientific point of view, this year's undoubtedly dominant theme was large language models, machine learning, and Artificial Intelligence,

and their applications across the most diverse technological, economic, and industrial fields, amongst others.

The ICCSA 2026 conference included 57 workshops, focusing on topical issues of utmost importance to science, technology, and society: from new computational approaches for earth science, to mathematical methods for image processing, new statistical and optimisation methods, several Artificial Intelligence approaches, sustainability issues, smart cities and related technologies, to name a few. In addition, ICCSA 2026 included six general tracks covering computational science and its applications: Computational Methods, Algorithms and Scientific Applications; High-Performance Computing and Networks; Geometric Modelling, Graphics and Visualisation; Advanced and Emerging Applications; Information Systems and Technologies; and Urban and Regional Planning.

For these Workshops Proceedings, we accepted 328 full papers, 23 short papers, and 3 Ph.D. Showcase papers from a total of 1184 submissions (acceptance rate 29.9%). Reviews were single blind, and submissions received 2.6 reviews each, on average. In the Main Conference Proceedings, we accepted 119 full papers, 3 short papers, and 2 Ph.D. Showcase papers from 431 submissions to the General Tracks of the Conference (acceptance rate of 29.9%). We would like to convey our sincere appreciation to the workshop chairs and co-chairs and program committee members, for their diligent work, commitment, and dedication.

The success and consistent maintenance of the ICCSA conference series in general, and of ICCSA 2026 in particular, rely upon the support of many people: authors, presenters, participants, keynote speakers, workshop chairs, session chairs, Organizing Committee members, student volunteers, Program Committee members, Advisory Committee members, International Liaison chairs, reviewers, and other individuals in various roles. Thus, we take this opportunity to wholeheartedly thank each and every one.

We also wish to thank the publisher, Springer, for accepting the proceedings, and for their kind assistance and cooperation during the editing process. We would cordially like to invite you to refer to the ICCSA website https://iccsa.org, where you can find the relevant details regarding this academic endeavour and our event.

June 2026

Chiara Garau
Ana Maria A. C. Rocha
Osvaldo Gervasi
Beniamino Murgante

# Welcome Message from the Organizers

On behalf of the Local Organizing Committee of ICCSA 2026, it is our great pleasure to welcome you to the 26th International Conference on Computational Science and Its Applications, held from June 30 to July 3, 2026, at the University of Minho in Braga, Portugal.

We are deeply honoured by the trust placed in us by the ICCSA General Chairs in organizing another edition of this successful conference series. We hope that ICCSA 2026 provided an inspiring environment for scientific exchange, collaboration, and discussion among researchers from all over the world.

The conference took place at the University of Minho, one of the most prestigious higher education institutions in Portugal. Founded in 1973, the University of Minho has campuses in Braga and Guimaraes and is widely recognized for its academic excellence, research activity, and strong international outlook.

Braga, one of the oldest cities in Portugal, is renowned for its historical heritage, cultural vitality, and welcoming atmosphere.

Located in the heart of the Minho region, the city combines tradition with modernity, offering visitors renowned gastronomy, beautiful landscapes, and the unique character of *Vinho Verde* wine.

The scientific program of ICCSA 2026 included plenary lectures delivered by distinguished scientists, together with a broad range of workshops covering several areas of Computational Science and its Applications. We believe that the conference provided excellent opportunities to share ideas, discuss emerging challenges, and foster new collaborations.

In addition to the scientific sessions, participants had the opportunity to enjoy a rich social program.

Planned activities included a Welcome Reception at Largo do Paço, the Rectorate of the University of Minho, located in the former Archbishop's Palace - one of the most emblematic historical buildings in the city center; a *Vinho Verde* wine-tasting experience at Quinta d'Amares, where particiapnts could discover the art of winemaking; and a guided visit to the coastal city of Viana do Castelo, renowned for its maritime heritage, traditional architecture, and beautiful Atlantic scenery. The conference gala dinner took place at Colunata Eventos, located within the Bom Jesus do Monte sanctuary, a UNESCO World Heritage Site, where ICCSA participants enjoyed delicious recipes and a wonderful view over the city of Braga.

The success of ICCSA 2026 would not have been possible without the dedication and enthusiasm of many collaborators and volunteers, whose hard work and commitment greatly contributed to the organization of the conference.

On behalf of the Local Organizing Committee, it was our honour to warmly welcome you to the beautiful city of Braga and we hope you had an enjoyable and productive conference.

We enjoyed meeting you in Braga.

Sincerely yours,

On behalf of the Local Organizing Committee.

June 2026 Ana Maria A. C. Rocha

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## Advanced Mathematics and Computing Models in Complex Data-Intensive Computational Systems (AMCM 2026)

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## Computational Methods, Statistics and Industrial Mathematics (CMSIM 2026)

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## Computational Optimization and Applications (COA 2026)

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## Computational Methods in Advanced Networking Technologies (CoMANT 2026)

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## Computational Astrochemistry 2026 (CompAstro 2026)

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## Computational methods for Porous materials (CompPor 2026)

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## Workshop on Computational Science and HPC (CSHPC 2026)

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## Cities, Technologies and Planning (CTP 2026)

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## Evaluating Inner Areas Potentials (EIAP 2026)

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## sustainablE mobiLity and Last mIle lOgisTic in urban context (ELLIOT 2026)

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## Econometrics and Multidimensional Evaluation in Urban Environment (EMEUE 2026)

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## Ecosystem Services in Spacial Planning for climate neutral urban and rural areas (ESSP 2026)

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## The 16th International Workshop on Future Information System Technologies and Applications (FiSTA 2026)

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## Geographical Analysis, Urban Modeling, Spatial Statistics (Geog-And-Mod 2026)

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## Generative and Neuro-Symbolic Artificial Intelligence for Real-World Systems (GNS-AI 2026)

### Workshop Organizers

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| Regina Sousa | University of Minho, Portugal |

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## Geomatics for Resource Monitoring and Management (GRMM 2026)

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| Marco Locurcio | Polytechnic University of Bari, Italy |

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## International Workshop on Information and Knowledge in the Internet of Things (IKIT 2026)

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## Intelligent Sustainable Development: from Models to Real-World Impact (ISD 2026)

### Workshop Organizers

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## Multidimensional Evolutionary Evaluations for Transformative Approaches (MEETA 2026)

### Workshop Organizers

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| Gaia Daldanise | CNR Institute for Research on Innovation and Services for Development, Italy |
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## Building multi-dimensional Models for assessing complex Environmental Systems (MES 2026)

### Workshop Organizers

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| Marta Dell'Ovo | Politecnico di Milano, Italy |
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## Computational Mechanics, Intelligence, and Data (MIND 2026)

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## Modelling Liveable Cities: Techniques, Methods, Challenges, and Perspectives Behind the X-Minute City (MLC 2026)

### Workshop Organizers

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## Mathematical Methods for Image Processing and Understanding 2026 (MMIPU 2026)

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## MOdels and indicators for assessing and measuring the urban settlement deVElopment in the view of NET ZERO by 2050 (MOVEto0 2026)

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## Numerical Aspects in Machine Learning For Dynamical Systems (NAMLYS 2026)

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## Numerical Methods and Machine Learning in Science & Engineering (NMLSE 2026)

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## 6th Workshop on Privacy in the Cloud/Edge/IoT World 2026 (PCEIoT 2026)

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## Preserving Our Past: Spatial and Remote Sensing Technologies for Cultural Heritage in a Changing Climate (POP 2026)

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## Scientific Computing Infrastructure (SCI 2026)

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## Socio-Economic and Environmental Models for Land Use Management (SEMLUM 2026)

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## Ports and logistics of the future - Smartness and Sustainability (SmartPorts 2026)

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## Sustainable evolution of long-Distance frEight and paSsenger Transport (SOLIDEST 2026)

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## Sustainability Performance Assessment: Models, Approaches, and Applications Toward Interdisciplinary and Integrated Solutions (SPA 2026)

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## Specifics of smart cities development in Europe (SPEED 2026)

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## Smart, Safe, and Health Cities (SSHC 2026)

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## Smart and Sustainable Island Communities (SSIC 2026)

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## Sustainable Tourism Economy, Silk Road, Reuse and Enhancement of Cultural Heritage (STESilkRoad 2026)

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## Theoretical and Computational Chemistry and its Applications (TCCM 2026)

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## Transport Infrastructures for Smart Cities (TISC 2026)

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## Transforming Urban Analytics: The Impact of Crowdsourced Mapping and Advanced AI Techniques on Future Cities (Tr-UrbAna 2026)

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## From structural to TRAnsformative-change of City Environment: challenges & solutions & perspectives (TRACE 2026)

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## Urban Artificial Intelligence for Modelling, Analysis & Planning (Urban plAnnIng 2026)

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## Urban Space Accessibility and Mobilities (USAM 2026)

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## Virtual Reality, Augmented Reality and Applications (VRA 2026)

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## Workshop on Advanced and Computational Methods for Earth Science applications (WACM4ES 2026)

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# Plenary Lectures

# Digital Twins for Cities – The Rise of the Socio-Technical System

Claudia van der Laag

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**Abstract.** Cities are entering a new era in which digital twins are no longer simply technical replicas of urban systems, but evolving socio-technical infrastructures that shape how cities are planned, governed, and experienced. Across the world, urban digital twins are being adopted to address some of the most pressing challenges of our time — climate adaptation, urban resilience, mobility transitions, decarbonisation, infrastructure management, and inclusive governance. Yet as these technologies become increasingly sophisticated, a fundamental question emerges: can digital twins truly support more democratic and human-centred cities, or will they reinforce existing structures of power and expertise? In this keynote, Claudia van der Laag explores the transformation of urban digital twins from data-driven modelling tools into collaborative platforms for urban decision-making and societal change. It argues that the future of digital twins lies not only in advances in artificial intelligence, real-time data integration, simulation, and predictive analytics, but equally in the ability to connect technological innovation with governance, participation, and human agency. Drawing on emerging international research and practical case studies, the keynote examines the complex ecosystem surrounding urban digital twins, bringing together planners, policymakers, researchers, technologists, and communities. It highlights how digital twins increasingly function as meeting points between multiple forms of knowledge — technical, political, social, and experiential — and why interdisciplinary collaboration is essential for their success. The talk critically reflects on the tensions between technological ambition and civic inclusion, exploring themes such as transparency, interoperability, participation, and trust. It also discusses how digital twins can become powerful environments for scenario exploration, urban experimentation, and collective learning, enabling cities to better navigate uncertainty and complexity in an age of rapid urban transformation. Ultimately, this keynote presents a vision of digital twins not as neutral technological systems, but as living socio-technical infrastructures capable of reshaping urban governance itself. The challenge ahead is therefore not only how accurately cities can be modelled, but how inclusively they can be imagined, negotiated, and governed through these emerging digital environments.

# Prescriptive AI in Practice: Bridging Optimisation, Generative AI and Agentic Decision-Making

Bernardo Almada-Lobo

Universidade do Porto, Faculdade de Engenharia, INESC TEC, Portugal

**Abstract.** Prescriptive AI, viewed through the lens of mathematical optimisation and operations research, addresses complex business decision-making problems involving limited resources, multiple decision options and competing objectives. This talk considers the full decision pipeline: problem framing, model formulation, computational solution, implementation, monitoring and organisational adoption. The practical success of prescriptive AI depends less on algorithmic sophistication alone than on the quality of the translation between real-world decision contexts and formal optimisation models. In practice, this translation remains a major bottleneck. Objectives are often ambiguous, constraints are incomplete or tacit, data may be fragmented, and the operational consequences of a recommendation may be poorly understood. As a result, optimisation projects can fail even when the underlying mathematical model is technically sound. The talk will address the persistent gap between optimisation theory and deployment practice. While optimisation has generated substantial value in domains such as supply chain planning, logistics, production, revenue management, workforce planning and inventory control, many initiatives still face a significant risk of under-delivery. Common failure modes include incorrect problem framing, weak data readiness, brittle assumptions, infeasible or non-actionable recommendations, limited explainability, insufficient ownership by business users and inadequate post-deployment monitoring. Closing this gap requires moving from one-off model building to an operational lifecycle in which models are stress-tested, embedded in workflows, monitored for drift and revised as the business environment changes. Recent developments in generative and agentic AI create new opportunities to reduce these barriers. Generative AI can support the elicitation of decision-maker preferences, the structuring of unstructured operational knowledge, the drafting of candidate formulations and the explanation of model outputs in business language. Agentic AI can extend this role by orchestrating multi-step workflows that involve model formulation, solver-code generation, execution, debugging, infeasibility diagnosis, sensitivity analysis and human review. However, these capabilities should not be interpreted as replacing optimisation expertise. Rather, they create a new interface between human judgement, analytical modelling and computational decision support. This talk will discuss a cross-fertilisation agenda between optimisation, generative AI and agentic AI, with a focus on how these technologies should be calibrated to the decision at hand.

# Net-Zero Communities through Life Cycle Thinking: Canadian Lessons and Global Implications

Kasun Hewage

School of Engineering (Okanagan Campus), Clean Energy Research Centre (CERC), University of British Columbia (UBC), Canada

**Abstract.** This keynote presentation discusses how life cycle thinking supports the transformation of communities toward sustainable, resilient, and net-zero futures. Drawing on Canadian research, practice, and policy experience, the presentation highlights how integrated life cycle approaches can move beyond conventional carbon accounting to inform practical decision-making across buildings, infrastructure, energy systems, waste management, water systems, and industrial processes [1–8]. The keynote features research conducted at the Life Cycle Management Laboratory (LCML) at the University of British Columbia, Canada, an internationally recognized research hub led by Kasun Hewage. LCML brings together engineers, scientists, policy researchers, postdoctoral fellows, visiting scholars, and graduate researchers to translate data-intensive sustainability research into actionable climate solutions. The laboratory's work is organized around six interconnected research themes: energy systems, urban development, water systems, waste management, construction and asset management, and industrial processes and products. Together, these themes provide an integrated platform for advancing life cycle–based pathways to net-zero communities. Supported by strong partnerships with government, industry, and community stakeholders, LCML has contributed to a substantial body of applied sustainability research, including more than 400 journal articles, 100 conference papers, and numerous technical reports that have informed real-world planning and implementation. This keynote presentation highlights selected success stories that demonstrate how life cycle thinking can be translated into practical strategies for reducing environmental impacts while strengthening community resilience. These insights are especially relevant to the interdisciplinary focus of ICCSA 2026.

## References

1. Weerasinghe, O., Hewage, K., Razi, F., Fatmi, M., Sadiq, R.: Applicability of land use models for sustainable urban planning: a review. J. Urban Plann. Dev. ASCE, **151**(3) (2025). https://doi.org/10.1061/JUPDDM.UPENG-5705

2. Sultana, S. R., et al.: Looking beyond energy efficiency targets: life cycle sustainability of mechanical and water heating equipment in Canadian homes. J. Clean. Prod. Elsevier, **473**, 143469 (2024). https://doi.org/10.1016/j.jclepro.2024.143469
3. Liyanage, D. R., Hewage, K., Hussain, S. H., Razi, F., Sadiq, R.: Climate adaptation of existing buildings: a critical review on planning energy retrofit strategies for future climate. Renew. Sustain. Energy Rev. Elsevier, **199**, 114476 (2024). https://doi.org/10.1016/j.rser.2024.114476
4. Liyanage, D. R., Hewage, K., Karunathilake, H., Sadiq, R.: Feasibility of carbon-capturing in building heating systems: a life cycle thinking-based approach. International J. Greenhouse Gas Control. Elsevier, **132** (2023). https://doi.org/10.1016/j.ijggc.2023.104056
5. Moudgil, V., Sadiq, R., Bakhtavar, E., Paudel, A., Hewage, K.: A cloud-oriented data-analysis framework to analyze peak demand dynamics in institutional building clusters. Sustain. Cities Soci. Elsevier, **111**, 105553 (2024). https://doi.org/10.1016/j.scs.2024.105553
6. Liyanage, D. R., Hewage, K., Ghobadi, M., Sadiq, R.: Thermal resiliency of single-family housing stock under extreme hot and cold conditions. Energy Build. Elsevier, **323**, 114809 (2024). https://doi.org/10.1016/j.enbuild.2024.114809
7. Wijayasekera, S. C., et al.: Sustainability of waste-to-hydrogen conversion pathways: a life cycle thinking-based assessment. Energy Convers. Manage. Elsevier, **270** (2022). https://doi.org/10.1016/j.enconman.2022.116218
8. Jayasena, A., Hewage, K., Siddiqui, O., Sadiq, R.: Socio-economic and environmental cost-benefit analysis of passive houses: a life cycle perspective. J. Clean. Prod. Elsevier, **373** (2022). https://doi.org/10.1016/j.jclepro.2022.133718

# Machine Learning Based Methodologies for Grape and Wine Production

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**Abstract.** Wine production is a major area in the Portuguese economy. The sector accounts for approximately 2.6% of Portugal's GDP, and is crucial to the development of inland regions. Wine quality depends on grape quality, which is a result of different factors such as harvesting at the optimal point of maturity, or selecting the grapes according to quality features. The growing importance of precision agriculture demands novel methods to make the most out of the data generated. Machine learning approaches are particularly suitable for modelling complex processes, where too many arguments are involved. Many of the agricultural processes such as yield estimation or ripening fall into this category. However, several challenges may arise: even if models are available for particular cases, general models are difficult to come by, largely due to the high variability involved; with such models, there is a need for huge amounts of data, in a way which will not always be easy to obtain. This is particularly true in the case of grape production and the wine industry, where the number of grape varieties, climate, soil, etc., introduce a degree of variability that is uncommon in other sectors. One way of obtaining more information in such cases has been the use of images, whether RGB, multi-spectral, or hyperspectral. The use of images introduces additional challenges, such as data size and lighting conditions, which underscores the need for data-driven modelling methodologies. The use of machine learning (ML) techniques combined with images has been establishing itself as a viable alternative for predicting yields or quality parameters in grapes, and assisting with critical harvesting decisions. Several ML approaches have been proposed to handle such data characteristics, but selecting a suitable methodology that best addresses the problem under study and making sure it generalizes well is, most of the time, a cumbersome task. We will address three wine and grape production problems, yield estimation, grape quality assessment, and illness detection, presenting different difficulties. Yield estimation is a major aspect in the wine production industry. The number of berries is one of the most relevant yield aspects, and can be estimated using computer vision, namely image segmentation algorithms. Lighting is one of the key factors in computer vision approaches, and occlusions—which are common in this problem—can be minimized, but require estimation models to achieve reliable results. Early illness detection is, of course, of the utmost importance, with an impact on production and quality. Detecting early symptoms and distinguishing them from other conditions is a difficult task, which makes the use of machine learning algorithms advisable, using automatic visual inspection of the leaves, addressed as a pixel-based classification problem. However, the available datasets are limited and

complex to compile, as different diseases typically require very specific time-frames and locations. The use of generative models to overcome this obstacle, in conjunction with robust classification models, leads to models that are intended to be as general as possible. The evaluation of the grape's maturation profile based on the evolution of their oenological parameters over time is one of the most important aspects for ensuring wine quality, playing a decisive role in the definition of the optimal time for harvesting. The use of hyperspectral imaging combined with learning algorithms represents a faster and non-destructive grape ripeness assessment method. We focus in two fundamental aspects to address the resulting data variability: a possible wavelength bands selection (with the purpose of reducing the dimensionality of data without losing predictive power) and the generalization ability of the ML model under such demanding conditions.

# Contents

**Socio-Economic and Environmental Models for Land Use Management (SEMLUM 2026)**


Mispricing Energy Efficiency? Discrete Labels, Continuous Performance, and Policy Gaps in Urban Housing Markets . . . . . 3
*Giovanni Luzzatto, Marina Bertolini, Luca Doretti, Duccio Gamannossi degl'Innocenti , Giuliano Marella, and Rubina Canesi*

Composite Indices for Urban Blight Assessment: A Decision Support Approach for Urban Regeneration . . . . . 21
*Pierluigi Morano, Emma Sabatelli, Debora Anelli, and Francesco Tajani*

Managing Tourism Pressure: Impacts on Urban Real Estate in Italy . . . . . 38
*Paola Amoruso, Pierluigi Morano, Felicia Di Liddo, Marco Locurcio, and Francesco Tajani*

An Optimization Method to Ensure Reliability in the Assessment of Special Properties . . . . . 50
*Benedetto Manganelli, Melania Arenas Morente, Giuseppe Cerullo, Francesco Paolo Del Giudice, and Francesco Tajani*

From Literature Evidence to Method Selection: A Two-Layer MCDA Framework for Project Alternative Evaluation in Public Procurement . . . . . 62
*Debora Anelli, Francesco Tajani, Pierluigi Morano, João Zambujal-Oliveira, and Maria Rosaria Guarini*

A Territorial Adaptive Composite Index for Urban Energy Poverty: Local Vulnerability Drivers . . . . . 79
*Alice Renè Di Rocco, Maria Rosa Trovato, and Francesco Nocera*

Holistic Sustainability Evaluation: Preliminary Phases for a Methodology Application in Docks Dora, Turin (Italy) . . . . . 98
*Cristina Coscia, Francesca Pasquino, Elena Fregonara, and Chiara Senatore*

Balancing Sustainability and Performance: A Multi-criteria Comparison of Recycled, Bio-Based and Low-Carbon Materials Using the Analytic Hierarchy Process (AHP) . . . . . 116
*João Zambujal-Oliveira and Debora Anelli*

An Integrated Framework for ESG Assessment and Action Planning in Eco-Industrial Parks ..... 132
*Pierluigi Morano, Debora Anelli, Francesca Fariello, Emma Sabatelli, and Francesco Tajani*

A Methodological Framework for Identifying Compromise Solutions in Complex Urban Squatting Conditions ..... 145
*Pierluigi Morano, Debora Anelli, Emma Sabatelli, and Francesca Fariello*

Rent and Buy Market Interactions: a Focus on Energy Performance and Building Technological Systems ..... 156
*Pierluigi Morano, Felicia Di Liddo, Aurora Ruggeri, Francesco Tajani, and Giuseppe Emmi*

The Impact of Different Polluting Site Typologies on Residential Real Estate Values: a Systematic Literature Review ..... 172
*Pierluigi Morano, Felicia Di Liddo, Marco Locurcio, Antonella Roma, and Francesca Fariello*

A Methodological Approach to Assessing the Territorial Impacts of Industrial Decarbonisation on Real Estate Values ..... 190
*Pierluigi Morano, Felicia Di Liddo, Francesca Fariello, and Marco Locurcio*

**Sustainability Performance Assessment: Models, Approaches, and Applications Toward Interdisciplinary and Integrated Solutions (SPA 2026)**

The Corporate Social Responsibility in Agrifood System: An Integrated Methodological Approach to Assessing Corporate Integration and Communication ..... 207
*Alessandro Scuderi, Luisa Sturiale, Lorenzo Nicotra, and Marcella Bucca*

Tourism as a Spatially Structured Territorial System: A STESY-Based Interpretation of the Bay of Cádiz Tourism Ecosystem ..... 224
*Macarena León, Marieta Agea, Ángela Pimentel, Rachele Vanessa Gatto, and Francesco Scorza*

From Metropolitan Shadow to Territorial Autonomy: A Spatial and Strategic Assessment of the Tourism Ecosystem in North-Holland ..... 236
*Alberico Tedesco, Rachele Vanessa Gatto, and Francesco Scorza*

The Integration of Strategic Environmental Assessment into Urban Planning in the Emilia-Romagna Region ..... 250
*Simona Tondelli and Elisa Conticelli*

Integrating Wine Specialization into a Territorial Tourism Dimension: A STESY-Based Interpretation of La Rioja ..... 264
*Erica Rosa Matera, Annalisa Lo Re, Annamaria Giannandrea, Rachele Vanessa Gatto, and Francesco Scorza*

Rebalancing Tourism Flows in Kotor, Montenegro: Application of STESY Framework for Transitioning from Cruise-Based Pressure to Extended Stay .... 277
*Carmine Campagna, Michele Pio Petronella, Martina Sassone, Rachele Vanessa Gatto, and Francesco Scorza*

From Linear Accessibility to Distributed Territorial Activation: A STESY-Based Approach for the Lofoten Islands ..... 289
*Antonella Dattoli, Sabrina Giannitti, Consita Palmieri, Rachele Vanessa Gatto, and Francesco Scorza*

Symbiotic Territories: Application of the STESY Framework for Rebalancing Tourism Flows Between Granada and Sierra Nevada ..... 302
*Martina Caterina Addabbo, Sonia Legrottaglie, Dalila Sigrisi, Rachele Vanessa Gatto, and Francesco Scorza*

Comparing User Preference for AI-Assisted Search bar, AI+VR Search-Interaction, Gamified Quiz-Driven Product Bundling: Towards Cross-Disciplinary Intelligence and Sustainability ..... 315
*Chien-Sing Lee, Amanda Sze-Yuen Ng, Zi-En Fong, Xin-Tian Goh, Rachel Yee-Enn Choong, and Jia-Wen Yew*

From Mega-Event to Measurable Legacy: Localising the SDGs Through the UEFA EURO 2032 Sustainability Concept and Strategy ..... 336
*Andrea De Toni, Alice Franchina, and Eugenio Morello*

**Specifics of Smart Cities Development in Europe (SPEED 2026)**

Small and Medium-Sized Enterprises as Providers of Regional Environmental Open Data: Connecting LCA Indicators with ESG Reporting and Sustainable Regional Development ..... 353
*Laura Miháliková and Denisa Malá*

Smart Governance and Data-Driven Employment Policies in Less Developed Regions: A Regional Governance Model from the Banská Bystrica Case ..... 368
*Lucia Dobrotová*

Integrating Behavioral Economics and IoT for Energy Efficiency in Smart Cities: A Multi-case Study Approach ..... 386
*Maria Murray Svidronova*

Smart Innovations in Biosphere Reserves ..... 402
*Katarína Vitálišová, Mária Reháková, Anna Vaňová, and Darina Rojíková*

Development Agency as Source of Social Innovation in Catching-up Region: Evidence from Slovakia ..... 418
*Katarína Sýkorová*

Assess Flooding Impacts in Urban Environment: Integrating Fluid-Dynamic Simulations in Smart City Digital Twin ..... 435
*Enrico Collini, Marco Fanfani, Federico Galli, Paolo Nesi, and Paola Zamperlin*

Understanding Short-Term Rental Monitoring for Sustainable Data-Driven Destination Management ..... 450
*Zuzana Gajdošíková, Tomáš Gajdošík, and Beáta Vaneková*

**Smart, Safe, and Health Cities (SSHC 2026)**

Integrating Computational Design and Space Syntax in Urban Planning and Design Education: A Data-Driven Pedagogical Model ..... 465
*Chiara Garau, Mana Dastoum, and Reza Askarizad*

Associations and Public Facilities as Infrastructures of Slowness. Proximity and Sociality at Neighbourhood Level ..... 484
*Giulia Pedilarco, Barbara Caselli, and Michele Zazzi*

Urban Data-Driven Energy Planning: Insights and Challenges from Italy and Portugal ..... 501
*Carmen Guida, Paulo Ricardo Batista, and Gerardo Carpentieri*

Configurational Accessibility and Mobility Patterns in a Port-City Interface: A Space Syntax Analysis of Central Catania ..... 518
*Vincenza Torrisi, Sheila Bellia, Reza Askarizad, Matteo Ignaccolo, and Chiara Garau*

A Digital-Twin-Oriented Monitoring Framework for Traffic-Related Environmental Hotspots and Future Nature-Based Solutions in Catania ..... 536
*Vincenza Torrisi, Sheila Bellia, Matteo Ignaccolo, Miriam Distefano, Alessandro Zaldei, Giovanni Avola, and Ezio Riggi*

Remote Work and Residential Attractiveness Across the Centre–Periphery Gradient ..... 553
*Veranika Kaleyeva*

A Data-Driven Framework for Cycle Path Quality: Integrating User Perception and Sensing . . . . . 566
*Martina Carra, Roberto Ventura, Stefano Raccagni, Michele Pezzagno, David Vetturi, and Benedetto Barabino*

**Transport Infrastructures for Smart Cities (TISC 2026)**

Operationalizing National Road Design Guidelines: A Python Tool for Geometric Design Consistency Assessment . . . . . 581
*Lambros Mitropoulos and Katerina Voudouri*

Circular Management of Tunnel Excavation Materials in Transport Infrastructures: An LCA Approach . . . . . 593
*Mattia Di Sessa, Daniele Soraggi, Orazio Baglieri, and Ilaria Delponte*

Reclaiming the Sea: Cagliari's Waterfront Renaissance . . . . . 612
*Kevin Panetto, Riccardo Zedda, Mauro Coni, Chiara Garau, Francesca Maltinti, and Nicoletta Rassu*

**Author Index** . . . . . 629

# Socio-Economic and Environmental Models for Land Use Management (SEMLUM 2026)

# Mispricing Energy Efficiency? Discrete Labels, Continuous Performance, and Policy Gaps in Urban Housing Markets

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**Abstract.** Energy Performance Certificates (EPCs) have been designed to overcome information asymmetries in housing markets, making the energy efficiency of homes an observable and comparable property characteristic. However, the energy classes used by EPCs can influence housing prices in ways that go beyond the underlying level of energy performance itself. This paper investigates whether the market valuation of energy efficiency follows the logic of energy consumption or the structure of EPC classes as discrete labels. Using listing data from six urban housing markets in the Veneto region (Italy), we estimate city-specific hedonic price models with spatial controls under two alternative representations of energy efficiency: a categorical one, based on EPC class dummies, and a continuous one, derived from representative values of non-renewable primary energy consumption. Results show that energy efficiency positively impacts housing prices, but capitalization patterns differ across markets and model specifications. While in some cities price premiums change smoothly along the EPC ladder and largely correspond to the energy performance gradient, in other cities thresholds, discontinuities, and non-monotonicity can be detected. These findings suggest that the representation of energy efficiency is not merely a modeling choice, but a substantive issue for both empirical analysis and policy design.

**Keywords:** Energy efficiency · Green premium · Housing markets

## 1 Introduction

The transition of the residential building stock towards better energy efficiency (EE) represents one of the key challenges in modern environmental and urban

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policy. In the European Union, buildings account for around 40% of total energy consumption and 36% of greenhouse gas emissions, making improvements in building efficiency a key pillar of decarbonization strategies. The long durability of buildings and their slow adaptation make EE not only an environmental issue but an economic one as well, with direct consequences for households and investors and important implications for the Real Estate (RE) market dynamics. A series of amendments to the Energy Performance of Buildings Directive (EPBD) contributed to further strengthening the regulatory and information-based system for managing building efficiency. One of the central instruments introduced through the EPBDs is the Energy Performance Certificate (EPC), which provides a standardized measure of EE through a publicly disclosed classification system. The introduction of such a certificate is intended to reduce the problem of information asymmetry and allow market participants to incorporate EE information into property valuation.

From a theoretical point of view, the relationship between EE and housing prices should reflect the net present value of future cost savings: dwellings with higher EE require less energy to produce the same amount of housing services, generating a stream of benefits that should be capitalized into property prices. Thus, the relationship between housing prices and EE should be monotonic and proportional to the expected level of savings. Empirically, however, this relationship appears difficult to detect due to high uncertainty concerning the parameters needed to estimate expected savings, in particular consumption patterns, current and future energy prices, and discount rates. For this reason, empirical studies typically rely on a physical measure of energy performance (mostly energy consumption or energy performance index) as a proxy for the future stream of energy savings. However, market participants rarely observe or process energy information in this form. In practice, they encounter EE primarily through EPC labels. Such a representation implies that labels correspond to intervals of performance rather than to precise values, and these intervals are not equally spaced along the energy scale. Identical transitions between adjacent classes therefore do not correspond to uniform changes in underlying consumption. The informational structure conveyed by EPCs is thus inherently discrete and non-linear. As a result, housing prices may respond more strongly to label membership than to the continuous gradient of energy performance itself.

This issue is relevant not only from an economic perspective but also from a policy one, since it concerns not only whether EE is capitalized in housing prices but also whether this capitalization is consistent with the underlying energy performance gradient. If prices respond disproportionately to discrete labels, the resulting market signals may deviate from the actual distribution of expected energy savings. Such deviations may reflect bounded rationality, informational frictions, or the fact that EPC labels also act as broader signals of housing quality. From a policy perspective, this matters because EPCs are intended to support efficient choices by improving transparency. When market responses are influenced by simplified signals such as labels, however, policy design becomes more complex and may require structured decision-support approaches capable

of integrating multiple dimensions and stakeholders' preferences. In this context, multicriteria methods have been proposed as useful tools to support the design of energy policies and incentive schemes [1–4].

This paper addresses the identified issue by comparing two alternative representations of energy performance. The first approach uses categorical EPC classes as explanatory variables to capture the discrete, label-based structure through which energy information is disclosed in the market. The second approach relies on a linear relationship that uses the non-renewable primary energy consumption associated with each class as an explanatory variable, providing a benchmark consistent with a proportional valuation of energy performance. The comparison is conducted across six local housing markets in the Veneto region, allowing capitalization patterns to vary across cities. By contrasting the price schedules implied by the two specifications, the study examines whether the observed structure of energy premiums is aligned with the underlying consumption gradient or instead reflects discontinuous and uneven responses to EPC labels.

The remainder of the paper is organized as follows. The literature review is presented in Sect. 2, where special attention is paid to alternative ways to represent energy performance in RE models. Section 3 presents the methodological approach and the econometric models. Section 4 describes the case study and the dataset. Section 5 discusses the empirical findings and compares the capitalization pattern generated by the two alternative approaches. Section 6 concludes.

## 2 Literature Review

In the past two decades, the widespread adoption of EPCs in residential markets has helped establish EE as an explicit property attribute, making it a well-studied topic in RE. With a rapidly growing body of literature on the topic, one broad empirical regularity has become increasingly clear: energy-efficient houses tend to be priced above otherwise comparable properties. This regularity is typically referred to as the "green premium". Nonetheless, the literature is marked by considerable diversity in the estimated effects and methodological inconsistencies. An important aspect of this heterogeneity pertains to the way energy performance is operationalized in models. Specifically, three main strategies can be identified.

The first specification involves modeling energy performance as a continuous variable. Such measures may include, among others, energy consumption, energy expenditure, or synthetic performance indices. From the perspective of economic theory, this strategy is the most intuitive, since it preserves the physical dimension of energy consumption and implies that price effects scale proportionally with potential savings. Empirical evidence broadly supports this interpretation. In the United States, a 1% decrease in energy expenditure per square meter has been associated with an increase of about 2% in the self-reported house value [5]. Similarly, positive effects are estimated in European housing markets. For instance, a 10% improvement in a continuous energy performance index

is associated with an increase of around 2.2% in prices in the Dutch housing market [6], while in Sweden a 1% drop in energy consumption relates to a 0.4% growth in transaction prices [7]. In Germany, a decrease of 100 kWh/m$^2$ in energy consumption is associated with a 6.9% price premium [8], and a 1% increase in the energy performance score is associated with a 0.11% increase in price [9].

The second strategy treats energy performance as a set of distinct EPC classes that serve as categorical independent variables, each receiving a dedicated coefficient and thus producing a flexible price schedule. This specification closely resembles the way in which energy performance is communicated to market participants through distinct classes or labels rather than through consumption values. However, in practice, this strategy often results in irregular premiums concentrated at top-rated classes, with limited statistical significance at intermediate levels. This pattern emerges, for example, in Barcelona, where only certain EPC classes have a significant impact on price and there is substantial heterogeneity in the effects observed across different market segments [10]. In Alicante, evidence suggests that the absence of information disclosure may work in favor of less efficient houses, which trade close to more efficient properties [11].

Some researchers adopt an intermediate approach by representing EPC classes as numeric or ordinal variables, assigning, for instance, values from 1 (class G) to 7 (class A) and estimating a single linear effect [12–15]. While this strategy is concise and preserves the ordering of energy performance, it implies strong assumptions: all classes are equally spaced in terms of energy consumption and the price premium associated with moving from one class to the next is constant. As a result, the estimate should be interpreted as an average gradient that is likely to conceal possible discontinuities, threshold effects, and non-linearity.

Finally, a limited but especially valuable set of studies compares continuous and categorical representations within a consistent framework. These contributions are particularly important because the two representations cannot be regarded simply as different codings of the same information. Indeed, when applied in the Belfast housing market, both strategies result in positive premiums, although the categorical specification reveals more pronounced differences across market segments [16]. Similar patterns have been found in Dublin and in the England and Wales housing markets, with energy scores and EPC classes showing comparable but not identical patterns [17,18]. These findings suggest that continuous and categorical models may capture somewhat different facets of market behavior. However, a systematic, in-depth comparison of the two approaches across local markets within a single empirical setup is still relatively uncommon. In the vast majority of cases, researchers view them as alternative methods and do not test whether categorical price schedules are consistent with the corresponding continuous energy performance gradient. As a result, the literature still lacks a systematic assessment of the discrepancy between the two strategies. This argument is further supported by recent regression discontinuity evidence. Studying the French housing market, Lu and Spaenjers [19] document significant discontinuities in the estimated price premiums at every threshold between consecutive classes, despite smooth changes in underlying energy con-

sumption. Estimated discontinuities range between 1.9% and 4.5%, indicating that the label itself adds an effect beyond the continuous measure of energy performance. This finding suggests that market valuations may depend on EPC classes not just as a proxy for EE but as salient informational labels. Consistent behavioral evidence in this context shows that many households have poor understanding of EPCs and interpret energy classes as quality ratings rather than as precise indicators of future energy consumption [20].

Overall, the literature highlights an important inconsistency in current understanding. Continuous representations are more consistent with economic theory and assume a proportional relationship between prices and the energy performance gradient, while categorical ones better reflect the way information is communicated in the market but lead to irregular premium distributions and sometimes discontinuous pricing patterns. These two specifications reflect distinct ways in which information processing takes place: continuous models correspond to the scenario in which buyers fully internalize their marginal energy savings, while categorical models describe situations where labels serve as salient cues for the valuation process. Despite their theoretical importance, relatively few papers examine whether different approaches yield different results and how consistent the price schedules implied by categorical specifications are with the underlying energy performance gradient. This paper addresses this gap by adopting both strategies in a multi-city setting and comparing the distribution of class-based premiums with the linear benchmark implied by energy consumption.

## 3 Methodological Framework

The empirical strategy involves three stages designed to estimate and compare the price premiums associated with EE through two different representations of energy performance: categorical, based on EPC classes, and continuous, based on energy consumption. Each city is analyzed independently to account for different capitalization processes in distinct local housing markets. To maintain consistency across all estimations, both approaches use the same dataset, control variables, and spatial structure. Any discrepancy in the price schedule between the two models can therefore be attributed to the way energy performance is defined.

### 3.1 Phase 1: Baseline Hedonic Models

Phase 1 adopts a standard hedonic pricing approach, under which housing prices reflect the implicit valuation of a bundle of dwelling attributes [21,22]. For each city, the following semi-log specification is estimated:

$$\ln(p_i) = \mathbf{X}_i'\boldsymbol{\beta} + \alpha_{\mathrm{OMI}(i)} + f(E_i) + \varepsilon_i, \tag{1}$$

where $\ln(p_i)$ denotes the logarithm of the listing price per square meter of dwelling $i$; $\mathbf{X}_i$ includes structural characteristics, building attributes, and amenities; $\alpha_{\mathrm{OMI}(i)}$ denotes a fixed effect associated with the Osservatorio del Mercato

Immobiliare (OMI) microzone of dwelling $i$; and $f(E_i)$ represents the component of the hedonic price function associated with energy performance. Estimated coefficients are interpreted as semi-elasticities, with percentage effects computed as $(e^{\beta} - 1) \times 100$.

In the first specification (A), energy performance is represented by six EPC class dummies, with class G used as the reference category and classes A1 to A4 aggregated into a single group:

$$f_A(E_i) = \sum_{k \in \mathcal{K}} \theta_k^A EPC_{i,k}, \qquad \mathcal{K} = \{A, B, C, D, E, F\}. \tag{2}$$

In the second specification (B), energy performance is modeled as a continuous variable through the non-renewable primary energy performance index ($\text{EP}_{gl,nren}$):

$$f_B(E_i) = \theta^B \, EP_{gl,nren,i}. \tag{3}$$

Under standard capitalization theory, the coefficient is expected to be negative, reflecting the inverse relationship between energy consumption and property values. Since individual-level values of $\text{EP}_{gl,nren}$ are not directly available for listings, EPC classes are mapped into a continuous proxy by assigning each class the midpoint of its relative $\text{EP}_{gl,nren}$ interval. These values should not be interpreted as absolute energy performance levels, but as normalized class-specific indicators, expressed relative to the reference building used in the certification system. For class G, which is open-ended, a representative value is obtained by extending the consumption gradient across adjacent classes, using a linear approximation based on the variation between contiguous classes. This approximation is necessary given the data availability constraints and is consistent with the structure of the certification system. However, it can introduce measurement error in the continuous specification, as within-class heterogeneity in energy performance is ignored, thereby reducing the effective variation in the explanatory variable. Table 1 reports the representative values used in the analysis.

**Table 1.** Relative representative values of $\text{EP}_{gl,nren}$ by EPC class.

| EPC class | $\text{EP}_{gl,nren}$ |
|---|---|
| A | 0.50 |
| B | 1.10 |
| C | 1.35 |
| D | 1.75 |
| E | 2.30 |
| F | 3.05 |
| G | 3.97 |

### 3.2 Phase 2: Spatial Diagnostics and Spatial Model Specification

Housing prices are typically characterized by spatial dependence, as nearby dwellings share locational amenities, neighborhood characteristics, and local market dynamics. Ignoring this dependence may lead to biased or inefficient parameter estimates [23]. For this reason, the baseline OLS models are complemented by spatial diagnostics.

Residual spatial autocorrelation is first assessed using Moran's I statistic:

$$I = \frac{n}{S_0} \frac{\mathbf{e}'\mathbf{W}\mathbf{e}}{\mathbf{e}'\mathbf{e}}, \tag{4}$$

where $\mathbf{e}$ is the vector of residuals, $\mathbf{W}$ is a city-specific spatial weight matrix based on a $k$-nearest-neighbors structure, and $S_0$ is the sum of spatial weights. For each city, the minimum number of neighbors required to ensure a fully connected spatial graph is selected. When significant spatial dependence is detected, Lagrange Multiplier diagnostics are used to guide model selection. If dependence is consistent with a spatial lag process, a Spatial Autoregressive (SAR) model is estimated:

$$\mathbf{y} = \rho\mathbf{W}\mathbf{y} + \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon}, \tag{5}$$

where $\rho$ captures endogenous spatial spillover effects in price. If dependence instead reflects omitted spatially correlated factors, a Spatial Error Model (SEM) is adopted:

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \mathbf{u}, \quad \mathbf{u} = \lambda\mathbf{W}\mathbf{u} + \boldsymbol{\varepsilon}, \tag{6}$$

where $\lambda$ measures the strength of spatial correlation in the error term. Since the two model specifications differ only in the coding of energy performance and are otherwise estimated on the same data with the same controls, the selected spatial structure is expected to remain stable within each city. This is important because it allows the comparison between categorical and continuous representations to be interpreted as substantive rather than as an artifact of different spatial specifications.

### 3.3 Phase 3: Comparison of Pricing Structures

The final stage involves the comparison of the price schedules generated by the two representations of energy performance. While the categorical approach generates class premiums relative to class G, the continuous approach provides a linear price-consumption schedule. To obtain comparable class premiums under the continuous approach, the estimated slope coefficient is evaluated at the representative $\mathrm{EP}_{gl,nren}$ levels for each EPC class. This comparison is particularly informative because both specifications are estimated using the same empirical setup—the same city, the same sample, the same controls, and the same spatial structure. Any difference between the price schedules is therefore not driven by technical aspects of estimation, but rather by whether market prices follow energy consumption on a proportional basis or respond to the labeling process inherent in EPC classes.

The analysis is conducted graphically and quantitatively. Graphically, class premiums are plotted against the representative consumption levels and compared with the corresponding linear benchmark implied by the continuous specification. This allows for direct detection of threshold effects, non-monotonicity, compression of premiums in intermediate classes, or disproportionate premiums at the highest efficiency levels. Numerically, the gap between the two price schedules is measured, for each city, as the sum of absolute differences between the observed class-based premiums $\theta_k^A$ and their continuous benchmark counterparts $\theta_k^B$:

$$D_{A,B} = \sum_{k=1}^{6} \left| \theta_k^A - \theta_k^B \right|. \tag{7}$$

In this comparison, $\theta_k^B$ denotes the class-specific premium implied by the continuous model, obtained by evaluating the estimated consumption coefficient at the representative $\mathrm{EP}_{gl,nren}$ value of class $k$ relative to class G. Higher values of $D_{A,B}$ indicate a greater divergence between the observed class-based pricing structure and the smooth proportional benchmark. Taken together, these steps provide a detailed characterization of how EE is priced in each city, making it possible to assess whether the market signal associated with EPCs is consistent with the continuous gradient of energy performance or whether it exhibits systematic distortions.

## 4 Case Study and Data

The empirical analysis focuses on six provincial capitals of the Veneto region: Padova, Rovigo, Treviso, Venezia, Verona, and Vicenza. The choice of these municipalities reflects the design of a comparative study aimed at assessing how energy performance is reflected in prices in different urban environments operating under the same institutional setup. There are considerable differences across these markets regarding price levels, building stock composition, urban density, and socio-economic conditions. This heterogeneity matters because it affects both the distribution of EPC classes and the economic environment in which those certificates are evaluated. At the same time, any meaningful comparison between cities requires a consistent measure of EE. This requirement is satisfied by the Italian Energy Performance Certificate (Attestato di Prestazione Energetica—APE), which classifies buildings on the basis of their $\mathrm{EP}_{gl,nren}$. This common certification framework ensures that cross-city differences in estimated price schedules can be interpreted as market-specific rather than measurement artifacts.

The dataset encompasses 5,910 residential listings collected from online RE platforms in January 2026. In the absence of publicly accessible transaction-level microdata for Italy, listing prices are widely used in empirical housing market research [15,24,25]. Although asking prices typically differ from transaction prices due to negotiation dynamics, available evidence indicates that average negotiation margins in the north-eastern Italian residential market are limited

to around 5% [26]. The discount is assumed to be relatively stable across dwelling types and market segments, and in a large and heterogeneous sample such as the one considered here, extreme negotiation outcomes are likely to average out. Moreover, the adoption of a log-linear specification implies that the analysis focuses on proportional price differentials rather than absolute price levels: since a stable negotiation margin acts as a near-constant scaling factor, its effect on estimated percentage premiums is neutralized. This makes listing prices a suitable basis for estimating and comparing energy price premiums, while acknowledging that potential systematic variation in negotiation discounts across different property types cannot be directly tested and represents a residual source of uncertainty in the estimates.

To improve the quality and comparability of the data, the sample is limited to listings published no more than six months before data retrieval. Observations lacking geographic coordinates are omitted, since geographic location plays a crucial role in the analysis. Listings with missing price information, unusual transaction types (such as auctions, bare ownership transactions, and transactions involving several properties) are filtered out, along with extreme outliers with prices below €50,000 or above €3,000,000. Duplicates are removed as well. Additional processing involves combining the structured listing information with text-extracted variables to fill gaps in the data on various property attributes, such as energy class, building condition, and building age. The final sample consists of 2,242 observations, distributed across cities as follows: Padova (693), Rovigo (159), Treviso (328), Venezia (392), Verona (326), and Vicenza (308). Average price per square meter varies from approximately €1,250 in Rovigo to more than €3,800 in Venezia, reflecting differences in market positioning and local demand conditions. For each property, the dataset includes information about property size, number of rooms and bathrooms, building age, building condition, and a large set of amenities. Each observation is matched to its OMI microzone, whose fixed effect accounts for within-city locational differences in the models. Energy performance is recoded according to the Italian EPC scale, ranging from A4 (best class) to G (worst class). In order to keep the results interpretable and to preserve sufficient numbers of observations in each class, all subclasses of class A (A4–A1) are aggregated into a single A category. Finally, in line with the methodology described in Sect. 3, each class is matched to the corresponding relative value of $EP_{gl,nren}$.

Figure 1 shows the distribution of EPC classes in each city and highlights considerable variations in the housing stock composition. Treviso, Vicenza, and Padova display relatively large shares of properties in the highest-rated classes, whereas Rovigo and Venezia show relatively larger shares of low-rated properties. These distributional differences partly reflect the quality composition of local housing supply. Treviso and Padova, for instance, have seen substantial recent construction activity, which tends to concentrate in the higher EPC classes. By contrast, Rovigo and Venezia display an older and less recently renovated building stock, which translates into lower average energy performance. This context is relevant for interpreting the econometric results, since the capitalization of

EE is likely to interact with both the informational environment and the supply composition of each local market.

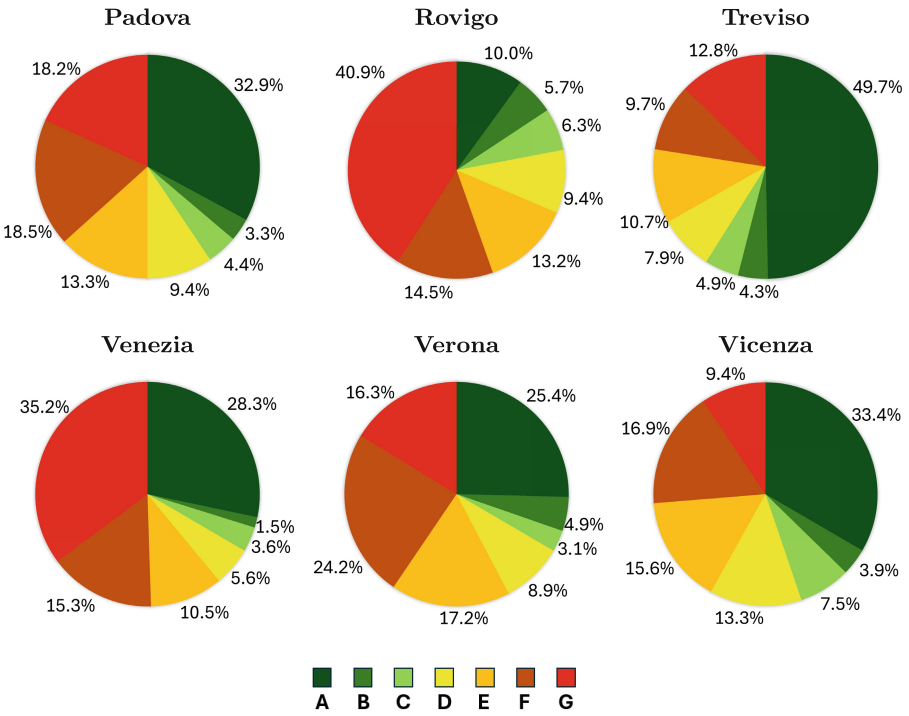


**Fig. 1.** Distribution of EPC classes across cities.

Table 2 summarizes the distribution of the main categorical housing characteristics by city. The descriptive evidence confirms strong cross-city heterogeneity in dwelling types, construction periods, and building conditions. This broader variation provides essential context for the econometric analysis, since the capitalization of energy performance is likely to interact with the composition and quality of the local housing stock.

## 5 Results and Discussion

EE is positively valued in all six housing markets, although the nature of this valuation strongly depends on how energy performance is represented. First, the econometric model specifications prove stable under both representations of energy performance. Based on residual spatial autocorrelation and Lagrange Multiplier diagnostics, OLS models are retained for Rovigo and Verona, while SEMs are selected for Padova, Treviso, Venezia, and Vicenza. This stability is

**Table 2.** Distribution of housing characteristics by city (%).

| Variable | Level | Padova | Rovigo | Treviso | Venezia | Verona | Vicenza |
|---|---|---|---|---|---|---|---|
| Energy class | | | | | | | |
| | A | 32.9 | 10.0 | 49.7 | 28.3 | 25.4 | 33.4 |
| | B | 3.3 | 5.7 | 4.3 | 1.5 | 4.9 | 3.9 |
| | C | 4.4 | 6.3 | 4.9 | 3.6 | 3.1 | 7.5 |
| | D | 9.4 | 9.4 | 7.9 | 5.6 | 8.9 | 13.3 |
| | E | 13.3 | 13.2 | 10.7 | 10.5 | 17.2 | 15.6 |
| | F | 18.5 | 14.5 | 9.7 | 15.3 | 24.2 | 16.9 |
| | G | 18.2 | 40.9 | 12.8 | 35.2 | 16.3 | 9.4 |
| Property type | | | | | | | |
| | Apartment | 53.8 | 42.1 | 59.2 | 65.5 | 62.6 | 59.7 |
| | Penthouse | 15.9 | 8.2 | 23.8 | 15.6 | 17.2 | 20.1 |
| | Detached house | 24.0 | 36.5 | 14.9 | 13.8 | 16.2 | 15.6 |
| | Multifamily | 6.3 | 13.2 | 2.1 | 5.1 | 4.0 | 4.6 |
| Construction period | | | | | | | |
| | Pre-1945 | 8.8 | 1.9 | 5.8 | 37.8 | 18.7 | 7.8 |
| | 1946–1970 | 32.9 | 45.3 | 28.1 | 24.5 | 37.7 | 22.1 |
| | 1971–1990 | 15.4 | 21.4 | 8.5 | 6.6 | 12.9 | 18.2 |
| | 1991–2020 | 15.0 | 22.0 | 12.2 | 7.9 | 12.0 | 21.4 |
| | 2021–2026 | 27.9 | 9.4 | 45.4 | 23.2 | 18.7 | 30.5 |
| Building condition | | | | | | | |
| | Good | 46.3 | 63.5 | 31.7 | 37.0 | 44.2 | 43.2 |
| | To renovate | 8.8 | 15.7 | 9.1 | 8.4 | 8.3 | 7.5 |
| | Renovated | 21.1 | 12.6 | 16.5 | 30.9 | 27.6 | 23.7 |
| | New | 23.8 | 8.2 | 42.7 | 23.7 | 19.9 | 25.6 |
| Amenities | | | | | | | |
| | Elevator | 41.0 | 18.2 | 49.4 | 29.6 | 49.1 | 48.1 |
| | Balcony | 55.4 | 62.3 | 38.1 | 36.0 | 60.1 | 41.2 |
| | Terrace | 56.6 | 49.1 | 67.4 | 55.9 | 32.5 | 61.7 |
| | Prestigious building | 9.7 | 2.5 | 13.7 | 70.9 | 17.2 | 8.8 |
| | Garage | 61.8 | 39.6 | 38.4 | 39.0 | 36.5 | 43.8 |
| | Parking | 41.0 | 37.1 | 34.8 | 18.9 | 22.7 | 40.3 |
| | Private garden | 31.2 | 53.5 | 22.9 | 22.4 | 27.0 | 22.7 |
| | Shared garden | 25.7 | 15.7 | 17.1 | 26.5 | 18.7 | 28.6 |
| | Furnished | 20.2 | 33.3 | 20.1 | 37.8 | 35.0 | 21.4 |
| | Air conditioning | 64.1 | 57.2 | 53.4 | 65.1 | 60.4 | 58.1 |
| | Optical fiber | 75.0 | 20.1 | 18.0 | 28.1 | 17.5 | 52.9 |
| | Panoramic view | 74.2 | 20.1 | 18.0 | 20.9 | 10.1 | 50.0 |
| | Alarm system | 12.4 | 9.4 | 19.8 | 6.9 | 11.0 | 11.7 |
| | Security door | 45.0 | 8.8 | 1.0 | 16.8 | 18.4 | 45.5 |
| | Laundry room | 17.0 | 5.0 | 5.5 | 6.4 | 6.1 | 21.4 |
| | Cellar | 61.1 | 16.5 | 23.9 | 15.5 | 7.9 | 40.2 |

particularly important because it indicates that differences in estimated price schedules are driven solely by the codification of energy performance, not by changes in the underlying spatial structure.

Across both specifications, covariates show highly consistent signs, magnitudes, and levels of statistical significance. Structural features, dwelling type, building condition, construction period, and OMI fixed effects remain stable, showing that the two models describe the same price formation process in the housing market. Poor building conditions are consistently associated with lower prices, with estimated reductions ranging from −12% in Verona up to −21% in Padova and Treviso. Renovated and new houses command positive premiums, reaching up to 29% in some cases. More recent construction periods are also associated with positive premiums, although very old buildings (pre-1945) often carry positive values as well, possibly reflecting location in historic centres or the presence of architectural features valued by the market. More prestigious dwelling types, such as penthouses and detached houses, consistently attract higher prices than standard apartments. These patterns are rather stable across different cities, although the magnitude of individual effects differs considerably.

Turning to energy performance, the continuous specification yields a negative and statistically significant coefficient on energy consumption in all cities, consistent with theoretical expectations. Semi-elasticities vary from −5.31% in Venezia to approximately −9.23% in Rovigo (Table 3), indicating that higher energy consumption is associated with lower prices. The categorical specification reveals positive premiums for energy-efficient dwellings, although their distribution is irregular and appears much more flexible than under the continuous codification. In some cities, premiums change quite steadily across energy classes, while in others they show abrupt jumps, peaks at intermediate classes, and even reversals within the energy-class ranking.

**Table 3.** Selected model and estimated energy price premiums by city (%).

| | Padova | Rovigo | Treviso | Venezia | Verona | Vicenza |
|---|---|---|---|---|---|---|
| Model | SEM | OLS | SEM | SEM | OLS | SEM |
| A | 32.42 | 58.01 | 27.62 | 34.13 | 18.63 | 31.11 |
| B | 27.98 | 44.93 | 21.28 | –1.18 | 21.82 | 26.25 |
| C | 20.54 | 29.53 | 14.83 | 26.68 | 32.01 | 22.75 |
| D | 18.01 | 35.56 | 15.71 | 8.66 | 21.19 | 29.67 |
| E | 16.81 | 4.08 | 10.87 | 0.82 | 6.20 | 20.45 |
| F | 16.06 | 22.89 | 2.50 | 8.42 | 6.15 | 14.09 |
| $EP_{gl,nren}$ | –7.06 | –9.23 | –6.89 | –5.31 | –6.22 | –7.25 |

The two price schedules are compared graphically in Fig. 2. Treviso shows the best consistency between the two representations: the premium pattern in the EPC-based specification follows a nearly monotone progression that aligns

well with the linear benchmark. A similar pattern emerges in Padova, although with larger premiums at higher efficiency levels, suggesting that dwellings in the top energy classes attract additional value beyond what the consumption-based benchmark would imply. In both cities, the greater dynamism and activity of the local housing market appear to support a more accurate and structured capitalization of energy performance, in which price premiums align more closely with the underlying consumption gradient. At the other end of the spectrum, the largest discrepancies appear in Rovigo and Venezia, for distinct reasons. In Rovigo, the categorical premiums are markedly irregular, with large fluctuations between adjacent classes and only limited correspondence with the continuous gradient. This pattern is consistent with the characteristics of a less dynamic and less developed market, where an older building stock and a limited share of energy-efficient properties combine to amplify the perceived value of higher-rated dwellings, which may be rewarded with premiums that exceed what the consumption-based benchmark would justify. In Venezia, the pattern is characterized by discontinuities and threshold effects, including a slightly negative premium for class B and a sharp jump at the highest class. This is plausibly related to its distinctive demand profile, dominated by tourism-related and luxury demand, under which location, prestige, and architectural features drive price formation and the EE dimension carries comparatively less weight, which also explains the lowest semi-elasticity in the continuous specification. Verona and Vicenza occupy an intermediate position: in Verona, the maximum premium is observed for class C rather than class A, indicating the absence of a monotone progression; in Vicenza, there is a positive overall relationship, but classes C and B exhibit smaller premiums than D. These conclusions are consistent with the quantitative divergence measure: the sum of absolute deviations is lowest in Treviso (2.22) and moderate in Padova (5.77), compared with the higher values observed for Venezia (9.93) and Rovigo (15.1).

A relevant question concerns the extent to which these findings can be considered representative beyond the specific context of the Veneto region. The six cities analyzed fall predominantly within Italian climatic zone E, the most widespread zone in Italy. In this sense, the results regarding the relationship between energy consumption and housing prices can be considered broadly representative of this climatic context, where heating and cooling demand profiles are similar across cities. At the same time, the considerable heterogeneity documented across cities within the same region suggests that how EPC labels are perceived and processed by market participants differs substantially depending on local market dynamics, so that even within a shared climatic context the capitalization pattern cannot be assumed uniform. Generalizability to other climatic zones warrants further caution: where heating demand is lower or cooling costs are dominant, the energy demand profile changes considerably, and the economic benefit associated with a given EPC class may be perceived differently by market participants, potentially altering both the magnitude of estimated premiums and the degree to which categorical labels diverge from the continuous consumption gradient.

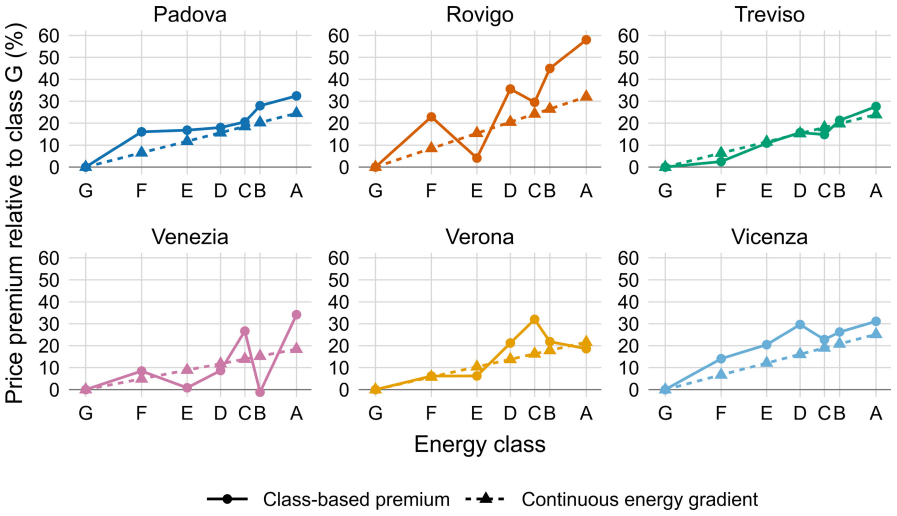


**Fig. 2.** Comparison between class-based and continuous consumption-based price premiums across cities.

Before turning to the broader implications, it is necessary to discuss the main limitations of the study. A first concern relates to sample size: in some cities, the number of observations in certain energy classes may be insufficient, leading to greater variability in the estimates and possibly to apparent irregularities in the premium schedule driven by sampling error rather than by genuine market behavior. This problem is most acute in thin markets such as Rovigo, where few transactions can amplify the apparent magnitude of discontinuities. A second limitation concerns the continuous specification of EE: as discussed in Sect. 3, the use of class-level representative values of $EP_{gl,nren}$ neglects within-class heterogeneity in energy performance and likely generates attenuation bias, so that the estimated consumption-price gradient should be treated as a stylized benchmark rather than a precise estimate. A third limitation concerns the use of listing prices rather than transaction prices. While the log-linear specification attenuates the impact of stable negotiation margins on estimated differentials, the assumption that negotiation discounts do not systematically vary with energy performance cannot be directly tested. If energy-efficient properties tend to attract more competitive offers, the estimated premiums may overstate the true transaction-price differentials. Overall, these limitations do not undermine the main comparative insights of the analysis, but access to transaction-level microdata including property-specific energy consumption would allow for more precise estimation and represents an important avenue for future research.

Despite these limitations, the implications for the understanding of how housing markets value EE are highly relevant. From a market perspective, the results highlight that the capitalization process is driven by the way information is perceived and interpreted. While the consumption specification identifies the

underlying physical dimension of performance, the categorical estimates show that buyers and sellers tend to react to EPC labels as simplified signals. EPCs seem to operate as heuristics—salient and easily understandable categories that shape quality expectations and operating cost perceptions—but they do not necessarily replicate the underlying consumption gradient in a proportional manner. This explains the occurrence of threshold effects, local amplifications, and non-monotonicities, which appear to be more frequent in markets characterized by higher information frictions and less structured demand.

From a policy perspective, the implications are equally relevant. The primary purpose of EPCs is to overcome information asymmetries and foster efficient housing choice and renovation by making energy performance transparent. However, the evidence presented here suggests that market signals may fail to properly reflect the economic value of energy savings. When prices respond discontinuously to categorical labels rather than continuously to the underlying performance gradient, investment incentives become distorted: threshold effects generate excessive premiums for properties that just cross a class boundary, while improvements that remain within a class may go unrewarded. The non-equidistance of EPC class intervals compounds this problem, since identical improvements in EE do not translate into equal class changes and therefore do not produce equal market rewards.

Overall, this analysis suggests that EPC-based public policies could benefit from the more prominent integration of consumption indicators alongside existing class labels, making the continuous dimension of energy performance more visible and accessible to market participants. Policy interventions should also account for the role of local heterogeneity: the informational effect exerted by the same classification system appears highly variable across housing markets, and a uniform policy approach is unlikely to be equally effective in contexts as different as Treviso and Venezia. More targeted and context-sensitive interventions, designed with awareness of local market structure, demand characteristics, and housing stock composition, are likely to produce more effective outcomes.

## 6 Conclusion

This study investigates how residential housing markets capitalize EE by comparing two alternative representations of energy performance: a categorical one, based on the classification of properties according to EPCs, and a continuous one, based on non-renewable primary energy consumption values. Using property-level listing data collected for six provincial capitals in the Veneto region, city-specific hedonic models with spatial controls are estimated to test whether class-based energy price premiums align with the underlying energy performance gradient or are driven by the discrete nature of EPC labels.

The empirical results show that EE generates a positive price premium in each of the six investigated cities. Under the continuous specification, the association between non-renewable primary energy consumption and housing prices is negative and consistent with a proportional capitalization of energy performance

benefits. The categorical specification, by contrast, frequently deviates from this benchmark: in Treviso and Padova the premium pattern tracks the consumption gradient reasonably well, while in Rovigo and Venezia it is characterized by threshold effects, non-monotonicity, and discontinuous jumps between adjacent classes. These findings suggest that EPCs play a dual role as market signals. On the one hand, they convey information about the actual energy performance of properties and the potential savings associated with lower energy costs. On the other hand, as categorical labels, they present this information in a simplified form that is not always consistent with the underlying performance gradient. Recognizing these mechanisms is important both for the interpretation of estimated energy premiums and for the design of empirical strategies capable of accounting for the physical and informational dimensions of energy performance in housing markets.

Looking ahead, several directions for future research emerge. In particular, access to transaction-level microdata with property-specific energy consumption measures would allow for more precise estimation of capitalization effects and a direct comparison between listing and transaction prices. Moreover, further research could explore how the informational role of EPCs varies across different climatic and market contexts, where the relative importance of energy demand components and local housing dynamics may alter the way energy performance is capitalized.

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## References

1. Banzato, D., Canesi, R., D'Alpaos, C.: Biogas and biomethane technologies: an AHP model to support the policy maker in incentive design in Italy. In: Bisello, A., Vettorato, D., Laconte, P., Costa, S. (eds.) SSPCR 2017. GET, pp. 319–331. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-75774-2_22
2. Canesi, R.: A multicriteria approach to prioritize urban sustainable development projects | Un approccio multicriteri per il ranking di progetti urbani sostenibili. Valori e Valutazioni **33**, 117–132 (2023). https://doi.org/10.48264/vvsiev-20233309
3. Morano, P., Tajani, F., Guarnaccia, C., Anelli, D.: An optimization decision support model for sustainable urban regeneration investments. WSEAS Trans. Environ. Dev. **17**, 1245–1251 (2021). https://doi.org/10.37394/232015.2021.17.114
4. Anelli, D., Ranieri, R.: Resilience of complex urban systems: a multicriteria methodology for the construction of an assessment index. In: International Symposium: New Metropolitan Perspectives, pp. 690–701. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-06825-6_65

5. Jafari, A., Valentin, V., Berrens, R.P.: Estimating the economic value of energy improvements in U.S. residential housing. J. Constr. Eng. Manag. **143**(8), 04017048 (2017). https://doi.org/10.1061/(ASCE)CO.1943-7862.0001343
6. Aydin, E., Brounen, D., Kok, N.: The capitalization of energy efficiency: evidence from the housing market. J. Urban Econ. **117**, 103243 (2020). https://doi.org/10.1016/j.jue.2020.103243
7. Högberg, L.: The impact of energy performance on single-family home selling prices in Sweden. J. Eur. Real Estate Res. **6**(3), 242–261 (2013). https://doi.org/10.1108/JERER-09-2012-0024
8. Taruttis, L., Weber, C.: Estimating the impact of energy efficiency on housing prices in Germany: does regional disparity matter? Energy Econ. **105**, 105750 (2022). https://doi.org/10.1016/j.eneco.2021.105750
9. Mense, A.: The value of energy efficiency and the role of expected heating costs. Environ. Resour. Econ. **71**, 671–701 (2018). https://doi.org/10.1007/s10640-017-0179-7
10. Marmolejo-Duarte, C., Chen, A.: The uneven price impact of energy efficiency ratings on housing segments: implications for public policy and private markets. Sustainability **11**(2), 372 (2019). https://doi.org/10.3390/su11020372
11. Cespedes-Lopez, M.-F., Mora-Garcia, R.-T., Perez-Sanchez, V.R., Marti-Ciriquian, P.: The influence of energy certification on housing sales prices in the province of Alicante (Spain). Appl. Sci. **10**(20), 7129 (2020). https://doi.org/10.3390/app10207129
12. Dell'Anna, F., Bravi, M., Marmolejo-Duarte, C., Bottero, M.C., Chen, A.: EPC green premium in two different European climate zones: a comparative study between Barcelona and Turin. Sustainability **11**(20), 5605 (2019). https://doi.org/10.3390/su11205605
13. Micelli, E., Gilberto, G., Righetto, E., Tafuri, G.: The economic value of sustainability. Real estate market and energy performance of homes. Valori e Valutazioni **34**, 3–16 (2023). https://doi.org/10.48264/VVSIEV-20233402
14. Podškubka, T., Rýdlová, B., Arlt, J.: Bridging the information gap: what are the impacts of EPCs on Prague's residential market selling prices? Financ. Internet Q. **21**(4), 39–50 (2025). https://doi.org/10.2478/fiqf-2025-0026
15. Dell'Anna, F.: Machine learning framework for evaluating energy performance certificate (EPC) effectiveness in real estate: a case study of Turin's private residential market. Energy Policy **198**, 114407 (2025). https://doi.org/10.1016/j.enpol.2024.114407
16. Davis, P.T., McCord, J.A., McCord, M., Haran, M.: Modelling the effect of energy performance certificate rating on property value in the Belfast housing market. Int. J. Hous. Markets Anal. **8**(3), 292–317 (2015). https://doi.org/10.1108/IJHMA-09-2014-0035
17. Stanley, S., Lyons, R.C., Lyons, S.: The price effect of building energy ratings in the Dublin residential market. Energ. Effi. **9**(4), 875–885 (2016). https://doi.org/10.1007/s12053-015-9396-5
18. Fuerst, F., McAllister, P., Nanda, A., Wyatt, P.: Does energy efficiency matter to home-buyers? An investigation of EPC ratings and transaction prices in England. Energy Econ. **48**, 145–156 (2015). https://doi.org/10.1016/j.eneco.2014.12.012
19. Lu, X., Spaenjers, C.: Energy labels, misreporting, and heuristic hedonic models. Real Estate Econ. **53**(6), 1200–1222 (2025). https://doi.org/10.1111/1540-6229.12535

20. Marmolejo Duarte, C.R., García-Hooghuis, A., García-Masiá, A.: How much and why are we willing to pay for energy-efficient homes? A stated preferences analysis in Barcelona. ACE Archit. City Environ. **14**(42) (2020). https://doi.org/10.5821/ace.14.42.9215
21. Lancaster, K.J.: A new approach to consumer theory. J. Polit. Econ. **74**(2), 132–157 (1966). https://doi.org/10.1086/259131
22. Rosen, S.: Hedonic prices and implicit markets: product differentiation in pure competition. J. Polit. Econ. **82**(1), 34–55 (1974). https://doi.org/10.1086/260169
23. Anselin, L.: Spatial Econometrics: Methods and Models. Studies in Operational Regional Science, vol. 4. Springer, Dordrecht (1988). https://doi.org/10.1007/978-94-015-7799-1
24. Barreca, A., Curto, R., Malavasi, G., Rolando, D.: Energy retrofitting for the modern heritage enhancement in weak real estate markets: the Olivetti housing stock in Ivrea. Sustainability **14**(6), 3507 (2022). https://doi.org/10.3390/su14063507
25. Bisello, A., Antoniucci, V., Marella, G.: Measuring the price premium of energy efficiency: a two-step analysis in the Italian housing market. Energy Build. **208**, 109670 (2020). https://doi.org/10.1016/j.enbuild.2019.109670
26. Banca d'Italia: Sondaggio congiunturale sul mercato delle abitazioni in Italia: Principali risultati, IV trimestre 2025. https://www.bancaditalia.it/pubblicazioni/sondaggio-abitazioni. Accessed 28 Apr 2026

# Composite Indices for Urban Blight Assessment: A Decision Support Approach for Urban Regeneration

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**Abstract.** Urban regeneration policies require operational tools capable of identifying priority areas, justifying investment choices, and monitoring change over time. In this context, urban blight can be understood as a multidimensional and context-dependent phenomenon, shaped by combinations of physical deterioration, socio-economic vulnerability, functional decline, and perceived insecurity. This work proposes a methodological framework for assessing urban blight at the intra-urban scale in a comparative and spatially explicit way. The framework draws on established practices for composite index construction and structures urban blight into three interrelated components: physical–environmental, economic, and social. The procedure includes: (i) the construction of three component indices, one for each dimension, through a TOPSIS-based aggregation of weighted indicators; (ii) the synthesis of the component indices into an overall index by means of the arithmetic mean; and (iii) the spatial representation of results through thematic maps. Indicators are selected and harmonized from available data sources; weights are derived through an entropy-based method; robustness checks are performed to assess result stability; and GIS-based mapping supports the identification and communication of priority areas. The proposed framework is intended to support priority setting, monitoring, and communication in urban regeneration policies, while remaining transferable across different urban contexts, subject to data quality and zoning choices.

**Keywords:** Urban blight · composite indicator · entropy weighting · TOPSIS · urban regeneration

## 1 Introduction

In recent years, urban policy has increasingly emphasized the need for regeneration strategies grounded in explicit and comparable evidence. This orientation is reflected in international and European sustainable urban development agendas that increasingly require integrated, evidence-based strategies to promote inclusive, safe, resilient and

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sustainable cities. The 2030 Agenda explicitly recognizes the importance of the urban dimension, with Goal 11 dedicated to making cities and human settlements inclusive, safe, resilient, and sustainable [1]. At the European level, this orientation is reflected in the promotion of integrated and place-based approaches through the Urban Agenda for the European Union, established by the Pact of Amsterdam (2016), and the New Leipzig Charter (2020), both of which strengthen multilevel coordination and the principles of good urban governance. In the same direction, initiatives linked to the green transition and the regeneration of the existing built heritage stress the need to combine sustainability and inclusion. Within this framework, the New European Bauhaus has been presented as a Green Deal initiative aimed at integrating sustainability, beauty, and inclusion in the transformation of living spaces [2].

These frameworks share a common operational implication: to make regeneration strategies effective and to guide public and private investment, it is essential to identify territorial priorities, justify decisions through explicit criteria, and monitor outcomes over time. Because cities are complex and differentiated systems, urban transformation does not occur evenly across space. While some areas concentrate opportunities and adaptive capacity, others tend to accumulate critical issues and signs of decline, with consequences for urban quality and territorial cohesion [3].

In both academic debate and planning practice, these conditions are often associated with the concept of urban blight, used to describe sets of critical issues affecting the built environment, the socio-economic structure, and urban functionality [4]. A key feature of the concept is the absence of a single, universally accepted definition. Urban blight varies according to the objectives of the analysis, the territorial scale, and the institutional context considered [5]. This ambiguity is not merely terminological, since it directly affects measurement and decision making. If urban blight may refer to physical deterioration, underuse, abandonment, socio economic vulnerability, loss of functions and services, negative reputation, or perceived insecurity, then the criteria used to identify and assess it must be made explicit [6]. This makes it necessary to move from generic definitions to operational ones that translate the phenomenon into observable and comparable measures.

From an interpretative perspective, urban blight can be understood as the result of relationships among physical and environmental, economic, and social components. These dimensions do not operate separately. On the contrary, the literature often describes urban blight as a set of interdependent and potentially self-reinforcing processes in which changes in one dimension affect the others [7]. For example, signs of deterioration such as building obsolescence, poor maintenance, and low-quality public space may reduce the perceived attractiveness of an area for residents, users, and firms. This can lead to lower demand, higher turnover, and a gradual contraction of activities and services [8]. In turn, the reduction of functions and economic activity may encourage further public and private disinvestment, worsening physical conditions and limiting available resources for maintenance and management [9]. At the same time, these dynamics can also affect the social dimension by increasing vulnerability, marginalization, and perceived insecurity [10, 11]. Urban blight may therefore emerge as a cumulative process in which the deterioration of one subsystem reinforces the fragility of the others and consolidates a negative reputation of the area [12].

Within urban policy, urban regeneration is one of the main strategies for addressing and mitigating the dynamics associated with urban blight by acting in an integrated way on the built environment, urban functions, and socio-economic conditions [13, 14]. In regeneration programmes, the identification of priority areas and the definition of the most effective solutions often fall to local administrations and other territorial actors, usually within the eligibility constraints and criteria established by funding programmes [15]. These decisions must be technically sound, but also justifiable and accountable. It is necessary to explain why one area should be prioritized over another, which dimensions of criticality are most relevant, and how such assessments can be updated and compared over time [16]. In this context, tools capable of measuring urban blight in a transparent, replicable, and comparable way play a strategic role, since they reduce discretion and interpretative fragmentation while strengthening the knowledge base for planning and monitoring activities [17].

## 2 Aim

Against this background, the present study proposes a methodological approach for assessing urban blight as a decision support tool for urban regeneration. The aim is to assist public authorities and private actors in identifying territorial criticalities, comparing different areas, and supporting the selection of intervention priorities. From a technical and analytical perspective, urban blight is treated as a multidimensional and process-based phenomenon articulated into three interconnected components: the physical–environmental component, which refers to the material and environmental conditions of the urban context; the economic component, which concerns dynamics of attractiveness, disinvestment, and territorial performance; and the social component, which relates to quality of life, vulnerability, and cohesion.

To address this objective, the paper develops a replicable procedure for constructing composite indices for the comparative assessment of urban blight. The methodological framework combines entropy-based weighting with TOPSIS aggregation to produce three component indices and a comparative synthesis across territorial units. Robustness checks are also included in order to assess the stability of the results. The procedure is intended to generate outputs that are interpretable and operationally useful, including rankings, component-based readings, and spatial representations, while keeping the main methodological assumptions explicit and facilitating transferability to different urban contexts.

The contribution does not rely on introducing a new weighting or aggregation technique, but on the structured integration of established methods into a transparent and replicable workflow specifically tailored to the assessment of urban blight. In particular, the framework combines component-based interpretation, entropy-based weighting, TOPSIS aggregation, robustness checks, and GIS representation in order to support not only measurement, but also priority setting and decision-making in urban regeneration policies.

The remainder of the paper is structured as follows. Section 3 reviews the background literature on multidimensional composite indices, with particular attention to applications based on the Entropy weight–TOPSIS approach. Section 4 illustrates the proposed

methodological approach through its 11 steps. Section 5 concludes by outlining the main implications of the study, its limitations, and avenues for future research.

## 3 Background

The quantitative measurement of complex and multidimensional phenomena such as urban blight often relies on composite indices. These indices aggregate sets of individual indicators into a synthetic measure that is interpretable and comparable. In fields such as sustainability and territorial assessment, this approach makes it possible to integrate heterogeneous dimensions and produce results that can support decision making. The literature on composite indices identifies a recurring sequence of stages in the construction of such measures and emphasizes the importance of ensuring transparency and replicability [18].

Even when the operational stages are partly standardized, the quality and validity of an index depend significantly on a number of methodological choices. Different choices may lead to different scores and rankings. Among the most influential are weighting and aggregation [19]. In general, weighting may rely on equal weights, subjective methods such as AHP, or objective data driven approaches. With regard to aggregation, the most common distinction concerns the degree of compensability among criteria, namely compensatory, non compensatory, and partially compensatory approaches.

Within this context, the Entropy weight–TOPSIS approach has often been adopted when the aim is to obtain a synthesis that is both replicable and easy to communicate. Entropy makes it possible to estimate weights in a data driven way, while TOPSIS produces a continuous score and facilitates comparison across territorial units. This combination is therefore well suited to rankings and cartographic representations.

The literature documents the use of Entropy weight–TOPSIS in several fields of territorial assessment. A first strand concerns sustainability and environmental assessment. Wang et al. (2019) [20] apply Entropy weight–TOPSIS to measure the development capacity of the green economy at the regional scale. Jing et al. (2024) [21] combine a DPSIR framework (Driving forces, Pressures, State, Impact, and Response) with Entropy weight–TOPSIS to assess cultivated land ecological security from a spatial and temporal perspective. Similarly, Deng et al. (2024) [22] use a DPSIR based framework for water environment assessment, while Guo et al. (2024) [23] apply DPSIR and Entropy weight–TOPSIS to tourism ecological security. Taken together, these studies show that the approach is effective in synthesizing heterogeneous environmental dimensions and making territorial differences more clearly interpretable.

A second strand concerns resilience and the response capacity of territories. Yang et al. (2022) [24] use Entropy weight–TOPSIS to construct an urban resilience index and complement the synthetic measure with an analysis of the factors associated with the observed differences. On large samples, Wang et al. (2024) [25] apply Entropy weight–TOPSIS within a multidimensional framework to compare a broad set of cities. Other studies adapt the same scheme to more local scales, for example for territorial classification and rural resilience assessment within PSR frameworks. These contributions show the usefulness of the approach for comparative assessment across both large and small territorial samples.

A third area concerns urban liveability and wellbeing. In these cases, the aim is to produce synthetic scores that are clear and comparable. Xiao et al. (2022) [26] apply Entropy weight–TOPSIS to an urban liveability index and use it to interpret differences across contexts. Similar approaches also appear in policy adjacent assessments, such as healthy city rankings based on multi indicator sets [27]. In this strand, the main contribution of the approach lies in its capacity to provide readable comparative outputs that can support interpretation and communication.

Finally, Entropy weight–TOPSIS is also used in contexts oriented towards the prioritization of investments and interventions. Zhang et al. (2021) [28] apply this combination to assess the multidimensional impacts of transport networks in a metropolitan area, obtaining scores that can be ranked and compared. An example closer to regeneration can be found in studies on mapping priorities, where entropy and TOPSIS are used to produce priority scores for planning units, such as ageing residential districts. Zhao et al. (2022) [29] also use this combination in comparative assessment exercises aimed at supporting planning and investment choices. These studies are particularly relevant because they show the potential of the approach for priority setting in spatially differentiated decision contexts.

Overall, these contributions show that Entropy weight–TOPSIS is a recurring operational scheme for constructing comparative composite indices in the territorial field. Its diffusion is linked to the replicability of the procedure, the readability of the outputs, and its capacity to support spatial comparison and decision making.

## 4 Methodology

The proposed approach falls within the field of multidimensional composite indices and follows the main established stages for their construction [18, 19]. The methodology is designed to address explicit objectives of objectivity, replicability, and comparability across territorial units, while producing interpretable and communicable results to support the planning and monitoring of urban regeneration policies.

Consistently with the multidimensional nature of the phenomenon, the procedure includes: (i) the construction of three component indices, namely physical-environmental, economic, and social, based on sets of indicators consistent with each dimension; (ii) the synthesis of these component indices into an overall index to support comparison and priority setting; and (iii) the spatial representation of results through thematic maps. The operational choices privilege a data driven logic, reducing dependence on subjective judgments that are difficult to replicate and enhancing the applicability of the procedure across different territorial contexts.

The methodological approach is structured into 11 steps, summarized in Fig. 1.

### 4.1 Step 1. Definition of the Phenomenon and of the Components to Be Measured

The first step is the operational definition of what is to be measured. The literature on urban blight shows that the concept is not univocal and can be interpreted in different ways; for this reason, the definition stage is essential to reduce ambiguity and make the index defensible from an interpretative perspective. In this framework, urban

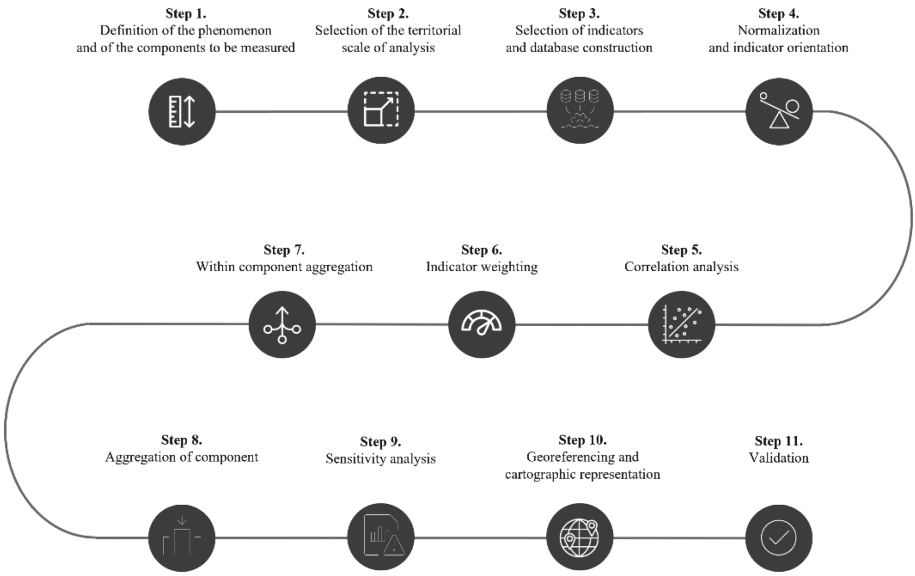


**Fig. 1.** Workflow of the proposed methodological approach.

blight is treated as a latent variable and, according to a formative measurement model, is determined by the combination of indicators: the latent construct is not reflected in the observed variables, but rather the observed variables contribute to defining the phenomenon [30].

The adopted framework therefore decomposes the phenomenon into three components, namely physical-environmental, economic, and social, which represent recurring forms through which urban blight manifests itself and allow for an integrated reading of the phenomenon, while keeping explicit the link between conceptual dimensions and the indicator system.

### 4.2 Step 2. Selection of the Territorial Scale of Analysis

The next stage consists in identifying the geographical scale at which the analysis is to be carried out, in order to ensure consistency between the territorial level considered, the nature of the observed phenomenon, and the operational purposes of the index. The choice of scale is relevant because it affects the interpretation of spatial concentrations and, consequently, the identification of priority areas. For this reason, the scale is defined by balancing analytical needs and informational constraints, taking into account: (i) decision making usefulness; (ii) sample size; (iii) data availability and quality; (iv) unit homogeneity; and (v) temporal stability.

In this context, the Modifiable Areal Unit Problem (MAUP) [31] must be considered: results may vary depending on the adopted scale and zoning system, since aggregation into areal units modifies the observed intensity and variability of the phenomenon. In practical terms, larger units tend to average out internal differences and reduce the ability to detect local hotspots; smaller units increase sensitivity to spatial discontinuities but

may prove more unstable in the presence of small numbers or greater data uncertainty. In sum, the territorial scale represents a compromise among descriptive capacity, statistical robustness, and operational feasibility, acknowledging that the unit of analysis is an integral part of the model.

### 4.3 Step 3: Selection of Elementary Indicators and Database Construction

Once the conceptual framework and the dimensions to be measured have been defined, the next stage concerns the construction of the information base of the index, which includes: (i) the selection of indicators and (ii) the collection, structuring, and quality checking of the underlying data. Indicator selection follows widely recognized methodological criteria adopted by international organizations such as OECD, Eurostat, and IMF, including relevance, accuracy, timeliness, accessibility, interpretability, and comparability. Operationally, the procedure starts with a literature review and the compilation of an initial list of candidate indicators, which is then screened against these criteria and the availability of verifiable data.

To support this stage, an indicator inventory was derived from the literature review (Table 1). The reported frequency, expressed as the number of studies, is based on counting the occurrences of each indicator within the review corpus. For each contribution, an indicator was recorded when it was explicitly adopted and operationalized as a variable for measuring urban blight, or closely related constructs. In this context the indicator inventory is used to guide the selection of candidate indicators, while the final selection depends on conceptual fit, the scale of analysis, and data availability.

Once the indicator set has been defined, data are collected, organized, and validated by prioritizing official and institutional sources, such as national and European statistics, administrative archives, and public open data. Consistency checks are performed on definitions, measurement units, spatial coverage, and reference periods in order to ensure homogeneity and comparability across territorial units. When data are available at spatial levels that differ from the chosen unit of analysis, GIS based processing may be required to harmonize the information according to a common zoning scheme, for example through spatial joins, overlays, and areal aggregation or disaggregation, while keeping the workflow transparent and replicable.

For each component, the final dataset is organized into a raw data matrix $X = [x_{ij}]$ of size $m \times n$, where the $m$ rows represent territorial units and the $n$ columns represent elementary indicators:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

### 4.4 Step 4. Normalization and Indicator Orientation

The next step concerns the normalization of indicators, which makes it possible to compare variables expressed in different units of measurement and orders of magnitude

**Table 1.** Indicator inventory from the literature review: frequency of occurrence by component

| Component | Indicator | No. studies |
|---|---|---|
| **Physical–environmental** | Litter / waste | 8 |
| | Dilapidated / deteriorated buildings | 6 |
| | Graffiti | 5 |
| | Abandoned / underused buildings | 5 |
| | Vacant lots | 4 |
| | Pollutant emissions | 3 |
| | Unpleasant odours | 3 |
| | Weeds / overgrown vegetation | 3 |
| | Poor street lighting | 3 |
| | Traffic | 2 |
| | Limited access to public transport | 2 |
| | Energy performance | 2 |
| **Economic** | Businesses and retail presence | 4 |
| | Unemployment | 3 |
| | Land and housing values | 3 |
| | Household expenditure | 2 |
| **Social** | Crime / safety | 6 |
| | Income | 4 |
| | Poverty | 3 |
| | Out-migration from the neighbourhood | 3 |
| | School quality | 2 |
| | Population density | 2 |

by transforming raw data into dimensionless values on a common scale. A preliminary issue concerns indicator orientation, that is, their polarity with respect to the phenomenon under analysis. Within the set of variables, positively oriented indicators may coexist with negatively oriented ones. In the first case, higher values indicate more critical conditions and are therefore associated with higher levels of urban blight; in the second case, higher values indicate better conditions and are therefore inversely related to the phenomenon. For aggregation purposes, all indicators must be oriented in the same interpretative direction.

In the present approach, Min–Max normalization is adopted, as it produces values between 0 and 1 and preserves the relative distances among observations. Denoting by $x_{min\,j}$ and $x_{max\,j}$ the minimum and maximum values of indicator $j$ in the sample, the transformation is defined as follows:

$$r_{ij} = \frac{x_{ij} - x_{minj}}{x_{maxj} - x_{minj}} \text{for positively oriented indicators}$$

$$r_{ij} = \frac{x_{maxj} - x_{ij}}{x_{maxj} - x_{minj}} \text{for negatively oriented indicators}$$

The application of this procedure allows the transition from the raw data matrix X = [$x_{ij}$] to the normalized matrix R = [$r_{ij}$]:

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix}$$

### 4.5 Step 5. Correlation Analysis

Once normalization has been completed, the next stage consists of a correlation analysis among indicators in order to identify possible informational redundancies. Strongly correlated indicators, whether positively or negatively, may capture very similar aspects of the phenomenon, and their simultaneous inclusion may introduce double counting. In such cases, one of the indicators may be excluded, giving preference to the one that is more robust or theoretically more relevant, or alternatively replaced with a less redundant variable [19]. In the present approach, consistently with the quantitative nature of the indicators and with the aim of detecting linear overlap, Pearson's correlation coefficient is adopted.

Following this check, an Exploratory Spatial Data Analysis (ESDA) may be included as an additional interpretative step in order to assess whether indicators or indices display patterns of spatial concentration, such as clusters or outliers. This possibility is relevant because urban blight is associated with spatial dynamics and discontinuities. ESDA supports the territorial interpretation of results but does not intervene in the weighting or aggregation of the index.

### 4.6 Step 6. Indicator Weighting

The next stage concerns the weighting of indicators. Weighting assigns to each indicator a weight $w_j$, representing its relative importance in the construction of the composite index. This step is crucial, since different weights may affect both scores and rankings. In the absence of clear normative grounds for differentiating the importance of indicators, the adopted approach privileges an objective and replicable logic, reducing dependence on discretionary assessments. From this perspective, the entropy method is used as a data driven weighting technique [25]. In information theory, entropy measures the degree of uniformity of a distribution. In the context of composite indices, an indicator is considered more informative when it better discriminates among units. Indicators with a more uniform distribution, that is, higher entropy, contribute less to differentiation and therefore receive lower weights; conversely, indicators with greater variability, that is, lower entropy, receive higher weights [24]. Starting from the normalized matrix R = [$r_{ij}$], the calculation proceeds as follows.

First, the proportion of the normalized value of indicator $j$ for territorial unit $i$ is computed as:

$$p_{ij} = \frac{r_{ij}}{\sum_{i=1}^{m} r_{ij}}$$

Second, the entropy of indicator $j$ is calculated as:

$$E_j = -\frac{1}{ln(m)} \sum_{i=1}^{m} p_{ij} ln\left(p_{ij}\right)$$

Third, the degree of divergence is obtained as:

$$d_j = 1 - E_j$$

Finally, the normalized weight is computed as:

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}$$

The resulting weights are then applied to the normalized matrix in order to obtain the weighted matrix $V = [v_{ij}]$:

$$v_{ij} = w_j \cdot r_{ij}$$

$$V = \begin{bmatrix} w_1 \cdot r_{11} & w_2 \cdot r_{12} & \cdots & w_n \cdot r_{1n} \\ w_1 \cdot r_{21} & w_2 \cdot r_{22} & \cdots & w_n \cdot r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_1 \cdot r_{m1} & w_2 \cdot r_{m2} & \cdots & w_n \cdot r_{mn} \end{bmatrix}$$

### 4.7 Step 7. Within Component Aggregation: TOPSIS

At this stage, the weighted indicators are combined into a component composite index. The choice of the aggregation technique is relevant because it incorporates assumptions about the degree of compensability among indicators, that is, the extent to which low performance in one criterion may be offset by high performance in other criteria. Consistently with the objective of obtaining a continuous, comparable, and easily mappable output, within component aggregation is carried out through TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), a distance-based method widely used in multicriteria problems. Compared with outranking methods such as ELECTRE and PROMETHEE, which require additional thresholds and parameters and mainly produce rankings, TOPSIS provides an immediate synthesis in the form of a cardinal score.

The principle of TOPSIS consists in evaluating each territorial unit according to its distance from two reference profiles: the ideal solution $A^+$ and the anti-ideal solution $A^-$

In the standard formulation, $A^+$ collects, for each indicator, the most desirable value, whereas $A^-$ collects the least desirable one. In the approach adopted here, however, the indicators are previously normalized and oriented with respect to urban blight, so that higher values indicate more critical conditions. As a result, $A^+$ represents the profile of maximum urban blight, whereas $A^-$ represents the profile of minimum urban blight.

The procedure is applied to the weighted matrix $V = [v_{ij}]$. The two solutions are defined as follows:

$$A^+ = \left\{v_1^+, v_2^+, \ldots, v_n^+\right\} A^- = \left\{v_1^-, v_2^-, \ldots, v_n^-\right\},$$

where, for each indicator $j$,

$$v_j^+ = max\left(v_{ij}\right), v_j^- = min(v_{ij})$$

The Euclidean distances of each territorial unit $i$ from the two solutions are then calculated as:

$$D_i^+ = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^+\right)^2}$$

$$D_i^- = \sqrt{\sum_{j=1}^{n}\left(v_{ij} - v_j^-\right)^2}$$

The closeness coefficient is defined as:

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}, 0 \leq C_i \leq 1$$

In the proposed approach, the closeness coefficient is interpreted as a relative urban blight score. Since the indicators are oriented so that higher values correspond to more critical conditions, values of $C_i$ closer to 1 indicate territorial units that are closer to the ideal profile of maximum urban blight, whereas values closer to 0 indicate proximity to the anti-ideal profile of minimum urban blight. Therefore, for each component, the resulting scores $I_i^{PE}$, $I_i^{EC}$, and $I_i^{SC}$ can be read as component-specific indices of relative criticality. These indices do not provide an absolute diagnosis, but position each territorial unit within the observed sample and make it possible to identify where physical-environmental, economic, or social criticalities are comparatively more intense. Within-component aggregation also reduces the risk of poorly justified compensations, since the aggregated indicators belong to the same conceptual dimension.

### 4.8 Step 8. Aggregation of Components: Overall Index Through the Arithmetic Mean

Once the three component indices, $I_i^{PE}$, $I_i^{EC}$, $I_i^{SC}$ , have been calculated, an overall urban blight index is constructed for synthesis and priority setting purposes. In the absence of robust theoretical grounds or unequivocal empirical evidence for assigning differential weights to the components, the simple arithmetic mean is adopted, as it preserves the transparency of the model and avoids an additional weighting step that could be potentially arbitrary.

The arithmetic mean implies compensability among components. However, the operational diagnosis remains supported by the component indices:

$$I_i^{TOT} = \frac{I_i^{PE} + I_i^{EC} + I_i^{SC}}{3}$$

For decision-making purposes, the overall index should therefore be interpreted as a screening and prioritization tool, rather than as a substitute for the component indices. Territorial units with high values of the overall index may be considered priority areas for intervention, but the interpretation of the three component indices is necessary to understand the nature of the criticality and to define appropriate regeneration strategies. For example, two areas may obtain similar overall scores while presenting different profiles: one may be mainly affected by physical-environmental deterioration, while another may combine moderate physical, economic, and social weaknesses. In this sense, the framework helps decision-makers manage trade-offs among components and supports a more targeted allocation of resources.

As an illustrative example, a territorial unit with a high overall urban blight index and particularly high physical-environmental and social component scores could be interpreted as an area where regeneration priorities should focus on the improvement of public space, building conditions, services, and social vulnerability. Conversely, an area with a high economic component score but lower physical and social criticalities may require interventions aimed primarily at strengthening local attractiveness, economic functions, and investment conditions. This type of component-based reading allows the index to move beyond a simple ranking and to support the definition of differentiated intervention strategies.

### 4.9 Step 9. Sensitivity Analysis

Sensitivity analysis is used to assess the robustness of the results with respect to methodological choices and the main sources of uncertainty that may affect a composite index [32]. In the present approach, sensitivity analysis focuses on weighting and adopts a one at a time, or OAT, procedure: one input is varied at a time while all others are kept constant, and the effects on the output are then observed. More specifically, for each indicator, the entropy weight is perturbed through progressive variations of $\pm 10\%$, $\pm 20\%$, and $\pm 30\%$, with the index recalculated each time using the same aggregation procedure, namely TOPSIS. The effects are assessed through: (i) the absolute difference from the reference value; (ii) the percentage difference; and (iii) changes in the ranking of territorial units.

### 4.10 Step 10. Georeferencing and Cartographic Representation of the Indices

Georeferencing makes it possible to move from a tabular reading to the spatial representation of the indices, highlighting patterns, concentrations, and territorial discontinuities, while supporting communication and priority setting. Operationally, index values are linked to the territorial units adopted as the scale of analysis and integrated with their corresponding geometries through GIS tools, so as to produce thematic maps. Different criteria may be used for the cartographic classification of values; in the present approach, a quintile classification is adopted, which divides the distribution into five classes of similar size, corresponding to about 20 per cent of the units in each class.

This facilitates comparison and interpretation in terms of relative position and priority. In this way, the cartographic output can be interpreted as a five level scale of urban

blight, ranging from very low to very high, and can be used to identify the most critical areas at a glance.

### 4.11 Step 11. Validation

The final stage concerns the validation of the approach, which can be tested in terms of its ability to be updated and its capacity to support decision making, considering that urban blight is linked to spatial dynamics and discontinuities and is therefore subject to change over time. From this perspective, the model can also be used ex-ante through *"what if"* exercises, by simulating the expected effects of urban regeneration interventions through the updating of indicators that are potentially sensitive to transformation. Operationally, the procedure includes: (i) the translation of the main project quantities into measurable variables; (ii) the identification and updating of the indicators involved through direct data, conversion parameters, or proxies; and (iii) the recalculation of the indices while keeping the model structure and the normalization, weighting, and aggregation rules unchanged, in order to preserve comparability with the reference framework.

Further checks may include comparisons with official measures or benchmarks and stability tests with respect to alternative methodological choices, for example by adopting less compensatory or non compensatory aggregation rules.

Taken together, these steps define the overall structure of the proposed methodological approach; Table 2 summarizes the methodological choices adopted and the corresponding main outputs associated with each step.

**Table 2.** Summary of the 11 steps of the proposed methodological approach, including the methodological choices adopted and the corresponding main outputs.

| Step | Methodological choice | Main output |
|---|---|---|
| Step 1. Definition of the phenomenon and of the components to be measured | Formative measurement model; three component structure | Conceptual framework and index structure, including components and indicator domains |
| Step 2. Selection of the territorial scale of analysis | Decision making usefulness; sample size; data quality and availability; homogeneity; temporal stability; MAUP consideration | Unit of analysis and territorial scope for index construction and comparison |
| Step 3. Selection of indicators and database construction | Quality criteria; data availability; database construction; data harmonization | Raw data matrix $X = x_{ij}$ for each component |
| Step 4. Normalization and indicator orientation | Indicator orientation; Min–Max normalization | Normalized matrix R = rij |

(*continued*)

**Table 2.** (*continued*)

| Step | Methodological choice | Main output |
|---|---|---|
| Step 5. Correlation analysis | Pearson correlation; optional ESDA | Refined indicator set controlled for double counting, plus optional interpretative evidence |
| Step 6. Indicator weighting | Entropy based weighting | Weight vector $w = [w_j]$ and weighted matrix $V = v = [v_j]$ |
| Step 7. Within component aggregation: TOPSIS | TOPSIS aggregation | Component indices $I_i^{PE}$, $I_i^{EC}$, $I_i^{SC}$ |
| Step 8. Aggregation of components: overall index through the arithmetic mean | Arithmetic mean aggregation | Overall index $I_i^{TOT}$ |
| Step 9. Sensitivity analysis | One at a time sensitivity analysis on entropy weights | Robustness measures, including absolute and percentage variations and ranking stability |
| Step 10. Georeferencing and cartographic representation of the indices | GIS based georeferencing; quintile classification | Thematic maps and comparable urban blight classes across territorial units |
| Step 11. Validation | Dynamic updating; optional what if analysis; benchmark comparison | Evidence on coherence and transferability, and indications for ex ante and ex post uses |

## 5 Conclusions

Urban blight cannot be reduced to a single physical condition or to a purely aesthetic or public order issue. Rather, it emerges from the interaction of physical and environmental deterioration, socio-economic fragility, functional weakness, and perceived insecurity, and may affect both central and peripheral areas, as well as consolidated and more recent urban fabrics. In this context, urban regeneration represents one of the main strategies for addressing these dynamics. Yet many policy instruments and regeneration programmes require local authorities to identify and justify priority areas under conditions of limited resources. Without clear and comparable metrics, these choices risk becoming discretionary and difficult to justify. This makes it necessary to adopt transparent procedures, based on explicit rules and observable data, that can support comparison, prioritization, and accountability [33, 34].

This study responds to that need by proposing a data-driven methodological framework for constructing composite indices for the comparative assessment of urban blight.

Its main contribution lies in defining a replicable procedure that makes the main methodological choices explicit, from indicator selection and normalization to weighting and aggregation, while aiming to preserve comparability across territorial units. The three-component structure, physical–environmental, economic, and social, makes it possible to combine an overall synthetic assessment for priority setting with a component-based reading that can inform more targeted and integrated intervention strategies.

From an operational point of view, the outputs of the framework are intended to be directly usable in decision-making processes. The component indices help distinguish different profiles of territorial criticality; the overall index supports ranking and comparison; and thematic maps make spatial patterns and discontinuities easier to interpret and communicate, including to non-specialist audiences. In this form, the framework can support three recurrent functions in urban regeneration governance: identifying priorities and target areas, monitoring territorial conditions and policy outcomes over time, and strengthening negotiation and accountability processes by making the assumptions behind decisions more explicit.

At the same time, the framework also has some limitations, many of which are typical of composite measures applied to complex territorial phenomena. First, the quality of the results depends on the quality, coverage, and temporal consistency of the underlying data. Missing values, non-homogeneous measures, or misalignments across data sources may weaken the reliability of the outputs. Second, even when methodological assumptions are made transparent, some choices continue to influence the results, including indicator selection, scaling procedures, missing data treatment, and assumptions about compensability. In addition, the indices are descriptive rather than causal: they support comparison and ranking, but do not in themselves explain the causes of urban blight. Finally, the analysis is affected by the Modifiable Areal Unit Problem, meaning that results may vary according to the scale and zoning system adopted. For this reason, qualitative checks and, where possible, multi-scale readings remain advisable when the framework is used to support operational decisions.

These limitations also suggest possible directions for further development. One improvement would be to explore weighting schemes that combine data-driven criteria with participatory inputs, so as to reflect contextual priorities without undermining transparency. A second direction concerns the extension of the framework across multiple spatial scales, particularly where more detailed territorial readings are required for operational purposes. Finally, applying the model to different urban contexts and comparing its outputs with external benchmarks or recognized measures could help strengthen both its transferability and its credibility in decision-making settings.

Future developments may also include the empirical application of the framework to specific case studies, the integration of participatory procedures for discussing component weights and intervention priorities, and the use of longitudinal data to monitor the evolution of urban blight before and after regeneration policies. In this way, the framework could be progressively extended from a comparative assessment tool to a monitoring and evaluation device for urban regeneration strategies.

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## References

1. United Nations: Transforming our world: The 2030 Agenda for Sustainable Development (A/RES/70/1). United Nations, New York (2015)
2. European Commission: A New European Bauhaus: Shaping a More Beautiful, Sustainable and Inclusive Form of Living Together, Brussels (2020)
3. Anelli, D., Morano, P., Tajani, F., Sabatelli, E.: Impacts of urban decay on the residential property market: an application to the City of Rome (Italy). In: Gervasi, O., Murgante, B., Garau, C., Taniar, D., Rocha, A.M.A.C., Faginas Lago, M.N. (eds.) ICCSA 2024. LNCS, vol. 14822, pp. 36–48. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-65318-6_3
4. Breger, G.E.: The concept and causes of urban blight. Land Econ. **43**(4), 369–376 (1967)
5. Lousada, A.L., Ferreira, F.A., Meidutė-Kavaliauskienė, I., Spahr, R.W., Sunderman, M.A., Pereira, L.F.: A sociotechnical approach to causes of urban blight using fuzzy cognitive mapping and system dynamics. Cities **108**, 102963 (2021)
6. Chakraborty, B., Dey, P.: A Composite urban blight identification and evaluation index (CUBIE): a systems-driven approach based on empirical evidence from Kolkata, India. Soc. Indic. Res. **176**(3), 1043–1070 (2025)
7. Ndhlovu, S., Mata, J.: Urban decay and the resilience factor in Bulawayo's downtown precinct (2019)
8. Hortas-Rico, M.: Sprawl, blight, and the role of urban containment policies: evidence from US cities. J. Reg. Sci. **55**(2), 298–323 (2015)
9. Pinto, A.M., Ferreira, F.A., Spahr, R.W., Sunderman, M.A., Govindan, K., Meidutė-Kavaliauskienė, I.: Analyzing blight impacts on urban areas: a multi-criteria approach. Land Use Policy **108**, 105661 (2021)
10. Gbekor, V.M.: Machine learning-based detection of urban blight. Carinthia Univ. Appl. Sci. (2021)
11. Costa, J.B., Ferreira, F.A., Spahr, R.W., Sunderman, M.A., Pereira, L.F.: Intervention strategies for urban blight: a participatory approach. Sustain. Cities Soc. **70**, 102901 (2021)
12. Barão, M.V., Ferreira, F.A., Spahr, R.W., Sunderman, M.A., Govindan, K., Meidutė-Kavaliauskienė, I.: Strengthening urban sustainability: Identification and analysis of proactive measures to combat blight. J. Clean. Prod. **292**, 126026 (2021)
13. Guarini, M.R., D'Addabbo, N., Morano, P., Tajani, F.: Multi-criteria analysis in compound decision processes: the AHP and the architectural competition for the chamber of deputies in Rome (Italy). Buildings **7**(2), 38 (2017)
14. Anelli, D., Morano, P., Fariello, F., Sabatelli, E.: Environmental, social and governance (ESG) assessment with a two-phase goal-programming-based optimization model: a comparative study of Envipark and Kalundborg eco-industrial parks. Front. Built Environ. **12**, 1731282
15. Grigorut, I.: Le politiche pubbliche nazionali per le città e le periferie nella prospettiva della rigenerazione urbana. WORKING PAPERS (1/2019), 1–11 (2019)
16. Morano, P., Tajani, F., Guarnaccia, C., Anelli, D.: An optimization decision support model for sustainable urban regeneration investments. WSEAS Trans. Environ. Dev. **17**, 1245–1251 (2021)
17. Manganelli, B., Murgante, B., Saganeiti, L.: The social cost of urban sprinkling. Sustainability **12**, Article no. 2236 (2020)

18. Joint Research Centre: Handbook on Constructing Composite Indicators: Methodology and User Guide. OECD Publishing (2008)
19. Greco, S., Ishizaka, A., Tasiou, M., Torrisi, G.: On the methodological framework of composite indices: a review of the issues of weighting, aggregation, and robustness. Soc. Indic. Res. **141**(1), 61–94 (2019)
20. Wang, M., Zhao, X., Gong, Q., Ji, Z.: Measurement of regional green economy sustainable development ability based on entropy weight-TOPSIS-coupling coordination degree: a case study in Shandong Province, China. Sustainability **11**(1), 280 (2019)
21. Jing, X., Tao, S., Hu, H., Sun, M., Wang, M.: Spatio-temporal evaluation of ecological security of cultivated land in China based on DPSIR-entropy weight TOPSIS model and analysis of obstacle factors. Ecol. Indic. **166**, 112579 (2024)
22. Deng, W., Li, X., Guo, Y., Huang, J., Zhang, L.: Ecological assessment of water environment in Huizhou region of China based on DPSIR theory and entropy weight TOPSIS model. Water **16**(18), 2579 (2024)
23. Guo, Y., Song, Y., Huang, J., Zhang, L.: Water Environment assessment of Xin'an River Basin in China based on DPSIR and entropy weight–TOPSIS models. Water **17**(6), 781 (2025)
24. Yang, M., Jiao, M., Zhang, J.: Research on urban resilience and influencing factors of Chengdu-Chongqing economic circle. Sustainability **14**(17), 10585 (2022)
25. Wang, J., Wang, Y., Lin, G.: Study on rural classification and resilience evaluation based on PSR model: a case study of Lvshunkou District, Dalian City, China. Sustainability **16**(15), 6708 (2024)
26. Xiao, Y., Chai, J., Wang, R., Huang, H.: Assessment and key factors of urban liveability in underdeveloped regions: a case study of the Loess Plateau, China. Sustain. Cities Soc. **79**, 103674 (2022)
27. Wen, Y., Li, Y., Zhang, Y., Liu, B.: Comprehensive evaluation of global health cities development levels. Front. Public Health **12**, 1437647 (2024)
28. Murgante, B., Tilio, L., Lanza, V., Scorza, F.: Using participative GIS and e-tools for involving citizens of Marmo Platano - Melandro area in European programming activities. J. Balkan Near East Stud. **13**, 97–115 (2011)
29. Zhao, D.-Y., Ma, Y.-Y., Lin, H.-L.: Using the Entropy and TOPSIS models to evaluate sustainable development of islands: a case in China. Sustainability **14**(6), 3707 (2022)
30. Anelli, D., Ranieri, R.: Resilience of complex urban systems: a multicriteria methodology for the construction of an assessment index. In: Calabrò, F., Della Spina, L., Piñeira Mantiñán, M.J. (eds.) NMP 2022. LNNS, vol. 482, pp. 690–701. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-06825-6_65
31. Dark, S.J., Bram, D.: The modifiable areal unit problem (MAUP) in physical geography. Prog. Phys. Geogr. **31**(5), 471–479 (2007)
32. Saltelli, A., Tarantola, S., Campolongo, F.: Sensitivity analysis as an ingredient of modeling. Stat. Sci., 377–395 (2000)
33. Calabrò, F., Minniti, G.E., Fotia, A., Pucinotti, R.: Recovery of historic real estate: life cycle costing and economic feasibility. Procedia Struct. Integr. **64**, 1759–1766 (2024)
34. Spatari, G., Lorè, I., Viglianisi, A., Calabrò, F.: Economic feasibility of an integrated program for the enhancement of the Byzantine heritage in the Aspromonte National Park. the case of Staiti. In: Calabrò, F., Della Spina, L., Piñeira Mantiñán, M.J. (eds.) NMP 2022. LNNS, vol. 482, pp. 313–323. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-06825-6_30

# Managing Tourism Pressure: Impacts on Urban Real Estate in Italy

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**Abstract.** This research examines the connection between urban tourism and the residential market. Specifically, the comparative method is applied by investigating three Italian cities, representing different levels of tourism development, namely, Bari (southern Italy), Perugia (central Italy), and Venice (northern Italy). The scope of the analysis spans from 2019 to 2024 and involves evaluating residential property sales and rentals, accommodation types, and tourists' arrivals to assess potential effects of tourism on the housing sector and spatial organization of urban areas. As found out, the effect of tourism on urban residential markets follows a non-linear pattern, underscoring the importance of local governance in tackling socio-spatial divides and developing housing policies. By integrating empirical evidence with a governance-oriented perspective, the study provides meaningful insights into the effective management of urban destinations facing diverse levels of tourism intensity.

**Keywords:** Urban tourism · real estate market · overtourism · residential market dynamics · property value

## 1 Introduction

In recent years, urban tourism has emerged as a critical driver of economic, social, and spatial dynamics within European cities. The intensification of international tourist flows - facilitated by enhanced transport networks, the proliferation of digital intermediaries, and increased global mobility - has integrated tourism as a structural element of contemporary urban economies. Cities, in this framework, operate as complex adaptive systems in which tourism interacts with multiple dimensions of urban development, affecting spatial configuration, economic activity distribution, and real estate market behavior.

Concurrently, evolving patterns of tourist consumption, particularly through the expansion of home-sharing platforms and alternative accommodation typologies, have redefined the interaction between tourism and urban space. These developments have

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intensified competition over land use and access to housing, positioning tourism as a key driver of real estate dynamics, affecting both price formation and the availability of long-term residential stock.

Manifestly, there are economic benefits in such a situation: creation of employment opportunities, development of the service sector and increased interest in heritage areas. However, destinations facing high volumes of tourists suffer from certain negative impacts associated with the rise in prices, limited access to housing for locals, and changes in city quarters in order to make them suitable for tourists and business.

Overtourism occurs when a certain destination is subjected to tourism pressure to the extent that the activities of the tourists interfere with the lifestyle of the local inhabitants. Overtourism is not necessarily related to the volume of tourists; rather, it depends on the intensity of their flow, urban planning, and ability of public authorities to control such processes [1, 2]. Most often, overtourism manifests itself in historic areas and densely populated urban environments characterized by limited infrastructure where natural resources and economic functions are heavily loaded.

In this context, the following research focuses on the impact of tourism development on the urban real estate market by examining three selected cities of Italy that differ in their stages of tourism development: Bari from Southern Italy, Perugia from Central Italy, and Venice from Northern Italy. This combination allows for understanding the interaction between tourism and various urban systems and economies of these cities as well as the influence exerted by tourism on real estate market organization.

### 1.1 Overtourism: Socio-economic and Spatial Impacts on Cities

Overtourism is an important characteristic of contemporary urban life, emerging out of complicated interplays between the various economic, social, infrastructural, and factual determinants. However, without proper spatial planning and regulation of cities, this phenomenon may threaten the stability of local communities and social order. On one hand, more tourists mean increased economic opportunities for cities through increased local expenditures, creation of jobs, and improved service availability. Nevertheless recent research is rather unanimous in their assessment that excessive growth generates significant problems to urban life by turning inner city districts into tourist-dominated [1].

On another hand, research focusing on the impact of overtourism on society reveals several consequences of high tourist pressure, including strain on urban infrastructure and resources, resulting in traffic issues, noise pollution, and increased competition between locals and tourists for urban resources. In addition to deterioration of the quality of life, such consequences undermine social harmony in the city and lead to other negative phenomena [1, 3]. Particularly, the increasing dominance of tourism-related development contributes to social disparities and exclusion of vulnerable population segments [4].

From an infrastructural standpoint, congestion caused by the density of tourists in certain locations and peak periods causes pressures on transportation systems, waste management, water resources, and overall urban maintenance systems. The problem is especially noticeable in historic city centers, which often lack flexibility, thereby increasing the likelihood of persistent congestion and resulting in higher costs [1].

In the wide range of issues related to overtourism, the connection between tourism and urban real estate is receiving more attention from researchers because it provides insight into social and spatial changes occurring in cities with high tourism demands. Particularly, the development of online intermediary services such as Airbnb and Booking.com has facilitated the transition of property from residential use to vacation rentals. Such developments have considerable implications for activity location and real estate investment strategies [5].

Empirical evidence suggests a positive correlation between the expansion of short-term rentals and rising property values. For example, Barron, Kung, and Proserpio [6] show that, using data from U.S. cities, find that increase in Airbnb listings are associated with statistically significant rises in rental prices and residential values, largely due to the contraction of long-term housing supply. European studies, including those by Cocola Gant [7] and Adamiak [8], corroborate these findings, showing that the growth of short-term rentals in highly attractive historic centers is linked to gentrification processes, spatial polarization of real estate prices and the gradual deterioration of traditional residential functions.

In Italy, official data from the National Statistical Institute (ISTAT) [9] indicate a marked increase in properties dedicated to tourist accommodation, particularly in cities with high cultural demand, leading to consistent effects on the availability of housing for residents. Such changes not only generate systematic increases in per-square-meter property values in central areas, as documented by the Real Estate Market Observatory of the Italian Revenue Agency (OMI) [10], but also progressively limit housing accessibility for the resident population, particularly among socioeconomically vulnerable groups, thus reducing the capacity of families to stay in traditional neighborhoods. The functional conversion of units into tourist accommodations intensify this trend, as the decisive criterion between residential and tourist use increasingly becomes economic profitability rather than the social function of housing, with structural consequences on urban demographic composition and the spatial distribution of the population [8].

Comparative empirical evidence in the literature further indicates that the increase in tourist rentals is frequently associated with a contraction of the stable resident population, with direct effects on demographic structure and socio-economic dynamics of cities, including forms of resident displacement, substitution by temporary residents, or property investors oriented toward tourism valorization rather than traditional neighborhood life [3]. These processes of residential replacement are embedded in broader gentrification mechanisms, wherein tourism attractiveness acts as a catalyst for urban rebranding oriented toward mass tourism consumption, to the disadvantage of established local residency and services for permanent inhabitants [11, 12]. In many European cities, depopulation of historic centers has been documented in association with rising housing prices and the progressive reduction of resident-oriented services, replaced by tourism-oriented activities, with negative consequences for social vitality, access to local infrastructure, and the resilience of historic urban communities. In Italy, locations of high historical-cultural value and great appeal to tourists exhibit a typical situation where the volume of tourists collides with spatial constraints and increasing numbers of short-term

rentals. This situation makes the interaction between local residential areas and tourist-related spaces particularly intense, requiring responsible urban governance and effective urban planning as the main instruments for overcoming these tensions.

To better understand the current issue, it is necessary to combine data about demographics, real estate price fluctuations, and the number of available beds/units aimed specifically at tourists. This insight may facilitate in assessing tourism-related impact on the availability of homes for local residents and identifying regulatory strategies which can ensure a balance between the interests of locals and tourists. In this context, overtourism can be seen not only as a disruptive factor which negatively impacts the quality of life and social justice but as a sign of more general processes occurring in urban housing markets of our time. Thus, researching overtourism requires a combination of urban planning theories with those of territorial economics and tourism.

## 2 Aim

This work presents a systematic analysis comparing the influence of tourism development on urban real estate dynamics, selecting three cases based on their location along the tourism development continuum. First, there is Bari, located in Southern Italy and representative of a case of emerging tourism; then, Perugia, an urban area in Central Italy experiencing a relatively low level of tourism impact and characterized by ongoing urban digital transformation; finally, Venice, located in Northern Italy, presenting a clear case of advanced and over-tourism. More than a mere description of phenomena, the present study aims to measure the influence of increasing tourist demand on urban areas. Specifically, the analysis focuses on the years 2019–2024, analyzing variations in real estate prices per-square-meter, the diffusion of short-term rentals and the presence of accommodation facilities, in order to identify potential correlations between tourism development and transformations in the urban residential market. The comparison across the three levels of tourism maturity further allows the identification of fundamental differences and recurring patterns in the responses of real estate markets and urban tissues to tourism pressure, highlighting how the intensity of the flows may modulate their effects on cities. The structure of this paper is presented below: in Sect. 3 a comparative analysis across the three case studies is carried out, with an in-depth investigation on the recent tourism trends and real estate dynamics in the contexts under analysis. In Sect. 4 the conclusions of the study and future developments are discussed.

## 3 Comparative Analysis Across Three Levels of Tourism Maturity

To investigate the mechanisms through which tourism interacts with the real estate market and the urban tissue, the current research proposes a comparative approach based on the analysis of urban contexts characterized by different levels of tourism maturity, allowing for the observation of both emerging phases and consolidated situations in the relationship between tourist flows and real estate transformations. In this perspective and in Italian territory, the cities of Bari, Perugia, and Venice represent emblematic cases: Bari as an emerging tourism context, experiencing rapid growth but not yet associated

with structural overtourism; Perugia as an example of moderate tourism pressure, characterized by a more balanced temporal distribution of flows and urban management also supported by the recent introduction of innovative digital tools; and Venice as a scenario of advanced overtourism, where visitor concentration has produced structural effects on the real estate market and social fabric.

Between 2015 and 2024, there is an expected increase in the number of tourists due to improvements in the airport infrastructure and lower costs of air travel. The growth will be characterized by a higher proportion of foreign tourists and seasonality, particularly during spring and summer. However, cultural richness can partially compensate for the negative impact [1]. Combining the data from the OMI and ISTAT databases reveals stable property value but some spatial disparities. Central areas demonstrate greater resilience in terms of their ability to withstand fluctuations in the market, whereas peripheral territories are susceptible to economic cycles. Therefore, the emergence of short-term rentals and other forms of accommodation represents the gradual increase in profit-oriented property management without massive depopulation and congestion issues [6, 8].

On the contrary, Perugia operates within a tourism environment that does not experience strong seasonality. Universities and various cultural events distribute tourists throughout the year. Accommodation facilities remain small-scale, and the increase in non-hotel units does not result in substantial changes in urban supply, preserving residential functions and limiting effects on the real estate market [2]. The case of Perugia is particularly illustrative, as the Municipality has recently implemented an Urban Digital Twin, which is a digital model that enables the prospective assessment of the impacts of planning decisions and policy interventions on the urban territory; it provides an effective tool to support sustainable urban management and guide the monitoring of ongoing transformations [13].

Venice, instead, represents the case in which the historically high overlap of tourist flows, and limited real estate availability have generated structural transformations of the urban tissue, with systematic conversion of residential properties into tourist units, polarization of property values, increased tourism profitability, and a significant reduction in the stable resident population, constituting a consolidated model of overtourism [9]. This scenario has necessitated public tourism management policies, such as regulation of daily flows, daily visitor tax, limits on the conversion of residential properties, and digital monitoring systems, highlighting how urban governance integrated with advanced tools represents a strategic element for the sustainable management of tourism pressure and the mitigation of negative effects on the real estate market and social fabric, in this case, more as a monitoring tool rather than with a predictive function.

The comparison of the three urban contexts allows for the delineation of a continuum of tourism maturity: from the emerging tourism of Bari, where flows begin to affect real estate dynamics without generating structural imbalances; to the moderate model of Perugia, with contained pressure, balanced temporal distribution of visitors, and a stable real estate market; and finally to the critical situation of Venice, where prolonged exposure to intense tourist flows has consolidated a structural relationship between tourism and real estate valorization, with profound implications for residential function, social sustainability, and urban planning. This comparative analysis suggests

that tourism should be seen as dynamic, multidimensional driver, whose impact on urban real estate markets and spatial organization is influenced by the intensity of visitor flows, seasonal variations, spatial patterns of tourism, demographic characteristics of the resident population, and the effectiveness of urban governance. The approach provides a conceptual framework that can guide the development of proactive management strategies and support sustainable urban tourism planning.

### 3.1 Data and Methods

To compare the real estate market and the tourism sector in the three selected cities - Bari, Perugia, and Venice - a comparative analysis has been conducted using variables related to both property values and urban tourism dynamics over the period 2019–2024. The temporal range of this study (2019–2024) is based on both data availability and analytical relevance. Specifically, 2019 has been selected as the baseline year since it represents the last full period preceding the onset of the COVID-19 pandemic, which generated widespread disturbances and structural changes across all sectors. The year 2024 has been chosen as the upper bound because, at the time of analysis, data for the second semester of the 2025 OMI quotations were not yet available; consequently, in order to ensure consistency over complete annual observations, the most recent fully available year has been adopted. The decision not to extend the analysis further back in time reflects the intention to capture recent dynamics associated with emerging tourism trends, which have become particularly relevant in the post-pandemic context. Future research could extend the temporal horizon to a full decade and incorporate the selected variables into an econometric model enriched with additional contextual factors—such as climate conditions, service provision, and demographic structure—in order to more comprehensively assess the influence of local characteristics, including tourism vocation, on real estate market values.

Real estate variables have been derived from residential property price quotations per-square-meter published by the OMI of the Italian Revenue Agency, referring to the second semester of 2019 and 2024 [14]. The analysis considered the average selling and rental values across homogeneous urban zones and is restricted to residential properties in normal conservation conditions in order to ensure comparability across the three case studies. Specifically, for each municipality, a central area and a peripheral area have been identified.

For the tourism dimension, official data from ISTAT on tourist flows in accommodation establishments have been used, focusing on the indicators of arrivals and overnight stays for the years 2019 and 2024, disaggregated by accommodation type (hotel and non-hotel sectors) [15]. These variables enable to verify the intensity and evolution of tourism demand in the three municipalities. In addition, the average length of stay (calculated as the ratio between overnight stays and arrivals) has been derived to highlight structural differences in tourism patterns and to relate these dynamics to the evolution of OMI real estate price quotations.

### 3.2 Comparative Analysis of Tourism and Real Estate in the Three Cities

#### 3.2.1 Trends in Real Estate Prices

In the case of Bari, real estate price data indicate various dynamics between the historic center (B10 OMI zone) and peripheral areas (D1 OMI zone). In the center, sales values increased slightly from €2,175/m$^2$ in 2019 to €2,200/m$^2$ in 2024 (+€25/m$^2$; +1.15%), whereas peripheral zones showed a notable decline from €1.600/m$^2$ to €1,450/m$^2$ (−€150/m$^2$; − 9.38%). Rental prices in the center rose moderately from €7.1/m$^2$ to €7.4/m$^2$ (+4.2%), while peripheral rents stayed stable at €5.25/m$^2$. These findings indicate a relatively balanced market in the central area of Bari, set against a contraction in peripheral zones, and suggest that rental prices face limited dynamism, consistent with a market in equilibrium and without significant structural changes.

In Perugia, the historic center (B1 OMI zone) recorded a substantial decline in sale values from €1,500/m$^2$ to €1,275/m$^2$ (−15%), while peripheral areas (D1 OMI zone) experienced a more moderate decrease from €1,250/m$^2$ to €1,145/m$^2$ (−8.4%). Conversely, rental prices increased significantly, particularly in the center, rising from €5.65/m$^2$ to €7.35/m$^2$ (+30.1%), whereas peripheral rents grew modestly from €5.6/m$^2$ to €5.8/m$^2$ (+3.6%). These results suggest that declining property sale values may coexist with sustained rental demand, indicating a possible reallocation in residential demand towards the rental segment.

In Venice, the historic center (San Marco, B24 OMI zone) registered a slight increase in sales prices from €4,700/m$^2$ to €4,750/m$^2$ (+1.06%), a trend also observed in the suburban area of Mestre Centro (E23 OMI zone). Regarding rental values, both central and suburban areas show minor declines (−3.57% and −9.37%, respectively). Overall, Venice maintains significantly higher price levels compared to the other cities, with stable sale prices and a slight contraction in rental rates, particularly in peripheral zones.

#### 3.2.2 Trends in Tourist Flows

In Bari, total tourist arrivals increased from 1,192,991 in 2019 to 1,556,312 in 2024 (+30.4%). By comparison, Perugia recorded 2,037,508 arrivals in 2019, rising to 2,234,351 (+9.7%), while Venice registered 9,979,780 arrivals in 2019, increasing to 10,664,823 (+6.9%). Overnight stays exhibited heterogeneous growth patterns: Bari increased from 2,688,879 to 3,612,174 (+34.3%), Perugia from 5,057,919 to 5,824,138 (+15.1%), and Venice from 37,951,808 to 38,843,559 (+2.3%).

Average length of stay, calculated as the ratio between overnight stays and arrivals, further highlights substantial differences. In 2019, it was 2.25 nights in Bari, 2.48 nights in Perugia, and 3.8 nights in Venice; by 2024, these values reached 2.32, 2.61, and 3.64 nights respectively, indicating a slight decline in Venice, a moderate increase in Perugia and relative stability in Bari.

A disaggregation by accommodation type reveals differentiated dynamics. In Bari, hotel arrivals declined slightly (−2.6%), while non-hotel arrivals more than doubled (+124%), with overnight stays showing a similar trend (+2.6% in hotels compared to + 108% in non-hotel accommodations). Perugia showed more balanced growth, with hotel and non-hotel arrivals increasing by +4% and +20%, respectively, and overnight stays by +15% in both sectors. Venice presented a decline in hotel activity (−4.7% arrivals; −6.9% overnight stays) but an increase in the non-hotel sector (+25% arrivals; +8.8% overnight stays). These patterns propose three distinct tourism configurations: Bari is

in a phase of rapid expansion driven by non-hotel accommodations; Perugia shows moderate growth with spatially balanced distribution; Venice reveals consolidation with high absolute volumes and internal reallocation toward non-hotel services.

### 3.2.3 Comparative Analysis of the Three Municipalities

A joint analysis of OMI real estate data and ISTAT tourism statistics shows differentiated interactions between tourism dynamics and property markets. Bari presents the strongest tourist growth between 2019 and 2024 (+30.4% arrivals; +34.3% overnight stays); nevertheless, this expansion has not caused significant increases in sales values, which remain stable in the center (+1.15%) and decline in peripheral areas (−9.38%). Rental growth in central Bari (+4.2%) is modest relative to tourism development, indicating an early stage of transformation in which increased flows have not yet produced structural effects on property values.

In Perugia, reasonable tourism growth (+9.7% arrivals; +15.1% overnight stays) coincides with pronounced contraction in central property sales prices (–15%) and moderate peripheral declines (−8.4%). Conversely, central rental values increased intensely (+30.1%), suggesting selective conversion of the housing market in response to moderate but growing tourist pressure.

Venice, with over 10 million arrivals and nearly 39 million overnight stays in 2024, exhibits very high absolute tourist volumes but a controlled growth (+6.9% arrivals; + 2.3% overnight stays), indicating a phase of consolidation rather than expansion. Real estate sale prices remain broadly stable (+1.06%), while rental values show a slight decline (−3.57% center; –9.37% suburban), suggesting a process of rental market normalization. The average length of stay further highlights these differences, with Venice recording the highest values (3.64 nights), followed by Perugia (2.61 nights) and Bari the lowest (2.32 nights).

The results allow the identification of three different urban profiles. Bari is characterized by rapid tourism growth accompanied by limited and non-structural effects on the residential market. Perugia shows moderate tourism alongside declining property sale values and a marked increase in central rental prices, indicating a targeted restructuring of housing market dynamics. Venice represents a mature tourism system, with high visitor volumes, relatively stable sale prices, and a slight contraction in rental levels. Overall, these findings suggest that the relationship between tourism and real estate markets is non-linear and depends on the level of urban maturity, the structure of local housing demand and the stage of tourism development. In cities where tourism is still expanding under relatively balanced conditions, real estate markets tend to grow together with visitor demand. Conversely, in highly saturated contexts affected by overtourism, rental markets may contract despite stable or increasing tourist flows. These results align with existing empirical literature suggesting that the impact of tourism on real estate dynamics is contingent, context-specific and mediated by structural characteristics of urban systems, including their development stage and housing demand composition [16, 17].

Figure 1 illustrates these trends: Bari shows the strongest growth in arrivals and overnight stays; Perugia displays moderate but significant increase and Venice maintains high absolute volumes with limited percentage variation.

The differences between sales and rental markets illustrated in Fig. 2 are particularly pronounced in Perugia, whereas Bari shows a more balanced dynamic and Venice is characterized by stable sales alongside a slight decline in rental value.

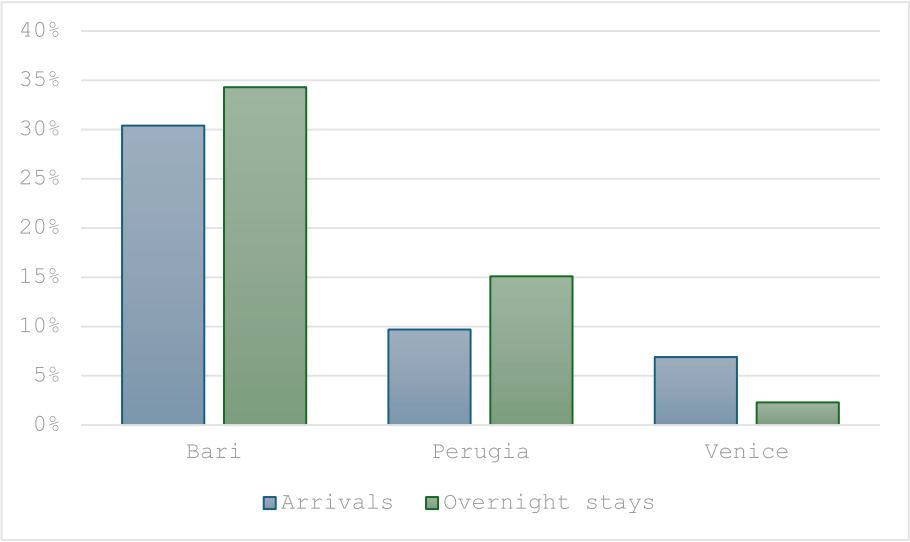


**Fig. 1.** Percentage variation in tourist arrivals and overnight stays (2019–2024)

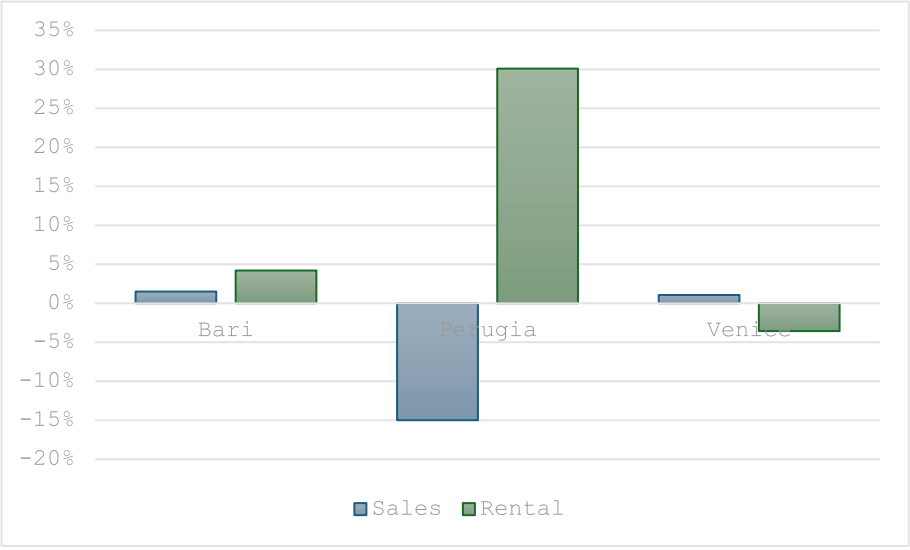


**Fig. 2.** Percentage variation in sales and rental values in central area (2019–2024)

Figure 3 compares central urban areas and shows how tourism expansion translates differently across property markets: strong rental growth in Perugia contrasts with moderate increases in Bari and slight declines in Venice, thereby visually supporting the differentiated urban configurations identified in the previous analysis.

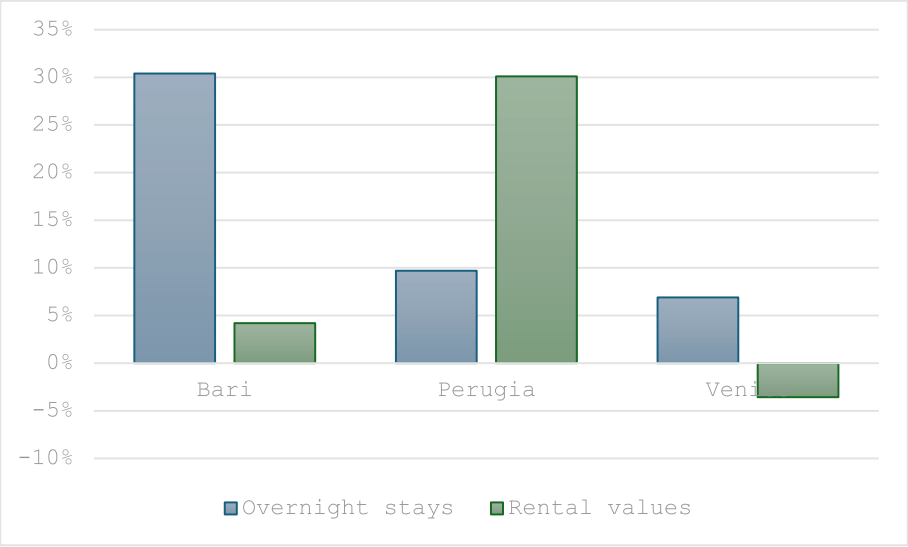


**Fig. 3.** Comparison of percentage variation in overnight stays and rental rates (2019–2024)

## 4 Conclusions and Future Developments

Analysis of the relationships between tourism and real estate in Bari, Perugia, and Venice for the period 2019–2024 reveals that there is no standardized response in the correlation between tourism and real estate. These relationships depend strongly on the level of tourism intensity, urban layout, and housing demand [18].

Tourism intensity does not appear to affect the price trends of residential properties in Bari significantly. An unprecedented increase in tourist flows in this location did not, at least in the immediate future, lead to a systematic rise in the sale prices of the real estate market. The data imply that an initial alignment of the two markets is observed, suggesting the intermediate stage of development: tourism increases, but distortions have not yet occurred.

In Perugia, a different trend prevails. In this case, the constant pressure from tourists combined with the relatively uniform distribution of tourists within the city results in declining prices for property purchases in the central parts of the city, whereas rents increase significantly. Such an imbalance indicates a change in the demand for properties towards rental housing. This may be attributed to the fact that both tourists and residents find rental housing more attractive than active property development.

Venice is an advanced tourist destination, characterized by very high visitor traffic. In this place, real estate prices have remained constant, whereas rents have slightly decreased. This trend demonstrates the constant strain exerted by tourists on real estate, resulting in diminishing accessibility and affordability for the local population. To attenuate this challenge, the local administration has introduced various measures, including regulating short-term accommodation and imposing a tourist tax. According to literature sources, such governmental actions are essential for mitigating the adverse consequences of overtourism and preventing locals from displacement. Evidence from other

European cities further indicates that tighter regulation of short-term rental markets can reduce accommodation pressure and control speculative behavior, although effective enforcement remains a critical issue [19]. Generally, governance approaches that combine regulatory instruments, stakeholder coordination, and long-term planning are increasingly perceived as necessary to rebalance tourism growth with the social and economic sustainability of urban housing systems.

Mutually, these findings confirm that increases in tourist demand do not generate uniform effects on real estate markets. Instead, results differ according to local territorial conditions, the structure of housing demand, and the current policy framework.

Nevertheless, the current study presents several limitations. First, the analysis is descriptive and comparative in nature and should be regarded as an initial step towards more advanced empirical research. Future studies could employ econometric models incorporating additional contextual variables—such as climatic conditions, service provision, infrastructure systems, and demographic characteristics—to more precisely quantify the impact of tourism on real estate markets and to better capture how the maturity of tourism development shapes this relationship. Second, extending the temporal scope would enable a more comprehensive understanding of the dynamics associated with varying levels of tourism intensity and their evolution across heterogeneous contexts over time. Finally, the study relies on a limited sample of three cities; although these cases reflect different tourism profiles, the restricted geographical scope limits the generalizability of the findings and underscores the need for a broader case selection in future research.

Additionally, future research could further explore the role of digital innovation in supporting urban management processes. In this regard, the Urban Digital Twin could be an instrument capable of integrating forecasting and monitoring functions. For instance, in a context such as Perugia, it could support local decision-makers in anticipating the potential effects of planning choices and tourism-driven changes on housing dynamics, promoting more well-considered and proactive interventions. In extremely saturated destinations like Venice, the same tool could instead function as a simultaneous monitoring system, assessing the success of regulatory measures.

These harmonizing applications focus on the potential of innovative technologies to improve policy adaptability, align tourism development with local housing needs, and reduce the difficult consequences associated with high tourism pressure. In this sense, they reveal how digital technologies can be incorporated into urban governance models to support both anticipatory analysis and ex-post evaluation.

In Italy, initial applications of Urban Digital Twins are evolving through pilot initiatives in some cities as Bologna, Perugia, Parma, and Genoa. By allowing simulation and continuous observation of tourist demand, real estate fluctuations, and infrastructural capacity, these technologies may contribute to defining more effective governance interventions, identifying and addressing emerging pressures in cities before they evolve into structural imbalances.

## References


1. Organisation for Economic Co-operation and Development (OECD): Overtourism? Understanding and Managing Urban Tourism Growth beyond Perceptions. OECD Publishing (2020)
2. United Nations World Tourism Organization (UNWTO): Overtourism? Understanding and Managing Urban Tourism Growth beyond Perceptions. UNWTO (2018)
3. Milano, C., Novelli, M., Cheer, J.M.: Overtourism and tourismphobia: a journey through urban tourism governance. Int. J. Tour. Cities **5**(4), 519–528 (2019)
4. Guerra, E.: Tourism, gentrification and social change in urban spaces. J. Urban Aff. (2018)
5. Guttentag, D.: Airbnb: disruptive innovation and the rise of an informal tourism accommodation sector. Curr. Issue Tour. **18**(12), 1192–1217 (2015)
6. Barron, K., Kung, E., Proserpio, D.: The effect of home-sharing on house prices and rents: evidence from Airbnb. Mark. Sci. **40**(2), 217–244 (2021)
7. Cocola-Gant, A.: Holiday rentals: the new gentrification battlefront? Urban Stud. **53**(8), 1790–1807 (2016)
8. Adamiak, C.: Short-term rentals and gentrification in European cities. Urban Stud. J. (2018)
9. Italian National Institute of Statistics (ISTAT): Demographic and accommodation capacity indicators of Italian cities (2023)
10. Real Estate Market Observatory (OMI): Urban property prices. Italian Revenue Agency - Ministry of Economy (2023)
11. Atkinson, R.: Domination or transformation? Gentrification and the nature of urban change. Urban Stud. **40**(12), 2343–2360 (2003)
12. Smith, N.: Uneven Development: Nature, Capital, and the Production of Space, 3rd edn. University of Georgia Press (2008)
13. Sartoretti, V., Minascurta, M.: Perugia's digital twin – an innovative model of urban governance. GEOmedia **28**(3) (2024). https://ojs.mediageo.it/index.php/GEOmedia/article/view/2017
14. Real Estate Market Observatory (OMI): Property prices quotations 2019–2024. Italian Revenue Agency - Ministry of Economy
15. Italian National Institute of Statistics (ISTAT): Capacity of tourist accommodation municipal 2013–2024
16. Barbić, T.: Impact of tourism activity on urban land and housing market activity: evidence from Croatia. Economies **12**(12), 337 (2024). https://doi.org/10.3390/economies12120337
17. Čeh Časni, A., Filić, J.: Tourism housing price nexus. Croat. Rev. Econ. Bus. Soc. Stat. **8**(2), 53–65 (2022). https://doi.org/10.2478/crebss-2022-0010
18. Sánchez Ollero, J.L., Urrestarazu Capellán, R., García Pozo, A.: The impact of cultural and urban tourism on housing. J. Tour. Herit. Res. **2**(4), 257–272 (2019)
19. Bei, G., Celata, F.: Challenges and effects of short-term rentals regulation: a counterfactual assessment of European cities. Ann. Tour. Res. **101** (2023). https://doi.org/10.1016/j.annals.2023.103605

# An Optimization Method to Ensure Reliability in the Assessment of Special Properties

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**Abstract.** The valuation of special properties is often characterised by a high degree of complexity due to limited market comparability, functional specificity, and the subjectivity involved in the estimation of key appraisal parameters. This issue is particularly relevant in the case of socio-healthcare facilities, whose market value is commonly assessed through the Discounted Cash Flow Analysis (DCFA). This paper proposes an innovative decision-support approach method aimed at improving the transparency, consistency, and replicability of DCFA-based appraisals. The method combines the income-based valuation logic of the DCFA with goal programming techniques, in order to rationalize the determination of the main variables affecting the value and to reduce the discretionary that typically characterises such estimates. Applied to the case of Italian private nursing homes, the proposed framework is intended to support a more structured and reliable estimation process, while also considering the different perspectives of the parties involved in the transaction. The study contributes to the current debate on the valuation of special properties by offering a simple and operational method for appraisal verification.

**Keywords:** Discounted Cash Flow Analysis · Goal Programming · Socio-Healthcare Facilities · nursing homes

## 1 Introduction

Over the last few decades, major economic shocks have made clear that inaccurate real estate valuations may generate effects far beyond individual transactions, influencing credit allocation, investment choices, and, in severe cases, the stability of the wider financial system. The global financial crisis triggered by the collapse of the U.S. subprime mortgage market remains the clearest example of how weaknesses in pricing, risk assessment, and collateral appraisal can amplify systemic fragility. In the years that followed, the growing relevance of categories such as Unlikely To Pay, Non-Performing Loans, and Distressed Assets further confirmed the strategic role of valuation practices within fragile financial environments [1]. More recently, the COVID-19 pandemic showed how rapidly real estate markets can change, particularly in relation to special-purpose assets,

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whose value is strongly affected by operational performance, regulatory constraints, and functional adaptability. In parallel, the current geopolitical instability connected with the war in Ukraine has contributed to a climate of caution in real estate investment, while the implementation of Next Generation EU programmes has increased the urgency of allocating resources efficiently, especially in projects involving the regeneration and enhancement of complex real estate assets.

Within this context, special properties represent one of the most challenging segments of the real estate market. These assets, often included within the broader category of Commercial Real Estate (CRE), are characterised by specific functional, technical, constructional, and dimensional features that make them difficult to compare with ordinary market products. Their value is not determined solely by location or physical characteristics, but also by the capacity of the asset to support a specific use over time, often under changing economic and social conditions. In many cases, these properties require functional reconfiguration in response to evolving demand, changing regulations, or new performance standards. As a result, their appraisal is inherently more complex than the valuation of standard residential or commercial properties, and traditional methods may prove insufficient unless supported by rigorous assumptions and well-grounded analytical frameworks.

In this context, even before the pandemic, several procedures had already been developed to make real estate appraisals more reliable [2, 3]. These include the calibration of capitalization rates within the Income Approach [4], the estimation of the marginal prices of intrinsic and extrinsic factors within the Market Approach [5], the definition of depreciation coefficients within the Cost Approach [6], and the identification of rational coefficients for estimating values other than market value [7].

Despite these advancements, the valuation of special properties still remains affected by a considerable degree of uncertainty, especially when appraisers are required to define parameters that are only partially observable in the market. The heterogeneity of these assets, the limited availability of comparable transactions, and the frequent need to interpret the effects of use, management, and transformation potential may widen the discretionary component of the valuation process. Consequently, even when the appraisal is formally structured, the final estimate may still be influenced by assumptions that are difficult to verify objectively. This issue is particularly relevant in phases of market instability, when variations in risk perception, investment behaviour, and expected performance can significantly affect real estate value judgments.

From this perspective, the current debate on valuation reliability appears closely connected to broader economic and institutional transformations. On the one hand, real estate markets are increasingly exposed to shocks that alter expected uses, returns, and risk profiles. On the other hand, both public and private actors are required to make decisions concerning complex properties under conditions of limited information and rapidly changing scenarios. In this framework, improving the transparency, consistency, and robustness of valuation procedures is not merely a technical matter, but also a broader economic necessity, since appraisal activities play a strategic role in supporting investment decisions, credit assessment, asset management, and effective allocation of public and private resources.

## 2 Aim

This paper investigates innovative approaches to the valuation of special properties, with particular attention to the limits of the conventional method applied, i.e. the Discounted Cash Flow Analysis (DCFA). Although the DCFA is widely used in the appraisal of this asset class, its application often depends on assumptions that are not fully verifiable, especially when defining key inputs such as revenues, operating costs, discount rates, exit yields, market trends, inflation expectations, and the time horizon of the analysis. As a result, the valuation process may become insufficiently transparent and difficult to reproduce consistently.

To address this issue, the study develops an empirical framework based on a set of appraisal case studies concerning healthcare properties located in Italy. By examining how the main variables of the DCFA are defined in professional practice, the paper seeks to identify recurring valuation patterns and to translate them into a more structured analytical model. More specifically, the research explores the use of goal programming as a decision-support tool for reducing the discretionary component of DCFA-based appraisals. Applied to the selected property type, this approach is intended to support a more transparent and consistent estimation of market value by organising the appraisal process within a clearer analytical structure. In this way, the proposed framework aims to reflect more coherently the different risk and return expectations of the parties involved in the transaction, particularly sellers and investor-buyers.

The paper is structured as follows. Section 3 presents the background to the study: taking into account a specific typology of special properties, represented by the nursing homes (RSAs), the analysis is focused on the socio-healthcare facilities, the Italian regulatory framework, the socio-demographic context, and the structure of the RSA market. Section 4 illustrates the proposed method and briefly discusses the main results. Finally, Sect. 5 summarizes the conclusions, limitations, and future developments of the research.

## 3 Background

### 3.1 Socio-healthcare Facilities

Socio-healthcare facilities are extra-hospital residential structures designed to provide integrated health and social-care services to frail, disabled, or non-self-sufficient individuals. Their primary purpose is to ensure continuity of care for persons whose needs cannot be adequately managed at home, while also supporting quality of life through assistance, supervision, and social integration.

Within this broad category, different facilities correspond to different levels of care intensity. Hospices are mainly devoted to palliative care for patients affected by incurable diseases. Nursing homes (RSAs) generally accommodate elderly persons who are fully or partially self-sufficient and primarily require hospitality and basic assistance. By contrast, residential healthcare facilities are intended for users whose conditions require a stronger integration of medical, nursing, and rehabilitative services.

In the Italian context, the RSAs represent the most relevant typology for the purposes of this paper. They are residential facilities for non-self-sufficient elderly persons and

disabled adults who require continuous medical, nursing, and rehabilitative support, combined with assistance in daily living activities. A related typology is represented by the RSAs, which mainly provide high-intensity personal and socio-rehabilitative care for older persons with severe psychophysical impairments or dementia, although with a lower level of complex healthcare than that typically associated with the RSAs.

For this reason, although the broader background includes several forms of residential care, the following discussion focuses primarily on the RSAs, as they are the socio-healthcare assets most directly aligned with the empirical and valuation scope of the paper.

### 3.2 Regulatory Framework

The regulatory framework governing residential socio-healthcare services in Italy is relatively limited at the national level and largely implemented through regional legislation. As a result, the term RSA has acquired partially different meanings across regions, with boundaries that are not always clearly distinguished from other forms of residential care, such as nursing homes, protected residences, geriatric rehabilitation institutes, and long-term rehabilitation facilities.

RSAs were introduced in Italy in the early 1990s within the multi-year healthcare investment programme established by Law No. 67/1988 and subsequently updated by Law No. 160/2019. The underlying rationale of this regulatory framework was the growing incidence of ageing and non-self-sufficiency within the Italian population, together with the need to provide extra-hospital residential care for individuals who could no longer be adequately assisted at home. In this context, residential care is understood not as a single healthcare act, but as an integrated set of health, social, protective, and hospitality services delivered on a 24-hour basis to non-self-sufficient persons in accredited facilities.

Through the National Health Service, the State undertook to ensure that frail and non-self-sufficient individuals affected by chronic illness or other conditions incompatible with home-based care could access appropriate residential services. However, the organization of extra-hospital residential care falls largely within regional competence. For this reason, most national acts operate as general framework provisions aimed at guaranteeing a minimum and uniform level of assistance across the country, while their effective implementation depends on formal regional transposition. This multilevel governance has generated significant territorial heterogeneity, including differences in admission criteria, age limits, service configuration, and the degree to which partially self-sufficient persons may be accommodated.

To reduce fragmentation and define minimum standards of care, the *Livelli Essenziali di Assistenza* (LEA) were introduced by the Decree of the President of the Council of Ministers of 29 November 2001 and subsequently replaced by the Decree of 12 January 2017, which established the current framework of essential levels of care. Within this system, the State identifies the services that must be guaranteed nationwide, while the Regions are responsible for their implementation, monitoring, and integration within local health planning. Compliance with LEA standards is overseen through the national monitoring system coordinated by the competent committee for the verification of essential levels of care.

Overall, the regulatory framework may therefore be divided into two main levels. State legislation establishes the general principles concerning minimum requirements, accreditation within the National Health Service, public funding mechanisms, and the institutional responsibilities of local authorities. Regional legislation, by contrast, defines the detailed quality requirements, authorization procedures, organizational criteria, and operational rules applicable within each territorial context. This framework is also highly relevant from an economic and valuation perspective. Accredited RSA facilities operate through a mixed revenue structure based on two main components: a healthcare tariff funded by the National Health Service for beds covered by contractual agreements with the Regions, and a hospitality fee paid by the resident, with possible municipal support in cases of economic hardship. Precisely because of this revenue structure, together with the long-term demand associated with ageing, socio-healthcare facilities have progressively emerged as an asset class of growing interest for investors.

### 3.3 Socio-demographic Context

Population ageing is one of the main structural drivers behind the growing demand for long-term care services in Italy. At the beginning of 2022, people aged over 65 were more than 14 million, corresponding to 23.8% of the total population and about 3 million more than twenty years earlier. The over-80 population exceeded 4.5 million, while centenarians reached about 20,000, a figure that has quadrupled over the last two decades. Demographic projections indicate that, by 2042, the population aged over 65 may rise to almost 19 million, accounting for 34% of the total, while the old-age index is expected to increase from 187.9% in 2022 to 295.0%.

This trend is closely associated with a growing incidence of frailty and dependency. In Italy, around 4 million people currently experience severe limitations in daily activities, and 92% of them still live at home. At the same time, longer life expectancy is accompanied by an epidemiological transition in which chronic and degenerative diseases increasingly replace infectious conditions, especially among older age groups. In this context, the rise in cardiovascular, cerebrovascular, and neurodegenerative diseases, including Alzheimer's disease and related dementias, is expected to intensify the need for integrated health and social care services.

These dynamics also have significant socioeconomic implications. As the ratio between active and inactive population becomes less favourable, the burden related to care provision, long-term assistance, and welfare expenditure is expected to grow. For this reason, population ageing should be understood not only as a demographic phenomenon, but also as a structural challenge for healthcare and social policy. Strengthening territorial and residential care services is therefore essential to reduce inappropriate hospitalization and to provide adequate support for frail and non-self-sufficient older persons.

### 3.4 RSA Market

Residential socio-healthcare facilities have expanded rapidly in Italy over the last 15–20 years, mainly in response to growing demand for long-term care services. Current estimates indicate that the sector includes nearly 300,000 beds, corresponding to about 2.5%

of the elderly population, although this figure should be treated with caution because regional classification systems are not fully homogeneous.

According to the Ministry of Health, in 2020 Italy had 7,858 public and accredited private residential healthcare facilities, with a total of 262,351 beds. Accredited private providers clearly dominate the sector, accounting for 6,540 facilities out of the national total. The territorial distribution is highly uneven: 67.3% of facilities are located in Northern Italy, compared with 17.3% in the Centre and 15.4% in the South and Islands. This imbalance is even more evident in terms of bed capacity, with 197,114 beds in the North, equal to 75.1% of the national total, while the Centre and the South and Islands account respectively for 14.5% and 10.3%.

A broader picture emerges from the Italian Institute of Statistics (ISTAT) data on residential socio-assistance and socio-healthcare services, which recorded 12,626 facilities and 411,993 operating beds in 2020. These data confirm the same territorial asymmetry in favour of the North. They also highlight the role of public funding: 68% of facilities located in the North receive public support, compared with 57% in both the Centre and the South and Islands; similarly, publicly funded beds account for 82% of the total in the North, 62% in the Centre, and 58% in the South and Islands.

When only beds allocated to socio-healthcare functions are considered, the national total is estimated at 318,497 units. Of these, 71.1% are concentrated in Northern Italy, while the Centre and the South and Islands account respectively for 14.3% and 14.7%. The four regions selected for the empirical focus of this study—Piedmont, Trentino, Veneto, and Tuscany—alone account for 103,524 beds, corresponding to 32.5% of the national total.

## 4 Method

Investments in socio-healthcare real estate are generally assessed based on the income-generating capacity of the underlying assets. For this reason, the market value of such properties is commonly estimated through the Income Approach, and more specifically through the Discounted Cash Flow Analysis (DCFA). This method is grounded in the assumption that an investor or developer is willing to pay for an asset an amount corresponding to the present value of all expected inflows and outflows generated by that asset over a given time horizon, discounted at an appropriately determined rate. The discount rate must reflect the intrinsic and locational characteristics of the property, since these factors directly affect the level of risk associated with the real estate operation. In essence, the method consists in capitalizing the net real estate income that the property is expected to generate over time.

The economic events of the last decades have highlighted the need for adequate professional expertise in real estate appraisal. Inaccurate valuations have produced negative effects first in financial markets and subsequently in the real economy, with many real estate assets being overvalued in relation to their actual market values. Within this context, the formalization of shared and consistent rules in the International Valuation Standards (IVS) has become increasingly important in order to establish a common language among professionals and to protect the public interest in the integrity of the valuation process [8]. Since real estate appraisal is an integral part of the wider business

environment [9], the integrity of the valuation process is essential to reduce the likelihood of systemic economic crises, such as the U.S. subprime crisis of 2007, and the related instability of financial markets that may ultimately trigger global disruptions.

The need to manage uncertainty, that is, to obtain reliable forecasts of real estate market values over the medium and long term—for example, in the case of properties used as collateral for mortgage lending—has encouraged the development and diffusion of innovative mass appraisal models. This process has also been facilitated by improvements in computing technology and by the availability of increasingly accessible software tools. Among the approaches experimented with in this field are genetic algorithms, spatial analysis models, fuzzy logic, and artificial neural networks. These models are characterised by a strong theoretical and methodological basis and are capable of automatically identifying causal relationships between explanatory variables and prices, as well as estimating real estate values in the short term [10–12].

Although these models are able to measure the marginal contribution of the factors influencing price formation, thus responding to the current need to standardize valuation procedures [13] and to reduce the excessive randomness of appraisals often associated with overconfidence in valuers' judgement [14], they are still viewed with considerable distrust by ordinary practitioners. This reluctance depends, on the one hand, on the complexity of the mathematical formalism underlying such techniques and, on the other, on the frequent scarcity of comparable market data. Such data would in fact be necessary to implement econometric procedures capable of adequately describing the price-formation mechanisms of assets within specific markets [15].

The method developed in this study draws on the operational logic of goal programming techniques. Since the 1960s, increasing attention has been devoted across different fields to the development of models based on goal programming. This approach enables the flexible and effective treatment of complex problems characterised by a high number of variables and constraints. A review of the international literature has shown that goal programming has been applied in several studies to real estate valuation, as well as to investment planning and investment appraisal [16–19].

In general terms, a goal programming problem can be interpreted as the optimal allocation of scarce resources that may be assigned to alternative uses. In this sense, a goal programming problem is characterized by resources available in limited quantities, alternative uses envisaged for such resources, constraints on the use of resources, and objective functions aimed at evaluating the contribution that each possible use of resources provides to the achievement of a predetermined goal.

In the present case, with reference to the method developed, the resources available in limited quantities are represented by the values that may be assigned to the different parameters, in relation to the sample of case studies collected, which constitutes an essential reference for replicating the ordinary behaviour of the valuer in the definition of the factors entering the DCFA. The alternative uses are represented by the economic parameters involved in the construction of the DCFA. The constraints are represented by the relationships linking the different parameters within the mathematical formulations that define a DCFA for the estimation of the market value of a special property.

The fundamental objective of the optimization method is the determination, according to the operational logic of Operations Research and the DCFA technique ordinarily

employed for the estimation of Market Value, of a compromise solution for the two parties involved in the transaction, namely the seller—whose aim is the maximization of market value—and the buyer—whose aim is the maximization of return.

It is well known that risk and return are directly correlated, and that, in a DCFA applied to economic feasibility assessments, the discount rate reflects the risk premium required by the subjects investing their own resources. According to the logic of the Weighted Average Cost of Capital (WACC), the two parties involved are the investor/buyer and the bank/credit provider.

Therefore, the compromise solution is the one that allows the maximization of the two objectives, each of them relating to one of the parties involved in the transaction, as expressed in Eq. 1:

$$Max\left(i + \frac{V}{Vmax}\right) \tag{1}$$

where:

- $i$ is the discount rate, determined through the application of the WACC;
- $V$ is the unit market value of the property;
- $Vmax$ is the maximum unit market value observed within the sample of case studies for the property type under valuation.

It should be noted that the ratio between $V$ and $Vmax$, introduced in Eq. 1, is necessary in order to make the two objectives dimensionally homogeneous, namely return for the buyer and capital perceived by the seller.

The main variables of the method are $i$, $V$, , and the market rent of the property ($Ca$). Since, in a DCFA, it is standard practice to assume that market rents evolve according to a geometric progression with ratio $(1 + s)$, where $s$ is the inflation rate, it follows that the only rental variable is the market rent at time zero ($Ca_0$).

The constraints of the model are defined as follows. First, Eq. 2 identifies the interval within which the rent $Ca0$ ordinarily varies, as a function of the Gross Operating Profit (GOP):

$$40\% \cdot GOP \leq Ca0 \leq 60\% \cdot GOP \tag{2}$$

Second, Eq. 3 defines the ordinary variation interval of entrepreneurial profit, equal to the difference between $GOP$ and $Ca_0$, expressed as percentages of operating revenues:

$$8\% \cdot R \leq GOP - Ca0 \leq 15\% \cdot R \tag{3}$$

Third, Eq. 4 expresses the variation range of the discount rate, according to the minimum ($i_{min}$) and maximum ($i_{max}$) values of the rates observed in the sample of case studies for the property type to which the asset under valuation belongs:

$$i_{min} \leq i \leq i_{max} \tag{4}$$

Finally, Eq. 5 synthesizes the construction of the DCFA matrix according, in addition to the parameters defined above, to the owner's costs ($K$), the Terminal Value—equal to the ratio between the market rent in the last year of the analysis period

$\left(Ca_n = Ca_0 \cdot (1+s)^n\right)$, net of owner's costs, and a net exit rate ($r$)—discounted, and the costs of property adaptation/re-functionalization ($CAPEX$):

$$V = \sum_{t=0}^{n} \frac{Ca_t - K_t}{(1+i)^t} + \frac{Ca_n - K_n}{r \cdot (1+i)^n} - CAPEX \tag{5}$$

As summarized in Eq. 5, the market value is therefore determined by the discounted balance of rents and owner's costs over the analysis period, increased by the discounted terminal value and reduced by the capital expenditure required for the adaptation or re-functionalization of the property.

Table 1 summarizes the algorithm of the optimization method developed, while Table 2 reports, for each parameter contributing to the definition of the method, the acronym adopted, the explanation of its meaning, and the related unit of measurement.

**Table 1.** Algorithm of the Optimization Method

| Component | Specification |
|---|---|
| Variables | $Ca_0$; $i$; $V$ |
| Constraints | $40\% \cdot GOP \leq Ca_0 \leq 60\% \cdot GOP$ |
| | $8\% \cdot R \leq GOP\text{-}Ca_0 \leq 15\% \cdot R$ |
| | $i_{min} \leq i \leq i_{max}$ |
| | $V = \sum_{t=0}^{n} \frac{Ca_t - K_t}{(1+i)^t} + \frac{Ca_n - k_n}{r \cdot (1+i)^n} - CAPEX$ |
| Objective function | $Max\ (i + \frac{V}{Vmax})$ |

To provide a preliminary assessment of the effectiveness of the proposed method, a descriptive statistical analysis was carried out by comparing known values with the algorithm outputs for three key variables: market rent, discount rate, and market value. For market rent, the Mean Absolute Percentage Error (MAPE) is 5.60%, with values ranging from 0.00% to 20.00%, a median of 3.39%, and a standard deviation of 6.43%; the Mean Absolute Error (MAE) is equal to €333.86/bed, ranging from 0.00€ to 1,375.04€/bed, with a median of 283.26€/bed. For the discount rate, the MAPE is 13.95%, with a minimum of 0.44%, a maximum of 33.33%, a median of 10.20%, and a standard deviation of 11.31%; the MAE is 0.59 percentage points, with values between 0.02% and 1.50% and a median of 0.50%. For market value, the MAPE is 9.07%, ranging from 0.28% to 28.08%, with a median of 7.62% and a standard deviation of 7.71%; the MAE is 9,802.12€, with values between 393.71€ and 30,960.41€ and a median of 6,740.25€. Overall, the algorithm shows the lowest deviations in the estimation of market rent, the highest variability in the estimation of discount rates, and satisfactory performance in the estimation of market value.

**Table 2.** Parameters of the Optimization Method

| Acronym | Parameter | Unit of measurement |
|---|---|---|
| $R$ | Operating revenues | €/bed |
| $Ca_0$ | Market rent at year zero of the analysis period | €/bed |
| $GOP$ | Gross Operating Profit = Revenues − Operating costs | €/bed |
| $i$ | Discount rate | % |
| $s$ | Inflation rate | % |
| $Ca_t = Ca_0 \cdot (1+s)^t$ | Market rent at year t | €/bed |
| $K_t = K_0 \cdot (1+s)^t$ | Owner's costs at year t | €/bed |
| $n$ | DCFA analysis period | Years |
| $r$ | Going out cap rate | % |
| $CAPEX$ | Capital Expenditure | €/bed |
| $V$ | Unit market value | €/bed |
| $V_{max}$ | Maximum unit market value for the property type considered | €/bed |
| $i_{min}$ | Minimum discount rate for the property type considered | % |
| $i_{max}$ | Maximum discount rate for the property type considered | % |

## 5 Conclusions

This study developed and tested a rational method for the valuation of special properties, conceived as a support tool for checking appraisals carried out through the most widely used procedure, namely DCFA. The method was designed to address the excessive and frequent subjectivity that often affects the estimation of the main parameters involved in valuation, including revenues, costs, discount rates, capitalization rates, analysis periods, market trends, and inflation trends. By applying goal programming techniques to a sample of appraisal case studies concerning RSAs located in Italy, the research made it possible to define a simple and transparent valuation approach aimed at rationalizing the determination of these variables and at providing an objective, easily replicable methodology that can be employed by the different actors involved in the valuation of this asset class.

The tool developed may provide effective support for both public and private institutions in the rapid verification of appraisals prepared by external valuers. Where the market value estimated by the valuer differs by no more than ±15% from the output generated by the algorithm, the appraisal may be considered reliable. When this threshold is not respected, a more detailed comparison with the valuer becomes necessary in order to understand the reasons underlying the discrepancy. In this sense, the optimization algorithm may accelerate the validation process, particularly in contexts in which

time is a decisive variable for the economic feasibility of an initiative, such as urban regeneration projects, settlement transformations, and real estate leasing operations.

Moreover, recent EU prudential reforms implementing the final Basel III framework—particularly Regulation (EU) 2024/1623 of 31 May 2024, which significantly amended Regulation (EU) No 575/2013 on prudential requirements for credit institutions—have reinforced the need to anchor the relationship between mortgage lending and real estate collateral to prudent and sustainable valuation criteria over the life of the loan. Within this perspective, the logic underlying the proposed algorithm is consistent with the need to define a reliable valuation boundary, derived from validated appraisals used as benchmarks, within which the credibility of an appraisal may be tested. Owing to its operational-research structure, the model generates a control output that may support the assessment of the reasonableness and sustainability of the estimated value.

Possible developments of the research concern, first, the application of the algorithm to a broader case-study sample, so as to improve its statistical robustness, and second, its experimentation on different property uses, in order to identify possible critical issues and further applications. The main limitation of the current model lies in the size of the database, which includes 25 case studies. Although the algorithm determines endogenously the main variables influencing the estimate—namely market rent, discount rate, and market value—it still requires exogenous inputs derived from the observed sample, such as the maximum market value used in the objective function and the minimum and maximum discount rates.

In addition, given its intended purpose as a rapid and operational tool for appraisal checking, the algorithm was developed without taking into account possible goodwill or badwill effects associated with differences between in-place rents and market rents. Nevertheless, the aim of the study was to define a methodology that can be easily implemented and progressively refined according to the context considered. From this perspective, the reliability of the model is also reflected in its ability to identify valuation outliers, thereby highlighting the need for further discussion with the valuer whenever significant discrepancies emerge between the estimated value and the model output.

Finally, in order to integrate valuation issues with broader concerns related to urban sustainability, the algorithm could be further expanded through the inclusion of constraints and parameters capable of accounting for ESG criteria, which are becoming increasingly relevant in real estate appraisal practice.

## References

1. Guidelines on management of non-performing and forborne exposures | European Banking Authority. https://www.eba.europa.eu/activities/single-rulebook/regulatory-activities/credit-risk/guidelines-management-non-performing. Accessed 14 Mar 2026
2. McIntosh, A.P., Sykes, S.G.: A Guide to Institutional Property Investment. Springer, Cham (1985). https://doi.org/10.1007/978-1-349-07154-8
3. Gabrielli, L., French, N.: Pricing to market: property valuation methods–a practical review. J. Prop. Invest. Finance **39**, 464–480 (2021)
4. Manganelli, B., Tajani, F., Morano, P.: La valutazione del rischio nell'analisi finanziaria di Ellwood per la stima indiretta di immobili urbani. Aestimum **55**(2), 19–41 (2009)

5. Tajani, F., Morano, P., Salvo, F., De Ruggiero, M.: Property valuation: the market approach optimised by a weighted appraisal model. J. Prop. Invest. Finance **38**, 399–418 (2020)
6. Manganelli, B.: Real Estate Investing. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-06397-3
7. Tajani, F., Morano, P., Locurcio, M., Amoruso, P.: A logical operating model for the assessment of the forced sale value in the judicial procedures. Valori e Valutazioni (2021)
8. Gilbertson, B., Preston, D.: A vision for valuation. J. Prop. Invest. Finance **23**, 123–140 (2005)
9. French, N.: Professional standards: RICS valuer registration scheme. J. Prop. Invest. Finance **29**, 582–587 (2011)
10. Harvey, J., Harvey, J.: The economics of planning controls. Urban Land Econ., 147–165 (1996)
11. Antipov, E.A., Pokryshevskaya, E.B.: Mass appraisal of residential apartments: an application of random forest for valuation and a CART-based approach for model diagnostics. Expert Syst. Appl. **39**, 1772–1778 (2012)
12. Morano, P., Tajani, F., Locurcio, M.: GIS application and econometric analysis for the verification of the financial feasibility of roof-top wind turbines in the city of Bari (Italy). Renew. Sustain. Energy Rev. **70**, 999–1010 (2017)
13. Mansfield, J.R., Lorenz, D.P.: Shaping the future: the impacts of evolving international accounting standards on valuation practice in the UK and Germany. Prop. Manag. **22**, 289–303 (2004)
14. Jansen van Vuuren, D.: Modified sales comparison method: valuing under (un) certainty. J. Prop. Invest. Finance **35**, 101–110 (2017)
15. Tajani, F., Morano, P.: An empirical-deductive model for the assessment of the mortgage lending value of properties as securities for credit exposures. J. Eur. Real Estate Res. **11**, 44–70 (2018)
16. Colwell, P.F., Cannaday, R.E., Wu, C.: The analytical foundations of adjustment grid methods. Real Estate Econ. **11**, 11–29 (1983)
17. Vandell, K.D.: Optimal comparable selection and weighting in real property valuation. Real Estate Econ. **19**, 213–239 (1991)
18. Byrne, P., Lee, S.: Different risk measures: different portfolio compositions? J. Prop. Invest. Finance **22**, 501–511 (2004)
19. Foo Sing, T., Patel, K.: Empirical evaluation of the value of waiting to invest. J. Prop. Invest. Finance **19**, 535–553 (2001)

# From Literature Evidence to Method Selection: A Two-Layer MCDA Framework for Project Alternative Evaluation in Public Procurement

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**Abstract.** Multi-criteria decision-aiding (MCDA) methods are increasingly used in public procurement to compare project alternatives when evaluation depends on technical, environmental, social, and economic criteria. Yet method selection is often treated as a purely analytical matter, whereas in regulated procurement it is also constrained by requirements of transparency, ex ante definability, auditability, and effective competition. Building on prior review evidence on MCDA applications in public procurement, this paper proposes a two-layer framework for method selection. The first layer assesses normative compatibility, filtering out methods whose inferential structure is difficult to predefine, explain, or verify within award procedures. The second layer assesses methodological adequacy in relation to the decision problem, considering weighting needs, compensatory logic, uncertainty, criteria interdependence, and robustness of the final ranking. The framework is then translated into an operational selection matrix linking recurrent procurement settings to coherent method families and modular configurations. The contribution is both conceptual and practical: it shows that MCDA method choice in public procurement is not method-neutral, but a design decision at the intersection of decision theory, procurement regulation, and evaluation practice.

**Keywords:** public procurement · MCDA · method selection · normative compatibility · decision framework · project alternative evaluation

## 1 Introduction

Public procurement increasingly relies on evaluation settings in which economic, technical, environmental, and social criteria must be assessed jointly. This is especially evident when project alternatives are selected under the logic of the *best quality/price ratio*, where

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the decision problem cannot be reduced to a single monetary metric. In such contexts, MCDA methods offer a structured way to support bid comparison, weight elicitation, and final ranking. Yet the growing diffusion of MCDA in procurement has not resolved a crucial issue: the choice of the method itself is often treated as implicit, conventional, or merely technical, rather than as a design decision that directly affects the transparency, traceability, and defensibility of the award procedure. More broadly, recent MCDA literature has moved away from the idea of a universally superior technique and has increasingly emphasized the context-dependence of method selection, especially with respect to the nature of the decision problem, the structure of the available information, and the type of output required [1–3].

The need for a more explicit rationale in method selection emerges clearly from the recent review by Anelli et al. [1], which analyzed 74 peer-reviewed studies published between 1998 and 2023 on the use of MCDA in public procurement in construction and infrastructure. That review showed, on the one hand, the persistent centrality of AHP and, on the other, the gradual emergence of techniques such as BWM, EDAS, MABAC, DEA, and more advanced hybrid configurations. At the same time, it highlighted three recurring weaknesses: the absence of a systematic reading of procurement dynamics by stages, the limited reporting of robustness checks and sensitivity analysis, and the still incomplete operationalization of environmental and social criteria. The same review also made explicit that method choice in procurement depends on properties required by practice, such as consistency of weights, transparency, computational burden, and stakeholder acceptance. These results suggest that the real gap in the literature is no longer the mere documentation of MCDA applications, but the lack of a structured device for selecting methods in relation to the characteristics of the procurement setting.

This gap becomes even more relevant when the regulatory context is taken seriously. In EU procurement law, award criteria must be linked to the subject matter of the contract, must allow effective competition, and—except where price or cost alone is used—must be accompanied by their relative weighting; more generally, the design of the procedure must make the evaluation architecture sufficiently clear and verifiable [4]. Within the Italian context, both the current public contracts framework and ANAC guidance reinforce the importance of transparency, ex ante definition of criteria and weights, and intelligibility of the scoring rules [5, 6]. For this reason, in regulated procurement settings, method selection cannot be based exclusively on analytical elegance or computational sophistication. It must also be aligned with procedural requirements such as explainability, pre-definability, auditability, and control of administrative discretion.

Starting from these premises, this paper aims to develop a normatively informed framework for MCDA method selection in public procurement, with specific reference to the evaluation of project alternatives. Its objective is specific: to transform the evidence already consolidated in the literature into a two-layer selection framework. The first layer concerns normative compatibility and operates as a preliminary filter, identifying the set of methods that are coherent with the procedural requirements of regulated procurement. The second layer concerns methodological adequacy and selects, within that feasible set, the methods—or methodological configurations—most appropriate to the actual structure of the decision problem, considering weighting needs, compensation logic, uncertainty, interdependence of criteria, and robustness of the final ranking.

Accordingly, the paper addresses the following research question: how can MCDA method selection in public procurement be structured so that it is both normatively defensible and methodologically coherent? The underlying argument is that, in public procurement, what must be designed is rarely a single isolated technique; rather, it is a methodological configuration capable of combining weighting, ranking, screening, and robustness checks in a context-sensitive and procedurally auditable way.

The reminder of the paper is: Sect. 2 explains the methodological framework evidences given by the literature review; Sect. 3 describes the two-layer structure of the framework; in Sect. 4 discussion and conclusions of the proposed methodological framework are reported.

## 2 From Review Evidence to Method Selection Properties

This contribution takes as its starting point the empirical basis built in the review published by Anelli et al. 2025 [1] which examined 74 studies that appeared between 1998 and 2023 on the use of MCDAs in public procurement, with particular reference to the public works sector and the logic of the *Most Economically Advantageous Tender* (MEAT). This review shows the centrality of AHP, the growth of emerging techniques such as BWM, EDAS, MABAC, DEA and advanced TOPSIS, the lack of standardization in the operationalization of environmental and social criteria, and the limited diffusion of sensitivity analysis and structured procedures for aggregating judgments. The same work, moreover, explicitly identifies among its objectives the analysis of the main advantages and limitations of the techniques used and proposes an operational framework oriented to link the choice of criteria, method selection, robustness checks and minimum reporting. These elements make it possible to process the results obtained, aimed at identifying the properties that guide their selection in the competition contexts.

In public procurement, the choice of method is intertwined with the needs of transparency, traceability, comparability of offers, controllability of discretion and organizational sustainability of the procedure. In this framework, MCDA techniques are no longer viewed as equivalent tools. Instead, they are regarded as differentiated evaluation devices, each characterised by a specific combination of properties. These properties include the degree of explainability of the inferential process, the compensatory structure of aggregation, the ability to process uncertain or mixed data, the aptitude to represent hierarchical or interdependent relationships, and the computational load required for administration. From this derives a methodologically important conclusion: the appropriateness of a technique also depends on its degree of incorporation into the administrative structure.

After careful consideration, the evidence from the review clearly shows that there are five key properties that are vital for selecting the most appropriate method. These include transparency and the ability to easily rebuild the procedure; a compensatory structure for aggregation; the ability to effectively handle uncertainty and mixed data; the ability to address hierarchical or interdependent problems; and the operational sustainability of the implementation. This recording is the foundation of the framework proposed in the following sections. Once the salient methodological properties have been isolated, it is possible to assess their consistency with the regulatory constraints of public procurement. On this basis, a more rigorous and more defensible criterion for choosing methods can be built.

# 3 Methodological Framework

## 3.1 The First Layer of the Framework: Regulatory Compatibility as an Eligibility Filter

The first layer of the framework concerns the regulatory compatibility of the MCDA method in the regulated context of public procurement. Its function is to act as an admissibility filter: before selecting the most appropriate technique with respect to the structure of the decision-making problem, it is necessary to circumscribe the set of methods that can be incorporated into an award procedure built according to the requirements of transparency, predetermination, verifiability and protection of competition. In this perspective, normative compatibility enters into the selection of the method as a set of constraints that define the space of viable methodological solutions. Table 1 shows the regulatory framework regarding the use of MCDAs in national Public Procurement.

On a conceptual level, public procurement law does not identify a specific evaluation algorithm; instead, it defines the conditions within which a decision support technique can be used in a legitimate and defensible way. In the European framework, the award criteria must be linked to the subject matter of the contract, must allow for an effective competitive comparison and must be accompanied by specifications such as to make the information provided by the tenderers verifiable. Where price is not the only criterion, the relative weighting of the criteria must also be made explicit in the procurement documents. Translated into methodological terms, these requirements imply that the evaluation model must possess an inferential logic that can be understood and formalized ex ante and reconstructed ex post.

In the Italian context, this approach is further clarified by Legislative Decree no. 36/2023, which places the contractual action within the principle of the result, to be pursued according to legality, transparency and competition, and attributes to transparency a function closely linked to the full verifiability of the procedure. Art. 108 also confirms the centrality of the most economically advantageous offer and, in labour-intensive contracts, limits the weight of the economic component, so as to preserve the substantial importance of technical quality. ANAC's interpretative indications also insist on the need for criteria, formulas and rules for awarding scores to be consistent with the subject matter of the contract, justifiable, intelligible and free of discriminatory effects. In terms of method selection, this means that a technique is normatively compatible when it can be included in a predetermined, controllable and rationally contestable decision-making structure.

Hence a significant methodological consequence: in public procurement, MCDAs participate directly in the construction of the evaluation rule. The choice of technique affects the form of the comparison between offers, the treatment of the compensations between criteria, the degree of traceability of the judgment and the defensibility of the final outcome. A method based on transformations that are difficult to read, on parameters that are difficult to predetermine or on poorly verifiable passages produces critical issues already at the level of its procedural incorporation. A method characterized by explicit steps, formalizable aggregation criteria and replicable results, on the other hand, presents greater consistency with the institutional structure of the award. The first layer of the

**Table 1.** Summary of regulatory framework of MCDA into Public Procurement

| No. | Government | Reference to law/standards and/or dispositions and regulations |
|---|---|---|
| 1 | United States of America | Competition in Contracting Act of 1984, Federal Acquisition Reform Act of 1984 |
| 2 | Australia | Commonwealth Procurement Rules (CPRs) commenced on 1 July 2022 (division 1-Section 4) |
| 3 | Italy | New Code of Contracts Legislative Decree no. 36/2023 + ANAC Guidelines no. 2+ Guidelines of the Ministry for Infrastructure and Sustainable Mobility for the drafting of the technical and economic feasibility project to be used as the basis for the awarding of public works contracts under the PNRR |
| 4 | Spain | Real Decreto Legislativo 3/2011, de 14 de Noviembre |
| 5 | France | Ordonnance n.2015-899 du 23 Juillet 2015 |
| 6 | Belgium | Loi sur les marchés publics du 17 juin 2016 art. 81 |
| 7 | United Kingdom | Public Contracts Regulations 2015 in England and Wales Public Contracts Regulations 2015 in Scotland, as well as the Utilities Contracts Regulation 2016 in England and Wales (the "UCR 2016" together with the PCR 2015, the "UK Regulations") and the Utilities Contracts Regulations 2016 in Scotland |
| 8 | Czech Republic | Zákon č. 134/2016 o veřejných zakázkách (§ 116) |
| 9 | Canada | Government Contract Regulations (Introduction section) |
| 10 | Germany | Gesetz gegen Wettbewerbsbeschränkungen + Verordnung über die Vergabe öffentlicher Aufträge + Vergabeverordnung für öffentliche Bauleistungen, Abschnitt 2 |
| 11 | Chile | Law of Bases of Administrative Contracts for supply and services, No. 19.886 (the Chilean Public Procurement Law, "PPL") and its regulation (Supreme Decree No. 250 of 2004, the Ministry of Finance; "PPL Regulation") |

framework is therefore used to identify the set of methods that meet this preliminary threshold of admissibility.

Operationally, the regulatory compatibility filter is divided into five requirements. The first is the transparency and explicability of the procedure, i.e. the possibility of making intelligible the way in which criteria, weights, parameters and rules of aggregation lead to the final result. The second is the predeterminability of the evaluation rules, which requires the ex ante definition of the essential elements of the model in the tender documents. The third is the verifiability and auditability of the outcome, understood as the possibility of reconstructing the decision-making process and replicating the result starting from the same inputs. The fourth is the controllability of administrative discretion, which admits the use of expert judgment within a methodological

structure capable of making its assumptions, limits and consequences visible. The fifth is the ability to sustain an effective competitive comparison, i.e. the ability of the method to produce a meaningful comparison between offers without opaquely altering the relationship between quality and price or absorbing insufficient performance through poorly manageable compensations.

The first layer does not yet select the most appropriate method in an analytical sense. It delimits the set of methods that can be used in a manner consistent with the procedural rationality of procurement. Only within this set does it become possible to activate the second layer of the framework, dedicated to methodological adequacy with respect to the structure of the decision problem, the type of data available and the form of the result required by the procedure.

### 3.2 The Second Layer of the Framework: Methodological Adequacy

Once the set of methods compatible with the constraints of public procurement has been delimited, through the first layer, the selection requires a second step, dedicated to methodological adequacy. In this phase, the guiding criterion is the consistency between the structure of the decision problem and the logic of operation of the method. The recent literature on MCDA clearly shows that the choice of technique depends on the nature of the decision, the form of information available, the type of aggregation required and the configuration of the expected output. In the context of public procurement, this verification is of particular importance, since the evaluation is rarely limited to a simple final ranking and is more often divided into a sequence of distinct functions: structuring of criteria, determination of weights, processing of qualitative and quantitative data, possible screening of tenders and final summary [7].

The review referred to [1] provides, from this point of view, a methodologically important indication. The widespread presence of hybrid configurations signals that adequacy should not be attributed to the method in the abstract, but to its placement within the evaluation pipeline. A technique may be particularly suitable in the weighing phase and less effective in the ranking phase, or show the inverse relationship. Consequently, the second layer does not aim to identify a universally preferable technique, but to verify which method, or which combination of methods, is most consistent with the decision-making function to be performed in each segment of the procedure.

The first dimension of analysis concerns the prevailing evaluative function. In some contexts, the main problem consists in the construction and legitimization of weights; in others, the criticality is concentrated in the final ranking; in still others, the procedure requires a clear separation between the weighing phase and the ranking phase. This distinction is crucial, as different techniques respond to different needs: some methods offer a more structured representation of preferences, others provide greater speed and readability in the final synthesis, and still others are more effective when the problem requires modular configurations. Methodological adequacy therefore depends, first of all, on the correspondence between the function assigned to the method and the role it is called upon to play in the overall design of the evaluation [8, 9].

A second dimension concerns the compensatory structure of aggregation. Each method incorporates a particular logic of compensation between criteria, and this logic must be consistent with the substantive meaning of the decision. In contexts where the

administration accepts a strong synthesis between heterogeneous services, methods with a predominantly additive or proximity character are appropriate. In cases where some deficiencies should not be fully absorbed by high performance on other criteria, partially compensatory approaches, configurations with thresholds or outranking methods acquire greater methodological consistency. In this perspective, the second layer tests whether the selected technique adequately reflects the level of compensation that the decision problem allows or requires.

A third dimension concerns the nature of the data and the treatment of uncertainty. In procurement problems, especially when environmental, social or qualitative criteria come into play, the information base may be heterogeneous, incomplete, linguistic or poorly standardised. Under these conditions, the use of fuzzy extensions or hybrid configurations finds a solid methodological justification when it allows the epistemic structure of the problem to be represented more faithfully. The greater representative capacity, however, must be accompanied by a corresponding increase in methodological clarity, documentation of assumptions and robustness checks. The second layer therefore requires verifying whether the complexity of the method is proportionate to the quality and form of the information actually available [10].

A fourth dimension concerns the relational morphology of the problem, i.e. the degree of independence or interdependence between criteria and sub-criteria. When the problem can be represented in hierarchical form, methods based on linear structures are usually sufficient. When, on the other hand, the criteria interact in a relevant way, influence each other or produce feedback effects, models capable of representing these interactions explicitly become more appropriate. The choice of method, in this case, depends on the ability to grasp the real architecture of the problem without introducing levels of complexity disproportionate to the information benefit obtained. Also from this point of view, methodological adequacy is measured in terms of congruence between the properties of the problem and the inferential structure of the method [11].

The fifth dimension concerns the robustness of the ranking and the operational sustainability of the implementation. In public procurement, the quality of the final ranking also depends on its stability to plausible variations in weights, parameters, thresholds and basic assumptions. For this reason, robustness does not constitute an ancillary control, but a component of the judgment of methodological adequacy. Linked to this is the operational sustainability of the method: availability of calculation tools, replicability of operations, ease of audit, documentary burden and cognitive cost required of the commission. A method that is theoretically consistent with the structure of the problem may be inadequate when it requires a level of implementation that is not compatible with the organizational resources of the procedure [12]. The second layer therefore also incorporates a feasibility test, understood as the ability of the method to produce a robust result within realistic conditions of administrative use.

In the light of these considerations, the second layer of the framework can be formalized as a verification of congruence between five profiles of the decision-making problem: evaluative function, compensatory logic, data form, relational structure of criteria and expected operational robustness. In summary terms, the selection of the method can be guided by five ordering questions: the problem mainly requires a weighing phase, a ranking phase or a combination thereof; the compensation between criteria is either

fully acceptable or must be contained; the data are either stable and numerical or heterogeneous, uncertain and linguistic; the criteria are substantially independent or interact in a material way; Does the result remain stable under plausible changes in the basic assumptions? The joint answer to these questions allows to select, within the subset defined by the first layer, the methods or methodological configurations that are actually consistent with the cognitive, informational and operational structure of the problem.

In this perspective, the second layer completes the first and develops its logic on a properly methodological level. The first layer defines the set of methods admissible in the regulated context of the tender; the second identifies, within this set, those most congruent with the way in which the decision-making problem is constructed, with the type of information available and with the form of the result that the procedure requires. The point of arrival does not necessarily coincide with the selection of an isolated technique. In many cases, the most methodologically coherent solution takes the form of a modular configuration, in which different methods oversee different functions of the evaluation process. Table 2 shows the main MCDA techniques found in the field of Public Procurement and the relative pros and cons highlighted by the authors.

Rather than treating each technique as an isolated option, the literature suggests recurring methodological families characterized by distinct strengths and limitations in terms of transparency, compensation logic, uncertainty handling, and operational implementability.

**Table 2.** Strengths and limitations of MCDA families

| MCDA family | Representative techniques | Main strengths | Main limitations |
|---|---|---|---|
| Additive value/score-based methods | SAW, MAVT, MAUT, UF, SCORE | Simple structure; transparent aggregation; easy implementation and communication; suitable for combining multiple criteria into a synthetic score [8, 9] | Strong compensatory logic; sensitivity to weighting assumptions; possible difficulty in eliciting utilities or trade-offs; limited ability to represent uncertainty unless extended [13] |
| Pairwise comparison and weighting methods | AHP, FAHP, ANP, BWM, MACBETH, DEMATEL | Effective for structuring criteria and eliciting preferences; useful in group decision-making; consistency support in some methods; suitable for deriving weights and modelling interdependencies [10] | Dependence on expert judgement; cognitive burden when comparisons increase; possible inconsistency or rank reversal; higher complexity in network-based models [13, 14] |

(*continued*)

**Table 2.** (*continued*)

| MCDA family | Representative techniques | Main strengths | Main limitations |
|---|---|---|---|
| Distance- and utility-based ranking methods | TOPSIS, FTOPSIS, COPRAS, COPRAS-G, MABAC | Intuitive ranking logic; ability to handle benefit and cost criteria jointly; suitable for comparing alternatives across multiple attributes; some variants manage uncertainty better [15–18] | Results depend heavily on weighting and normalization choices; limited consistency control in weight elicitation; some variants require higher computational effort [12–15] |
| Outranking methods | PROMETHEE, F-PROMETHEE II, ELECTRE | Reduced full compensation among criteria; explicit use of preference/indifference thresholds; good stability of rankings; suitable when unacceptable performances should not be offset entirely [14–17] | Greater methodological complexity; more demanding parameter setting; lower immediacy for non-expert users; some methods do not provide easily interpretable final scores [11–13] |
| Efficiency-based methods | DEA, DEA-BoD | Relative efficiency assessment based on observed performance; benchmarking capability; reduced need for predefined utility functions; useful for comparing suppliers/entities on multiple criteria [10–13] | Sensitive to sample size and model specification; requires technical expertise; weaker suitability when a direct final award ranking is needed; interpretation may be less intuitive for procurement practice [14–17] |
| AI-based and learning methods | ANN, FNN | Adaptive capability; useful for pattern recognition and prediction; suitable when historical data are available; potential integration with other decision-support tools [16–19] | Limited transparency and explainability; higher modelling and validation requirements; weaker procedural intelligibility in regulated evaluation settings [15] |

(*continued*)

**Table 2.** (*continued*)

| MCDA family | Representative techniques | Main strengths | Main limitations |
|---|---|---|---|
| Robustness-oriented methods | SMAA | Suitable under uncertain, imprecise, or incomplete preference information; supports identification of robust alternatives [12–14] | Less immediate for practitioners; requires probabilistic or simulation-based interpretation; usually complementary rather than standalone [14–17] |
| Process-oriented decision support approaches | CBA, PANTURA | Supports collaborative and structured comparison; useful for highlighting advantages and improving process clarity [10–17] | Less standardised than mainstream MCDA methods; limited generalisability; more suitable as a complementary procedural support tool [16–19] |

### 3.3 Operationalization of the Framework: From Selection Logic to Decision Matrix

The two layers of the framework acquire applicative utility when they are translated into a selection matrix capable of linking the properties of the decision problem to the most coherent methodological families. The proposed operationalization has precisely this function: to transform a conceptual framework into a tool to support the design of the evaluation, while maintaining the procedural constraints of public procurement and the properly analytical needs of the decision. In this perspective, the choice of the method takes the form of an orderly selection procedure, in which regulatory compatibility defines the set of admissible methods and methodological adequacy makes it possible to identify, within this set, the configuration most congruent with the specific context [20, 21].

The matrix is the connecting device between the two layers. The first layer definitively introduces selection properties that clearly derive from the regulated structure of the tender. These properties include transparency and explicability of the procedure, predeterminability of criteria, weights and rules of aggregation, verifiability of the outcome, controllability of discretion and ability to sustain an effective competitive comparison. The second layer reorganises the choice based on the methodological properties of the problem. This includes the prevailing evaluation function, the admissible degree of compensation, the form and quality of the data, the possible interdependence between criteria and the expected robustness of the final ranking. The matrix combines these two families of properties and allows the selection of the method to be read as a problem of congruence between procedural requirements and the cognitive structure of the decision.

On the operational level, the framework can be used as a sequence of ordering questions. First, the administration or technical decision-maker identifies which methods are compatible with the required level of ex ante formalisation, intelligibility of the procedure and auditability of the outcome. Secondly, among the methods that exceed this preliminary threshold, consistency with the function that the method must perform in the evaluation pipeline is verified: determination of weights, final ranking, preliminary screening, treatment of uncertain data or robustness verification. Thirdly, the framework orients the choice towards a single technique or towards a modular configuration, when the different phases of the procedure require methodological properties not concentrated in a single method. The underlying logic is therefore sequential and compositional: admissibility filter, congruence check, composition of the evaluation solution.

The matrix shows that the most streamlined and institutionally standardised procedures tend to favour methods characterised by high traceability and easy formalisation. When it comes to the construction of weights, methods that can structure expert judgment with a controlled cognitive load are undeniably more consistent. When the procedure requires a clear separation between weighting and ranking, hybrid configurations are undoubtedly the best option, combining a structured technique for defining weights with a rapid and verifiable method for the final ranking. In contexts where some minimum performance doesn't need to be fully compensated by good results on other criteria, the matrix shows that partially compensatory or outranking approaches are effective. In the pre-qualification or comparative benchmarking phases, methods oriented towards efficiency analysis clearly acquire greater consistency. When linguistic data is incomplete or poorly standardised, the framework allows the use of fuzzy extensions or hybrid configurations. But there are strict rules about how to do this. The additional complexity must be documentable and compatible with the requirements of intelligibility of the procedure. The matrix justifies the use of methods capable of representing the structural relationships of mutual influence.

Overall, the framework can be expressed through five selection rules.

Rule no. 1 - If the priority is the legitimacy of weighing, with a strong need to make explicit the structure of the criteria, comparative judgments and consistency checks, AHP or BWM are preferable. The former maintains an advantage in terms of institutional familiarity and traceability; the second reduces the number of comparisons and cognitive load, being useful in procedures with compressed times or with many criteria [22].

Rule no. 2 - If the final ranking requires speed, simplicity and easily auditable formulas, it is appropriate to combine the weighing phase with a compensatory but traceable ranking method, such as EDAS, MABAC or TOPSIS. This hybrid configuration allows you to separate the construction of preferences from the final synthesis, maintaining readability of the process and containment of the operating cost.

Rule no. 3 - If the procedure requires minimum thresholds, technical filters or explicit compensation control, outranking methods, in particular PROMETHEE or ELECTRE, become more appropriate. These techniques are consistent when some deficiencies do not need to be fully neutralized by high performance on other criteria.

Rule no. 4 - If the problem is located upstream of the award, as in cases of preliminary screening, benchmarking or comparative efficiency analysis between operators, the use

of DEA, possibly combined with AHP or BWM in the subsequent phases, may be appropriate [23].

Rule no. 5 - If the information framework is highly uncertain, linguistic or poorly standardised, the use of fuzzy extensions or hybrid configurations may be justified, provided that it is accompanied by a proportional increase in methodological documentation. The weak standardization of environmental and social criteria and the limited use of sensitivity analysis constitute one of the main points of fragility of MCDA applications in procurement. In such contexts, the increase in the representative capacity of the model must be balanced by more stringent requirements for explainability and robustness [24].

In this perspective, the operational contribution of the framework consists in shifting the focus from the repertoire of available methods to the logic with which they are selected and combined. The matrix allows this logic to be explained in a concise and usable form, and prepares the ground for the illustrative application presented in the following paragraph.

Table 3 operationalizes the proposed framework by integrating the two selection layers into a single decision matrix. Each row links a recurrent selection profile to its procedural relevance in regulated procurement, the corresponding methodological implication, and the MCDA families that appear most coherent in operational terms. In this way, method selection is treated not as the identification of a universally preferable technique, but as the design of a context-sensitive evaluation architecture.

**Table 3.** Decision matrix of the proposed framework

| Selection profile | Procedural relevance in procurement | Methodological implication | Indicative coherent methods/families | Typical use in evaluation design |
|---|---|---|---|---|
| High transparency and explainability | The evaluation logic must be intelligible, reconstructable, and defensible within the award procedure | Prefer methods with explicit steps, understandable weighting logic, and traceable aggregation rules | AHP, BWM | Weight elicitation in procedures requiring strong institutional readability |
| Ex ante definability of rules and parameters | Criteria, weights, aggregation rules, and key parameters should be specified in advance in tender documents | Prefer methods whose structure can be formalized ex ante; avoid approaches requiring substantial ex post calibration | AHP, BWM, simple additive or distance-based ranking methods | Tender designs where predetermination and auditability are central |

(*continued*)

**Table 3.** (*continued*)

| Selection profile | Procedural relevance in procurement | Methodological implication | Indicative coherent methods/families | Typical use in evaluation design |
|---|---|---|---|---|
| Rapid and auditable final ranking | The final ranking should remain easy to compute, communicate, and verify | Combine structured weighting with transparent ranking methods | AHP/BWM + TOPSIS, EDAS, MABAC | Two-stage evaluation designs separating weighting from final ranking |
| Limited compensation across criteria | Weak performance on key criteria should not be fully offset by strong performance on others | Prefer partially compensatory or outranking logics, especially where thresholds or minimum acceptable performances matter | PROMETHEE, ELECTRE | Procedures with technical thresholds, non-compensable criteria, or controlled trade-offs |
| Preliminary screening or benchmarking | Some stages require comparative efficiency assessment rather than full award ranking | Use efficiency-oriented methods when the decision concerns pre-selection, benchmarking, or comparative performance | DEA | Pre-qualification, shortlist formation, benchmarking across operators or alternatives |
| Uncertain, mixed, or linguistic data | Environmental, social, and qualitative criteria may be weakly standardized, incomplete, or expressed linguistically | Use fuzzy or hybrid extensions only when the higher modelling burden is justified and remains explainable | Fuzzy MCDA, hybrid configurations | Evaluation settings with imprecise or heterogeneous information bases |
| Interdependent criteria structure | Technical, economic, environmental, and organizational criteria may influence one another | Use network-based methods only when interdependence is structurally relevant and cannot be reduced to a hierarchy | ANP | Decision problems with feedback effects and reciprocal influence among criteria |

(*continued*)

**Table 3.** (*continued*)

| Selection profile | Procedural relevance in procurement | Methodological implication | Indicative coherent methods/families | Typical use in evaluation design |
|---|---|---|---|---|
| Robustness-sensitive procedures | Rankings should remain stable under plausible variations of weights, thresholds, or assumptions | Support the ranking with sensitivity analysis, robustness checks, or ensemble validation | Hybrid/ensemble configurations, robustness-oriented combinations | Procedures exposed to contestation or requiring stronger ex post defensibility |
| Need for modular evaluation design | Procurement often includes distinct analytical functions: weighting, ranking, screening, and robustness testing | Prefer methodological configurations rather than a single technique when different stages require different analytical properties | Modular architectures (e.g. AHP/BWM + TOPSIS/EDAS; PROMETHEE for threshold checks; DEA for screening) | Complex evaluation settings requiring differentiated analytical functions |

## 4 Discussion and Conclusions

This paper's contribution definitively clarifies a crucial methodological point: in public procurement, the choice of MCDA technique is integral to the design of the assessment. The method selected influences the form of the comparison between offers, the degree of compensation between criteria, the traceability of the judgment, the robustness of the final ranking and, more generally, the defensibility of the outcome of the procedure. It is crucial to understand that selecting the method is not just an additional technical step. It is a key component of the evaluation design's quality. This approach is in clear continuity with the evidence from the review [1]. This showed the growing diffusion of MCDAs in procurement and the persistence of critical issues. These issues are related to the transparency of methodological choices, the limited use of robustness controls and the incomplete standardisation of environmental and social criteria.

On this basis, the paper proposed a two-layer framework. The first layer operates as a filter of regulatory compatibility and delimits the set of methods that can be incorporated into a procedure that requires predetermination of the rules, intelligibility of the procedure, verifiability of the outcome and control of discretion. The second layer, on the other hand, acts on the level of methodological congruence and allows to select, within the set thus defined, the techniques or configurations of techniques most consistent with the required evaluation function, with the compensatory structure of the problem, with the form of the available data, with the possible interdependence of the criteria and with the expected level of robustness. The most interesting element of the framework therefore lies in having formalized a logic of contextual selection, capable of making explicit steps

that in administrative practice often remain implicit or entrusted to habits that are not fully justified.

A further conceptual result of the work consists in having made clearer the distinction between single method and methodological architecture. The evidence in the literature and the proposed operational matrix converge in showing that, in many tender contexts, the most coherent solution does not coincide with the isolated adoption of a single technique. More often, the quality of the evaluation design depends on the combination of different functions: structured methods for the definition of weights, streamlined and verifiable techniques for the final ranking, possible preliminary screening tools, sensitivity analysis and robustness checks. From this point of view, the framework contributes to shifting the attention from the repertoire of available methods to the design of an evaluation configuration consistent with the decision-making and institutional context.

The work has some limitations. The framework derives from a theoretical-operational reworking of the evidence already consolidated in the literature and, although it has been accompanied by an illustrative application, it has not yet been subjected to extensive validation on real procedures. Furthermore, its formulation is strongly anchored to the context of regulated public procurement, in which the logic of the best quality/price ratio, the ex ante formalization of the evaluation rules and the need to make the procedural outcome controllable and defensible take on particular importance. Finally, the same initial review highlights conditions that may limit the full operation of the framework, in particular the weak standardization of some categories of criteria, especially environmental and social, and the still limited use of structured sensitivity analysis and methodological reporting procedures.

From these limits derive some directions of development. A first line of research concerns the empirical validation of the framework on real cases of selection between design alternatives, so as to verify whether the proposed double filter actually leads to more robust, transparent and better motivated methodological choices. A second line concerns the comparative extension to different institutional and regulatory contexts, useful for understanding the extent to which the regulatory dimension modifies the criteria for selecting techniques. A third line concerns the strengthening of the framework through the systematic integration of robustness checks, sensitivity analysis and minimum reporting protocols, so as to make the use of MCDAs in procurement more controllable, replicable and comparable [25–31].

Overall, the value of the contribution lies in having transformed the evidence in the literature into a more explicit methodological selection device closer to the real needs of public evaluation. The proposed framework does not identify a universally preferable technique. Rather, it offers a conceptual and operational basis for selecting and combining methods in a manner consistent with procedural constraints, with the structure of the decision-making problem and with the quality of the information available. In this sense, the paper argues that, in public procurement, the choice of the MCDA technique should be treated as an evaluative design decision in its own right, and not as a secondary element of the award process.

**Note:** The current study has been developed within the current research “Evaluation models for the preservation and the revitalization of the small towns”, Call for Research Projects 2024, Sapienza University of Rome.

## References


1. Anelli, D., Morano, P., Acquafredda, T., Tajani, F.: Structuring multi-criteria decision approaches for public procurement: methods, standards and applications. Systems **13**(9), 777 (2025). https://doi.org/10.3390/systems13090777
2. European Parliament, Council of the European Union: Directive 2014/24/EU of 26 February 2014 on public procurement and repealing Directive 2004/18/EC. Official Journal of the European Union L94, 65–242 (2014)
3. Repubblica Italiana: Decreto legislativo 31 marzo 2023, n. 36. Codice dei contratti pubblici in attuazione dell'articolo 1 della legge 21 giugno 2022, n. 78, recante delega al Governo in materia di contratti pubblici. Gazzetta Ufficiale della Repubblica Italiana, Serie Generale n. 77, Suppl. Ord. n. 12/L (2023)
4. Autorità Nazionale Anticorruzione (ANAC): Linee Guida n. 2, di attuazione del D.lgs. 18 aprile 2016, n. 50, recanti "Offerta economicamente più vantaggiosa". Approvate con Delibera n. 1005 del 21 settembre 2016, aggiornate al D.lgs. 19 aprile 2017, n. 56 (2018)
5. Autorità Nazionale Anticorruzione (ANAC): Parere di precontenzioso n. 219 del 23 aprile 2024. Art. 108 del d.lgs. 36/2023 – Criteri di aggiudicazione dell'offerta – Richiesta parere
6. Greco, S., Słowiński, R., Wallenius, J.: Fifty years of multiple criteria decision analysis: from classical methods to robust ordinal regression. Eur. J. Oper. Res. **323**(2), 351–377 (2025). https://doi.org/10.1016/j.ejor.2024.07.038
7. Alvarez, P.A., Ishizaka, A., Martínez, L.: Multiple-criteria decision-making sorting methods: a survey. Expert Syst. Appl. **183**, 115368 (2021). https://doi.org/10.1016/j.eswa.2021.115368
8. Kizielewicz, B., Tomczyk, T., Gandor, M., Sałabun, W.: Subjective weight determination methods in multi-criteria decision-making: a systematic review. Procedia Comput. Sci. **246**, 5396–5407 (2024). https://doi.org/10.1016/j.procs.2024.09.673
9. Corrente, S., Greco, S., Rezaei, J.: Better decisions with less cognitive load: the parsimonious BWM. Omega **126**, 103075 (2024). https://doi.org/10.1016/j.omega.2024.103075
10. Wu, Q., Liu, X., Zhou, L., Qin, J., Rezaei, J.: An analytical framework for the best–worst method. Omega **123**, 102974 (2024). https://doi.org/10.1016/j.omega.2023.102974
11. Behzadian, M., Kazemzadeh, R.B., Albadvi, A., Aghdasi, M.: PROMETHEE: a comprehensive literature review on methodologies and applications. Eur. J. Oper. Res. **200**(1), 198–215 (2010). https://doi.org/10.1016/j.ejor.2009.01.021
12. Schär, S., Pohl, E., Geldermann, J.: Analysing the compensatory properties of the outranking approach PROMETHEE. J. Multi-Criteria Decis. Anal. **32**(2) (2025). https://doi.org/10.1002/mcda.70013
13. Dulmin, R., Mininno, V.: Supplier selection using a multi-criteria decision aid method. J. Purch. Supply Manag. **9**(4), 177–187 (2003). https://doi.org/10.1016/S1478-4092(03)00032-3
14. Pastor-Ferrando, J.P., Aragonés-Beltrán, P., Hospitaler-Pérez, A., García-Melón, M.: An ANP- and AHP-based approach for weighting criteria in public works bidding. J. Oper. Res. Soc. **61**(6), 905–916 (2010). https://doi.org/10.1057/jors.2010.13
15. Alptekin, O., Alptekin, N.: Analysis of criteria influencing contractor selection using TOPSIS method. IOP Conf. Ser. Mater. Sci. Eng. **245**, 062003 (2017)
16. Del Giudice, V., De Paola, P., Morano, P., Tajani, F., Del Giudice, F.P., Anelli, D.: Depreciation of residential buildings and maintenance strategies in urban multicultural contexts. In: Values, Cities and Migrations: Real Estate Market and Social System in a Multi-cultural City, pp. 217–232. Springer International Publishing, Cham (2022). https://doi.org/10.1007/978-3-031-16926-7_16
17. Bana e Costa, C.A., Correa, E.C., De Corte, J.-M., Vansnic, J.C.: Facilitating bid evaluation in public call for tenders: a sociotechnical approach. Omega **30**, 227–242 (2002)

18. Matic, B., Jovanovic, S., Das, D.K., Zavadskas, E.K., Stević, Ž., Sremac, S., Marinković, M.: A new hybrid MCDM model: Sustainable supplier selection in a construction company. Symmetry **11**, 353 (2019)
19. Karimi, H., Sadeghi-Dastaki, M., Javan, M.: A fully fuzzy best–worst multi attribute decision making method with triangular fuzzy number: a case study of maintenance assessment in the hospitals. Appl. Soft Comput. **86**, 105882 (2020). https://doi.org/10.1016/j.asoc.2019.105882
20. Ma, W., Du, Y., Liu, X., Shen, Y.: Literature review: multi-criteria decision-making method application for sustainable deep-sea mining transport plans. Ecol. Indic. **140**, 109049 (2022). https://doi.org/10.1016/j.ecolind.2022.109049
21. Zaidan, B.B., et al.: An in-depth analysis of ensemble multi-criteria decision making: a comprehensive guide to terminology, design, applications, evaluations, and future prospects. Appl. Soft Comput. **167**, 112267 (2024). https://doi.org/10.1016/j.asoc.2024.112267
22. Gonzalez-Urango, H., Mu, E., Ujwary-Gil, A., Florek-Paszkowska, A.: Analytic network process in economics, finance and management: contingency factors, current trends and further research. Expert Syst. Appl. **237**, 121415 (2024). https://doi.org/10.1016/j.eswa.2023.121415
23. Najafi, A., Mirzaei, S.: RMCDA: the comprehensive R library for applying multi-criteria decision analysis methods. Softw. Impacts **24**, 100762 (2025). https://doi.org/10.1016/j.simpa.2025.100762
24. Morano, P., Tajani, F., Guarnaccia, C., Anelli, D.: An optimization decision support model for sustainable urban regeneration investments. WSEAS Trans. Environ. Dev. **17**, 1245–1251 (2021). https://doi.org/10.37394/232015.2021.17.114
25. Guarini, M.R., D'Addabbo, N., Morano, P., Tajani, F.: Multi-criteria analysis in compound decision processes: the AHP and the architectural competition for the chamber of deputies in Rome (Italy). Buildings **7**(2), 38 (2017)
26. Anelli, D., Morano, P., Tajani, F., Sabatelli, E.: Impacts of urban decay on the residential property market: an application to the City of Rome (Italy). In: Gervasi, O., Murgante, B., Garau, C., Taniar, D., C. Rocha, A.M.A., Faginas Lago, M.N. (eds.) ICCSA 2024. LNCS, vol. 14822, pp. 36–48. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-65318-6_3
27. Anelli, D., Ranieri, R.: Resilience of complex urban systems: a multicriteria methodology for the construction of an assessment index. In: Calabrò, F., Della Spina, L., Piñeira Mantiñán, M.J. (eds.) NMP 2022. LNNS, vol. 482, pp. 690–701. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-06825-6_65
28. Manganelli, B., Anelli, D., Tajani, F., Morano, P.: Capitalization rate and real estate risk factors: an analysis of the relationships for the residential market in the city of Rome (Italy). Real Estate Manag. Valuat. **32**(3), 101–115 (2024). https://doi.org/10.2478/remav-2024-0028
29. Banzato, D., Canesi, R., D'Alpaos, C.: Biogas and biomethane technologies: an AHP model to support the policy maker in incentive design in Italy. In: Bisello, A., Vettorato, D., Laconte, P., Costa, S. (eds.) SSPCR 2017. GET, pp. 319–331. Springer, Cham (2018). https://doi.org/10.1007/978-3-319-75774-2_22
30. Zambujal-Oliveira, J., Mouta-Lopes, M., Bangueses, R.: Real options appraisal of forestry investments under information scarcity in biomass markets. Resour. Policy **74**, 101735 (2021). https://doi.org/10.1016/j.resourpol.2020.101735
31. Tajani, F., De Paola, P., Cerullo, G.: Property valuation: a comparative analysis of innovative market approach methods. Aestimum (2025). https://doi.org/10.36253/aestim-17322

# A Territorial Adaptive Composite Index for Urban Energy Poverty: Local Vulnerability Drivers

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**Abstract.** Energy poverty is increasingly recognised as a multidimensional challenge affecting urban resilience, public health and social equity across European cities. Despite the availability of consolidated national indicators, existing monitoring frameworks often lack the spatial resolution required to support local decision-making and place-based policy design. This paper proposes an aggregated and territorially sensitive urban energy poverty index that integrates six analytical drivers socio-economic, building-related, energy, climatic, urbanistic and institutional within a flexible composite indicator structure. The methodological contribution lies in the integration of high-resolution local data with official European indicators and in the adoption of an entropy-based weighting system, which derives data-driven weights from the variability of indicators across neighbourhoods. The methodology is applied to the Mediterranean city of Catania (Italy), revealing pronounced intra-urban disparities in energy vulnerability, with composite index values ranging from 0,04 in affluent central areas to 0,74 in peripheral public housing districts. The results demonstrate that the proposed approach captures spatial patterns and dominant drivers of energy poverty that remain invisible in aggregated statistics, providing a robust analytical basis for targeted urban energy and social policies.

**Keywords:** Energy poverty · Urban vulnerability · Composite index · Territorial drivers · Mediterranean cities · Entropy weighting

## 1 Introduction

Energy poverty has become a central concern in European energy and social policy, particularly in the context of the energy transition, climate change and rising energy prices [1–3]. Originally framed around insufficient access to adequate heating, energy poverty is now increasingly understood as a broader condition of vulnerability encompassing cooling needs, housing quality, socio-economic deprivation and exposure to

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environmental stressors [4–6]. At the European level, monitoring frameworks based on EU-SILC data, such as consensual and expenditure-based indicators, including the Low-Income High Costs (LIHC) indicator, are widely adopted [7–9]. More recently, the Energy Poverty Advisory Hub (EPAH) has promoted a harmonised set of primary and secondary indicators to support policy development across Member States [10, 11]. While these instruments are effective at national and regional scales, they provide limited support for urban scale decision-making due to their coarse spatial resolution and limited sensitivity to local conditions [12–14]. These limitations are particularly evident in Southern European and Mediterranean cities, where climatic conditions, urban heat island effects and increasing cooling demand significantly affect household energy needs [15–17]. Existing indicators, largely calibrated on winter heating deprivation, tend to underestimate vulnerability in such contexts, neglecting summer thermal stress and microclimatic exposure [18–20]. Recent studies have highlighted that cooling-related energy poverty affects a substantial proportion of Mediterranean households, with significant health implications during increasingly frequent heatwaves [21, 22]. Against this background, this study advances the state of the art by proposing a territorially sensitive composite index specifically designed for urban energy poverty analysis. The methodological contributions are threefold: (i) the integration of high-resolution local data enabling neighbourhood-scale analysis; (ii) the adoption of an entropy-based weighting system that derives data-driven weights from the variability of indicators across neighbourhoods, moving beyond the equal-weight assumption commonly used in composite; and (iii) the explicit incorporation of summer thermal stress, addressing a persistent Mediterranean gap in existing monitoring frameworks. Taken together, these elements transform the index from a descriptive metric into an operational tool for intra-urban energy poverty diagnosis and policy targeting. The framework is applied to the city of Catania as a representative Mediterranean case study, providing empirical evidence of its ability to reveal intra-urban disparities and support place-based policy design. Catania represents an ideal test case due to its combination of significant socio-economic fragility (the lowest median household income among Italian metropolitan cities at € 12,200/year), ageing building stock with poor energy performance (52.1% in classes F-G), extreme summer climatic stress with temperatures reaching 46 °C and over 110 days per year with perceived temperatures above 35 °C. The paper is structured as follows: "Materials", which presents the neighbourhoods of Catania under analysis; "Methods", which presents the methodological approach developed; Results, which highlights the composite index values for the districts of Catania, Librino, Angeli Custodi/San Cristoforo and Corso Italia, for which the vulnerability profiles by driver and spatial distribution are presented and a driver decomposition analysis is proposed; "Discussion", in which some reflections are offered and certain results are compared with reference to intra-urban disparities and the limits of aggregate statistics. The Mediterranean Gap and Policy Implications are also highlighted. "Conclusion": A brief summary of the paper's content is provided.

## 2 Materials

Catania is characterised by marked contrasts in demographic structure, socio-economic conditions, building stock characteristics and urban morphology [23, 24].

Librino is one of the largest public housing districts in Southern Italy, developed from the late 1960s as part of a major urban expansion plan. Its urban form is defined by large-scale residential blocks, extensive road infrastructures and limited green areas. The neighbourhood is widely documented as an area of socio-economic fragility, with high unemployment rates, low educational attainment and a predominantly ageing building stock constructed before the introduction of national energy performance regulations [23]. Angeli Custodi/San Cristoforo, located in the historic centre, is characterised by compact morphology, narrow street networks and a high concentration of pre-1945 buildings. According to ISTAT sub-municipal indicators [23], the area records elevated levels of socio-economic vulnerability, demographic ageing and housing deprivation. Historic-centre districts in Catania have been widely analysed for their structural decay and limited maintenance. Zia Lisa, situated near the airport and major transport infrastructures, presents a heterogeneous urban fabric combining low-rise residential units, informal expansions and more recent constructions. The area is documented as having intermediate socio-economic conditions and limited availability of public services and green spaces [24]. Corso Italia, in contrast, is one of the most affluent coastal areas of Catania. It is characterised by high-quality residential buildings, wide boulevards, commercial activities and access to services. According to ISTAT income and education data, the area ranks among the highest in the municipality in terms of socio-economic indicators [23]. These four areas collectively represent the main socio-spatial configurations documented in Catania's urban literature, historic-centre districts, large-scale public housing estates, mixed peripheral zones and consolidated neighbourhoods, providing a diverse empirical context for the study. Figure 1 illustrates the municipalities of Catania and the districts that compose them.

Istat has produced a list of areas in Catania experiencing high levels of socio-economic hardship. The index is called IDISE (Index of Socio-economic Disadvantage of Individuals and Households at sub-municipal level) and is based on data verified as of 2021. Angeli Custodi has the highest Idise score in the city. The percentage of individuals living in households with no income is particularly high (52.7%), whilst those in low-income households account for 75.8%. The same applies to the low level of education (76.5%), and the number of young people aged 15 to 29 who are neither in employment nor in education and are not engaged in any training activity stands at 66.9%. The next highest percentages were also found in Librino, where the low level of education stands out, and in Zia Lisa regarding socio-economic deprivation.

Figure 2 identifies the Areas of Socio-Economic Deprivation in Urban Areas (ADU).

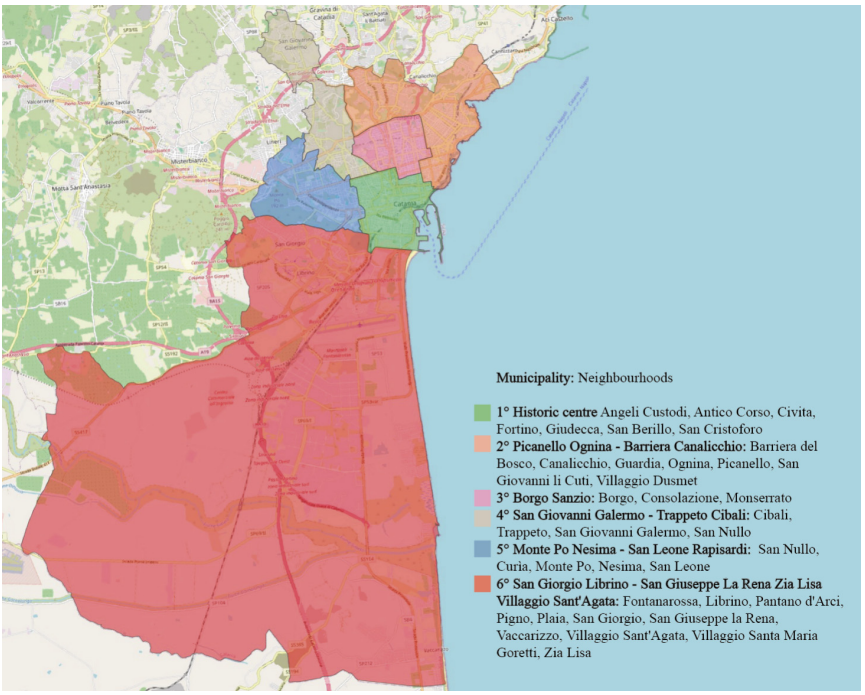


**Fig. 1.** Municipalities of Catania

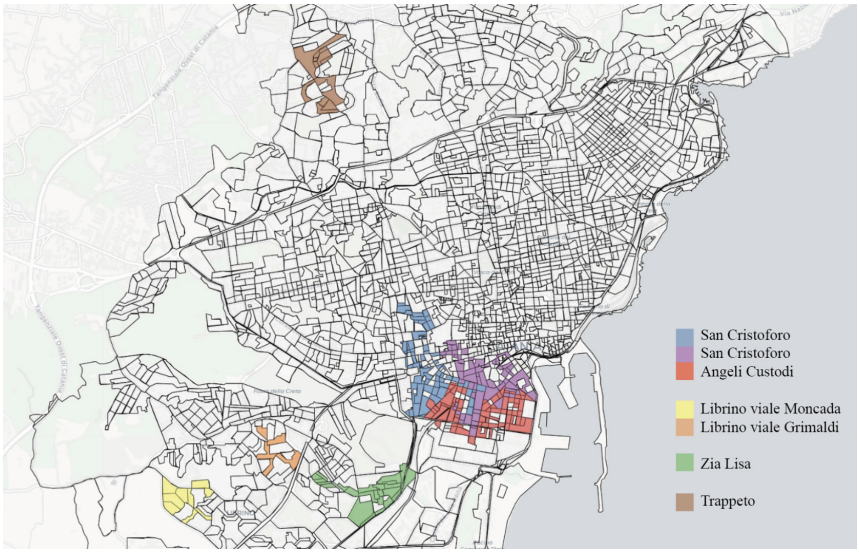


**Fig. 2.** Areas of Socio-Economic Deprivation in Urban Areas (ADU).

## 3 Methodology

The proposed methodological framework follows a structured, multi-phase approach designed to integrate heterogeneous data sources, derive data-driven weights, and ensure internal coherence and transparency in the construction of the composite index. The framework, illustrated in Fig. 3, comprises six sequential phases: (1) data collection from European and local sources; (2) definition of six territorial drivers; (3) normalisation of indicators; (4) driver weights through an entropy-based data-driven procedure; (5) composite index computation; (6) Spatial distribution of local vulnerability to energy poverty in the case studies and local driver decomposition analysis.

To assess the robustness of the index, a sensitivity analysis was performed by testing alternative weighting scenarios. In Scenario B, the weight of the IDISE index score increased by 10%, while the remaining weights were kept unchanged. In Scenario C the weight of the CDD index score was increased by 10%. In Scenario D the weight of the green space score was increased by 10%. The results confirmed the stability of the index and the consistency of neighbourhood rankings across scenarios.

Finally, the classification of vulnerability levels was based on quartile thresholds derived from the empirical distribution of Iuep values, defining four classes of increasing vulnerability: Low, Medium, High, Critical. This data-driven classification ensures a non-arbitrary interpretation of local energy poverty patterns and supports the identification of priority areas for policy intervention (Fig. 4).

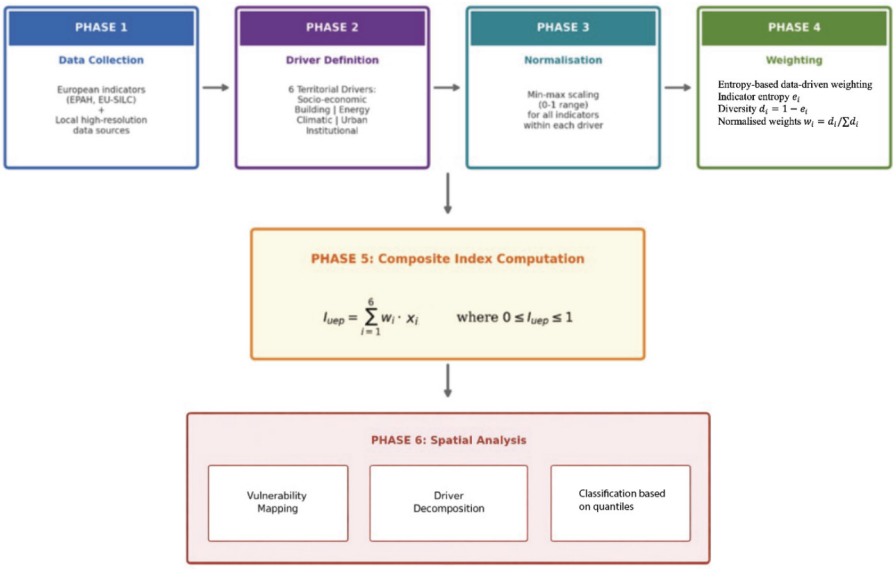


**Fig. 3.** Schematic representation of the six-phase methodological framework integrating European indicators with high-resolution local data through an entropy-based data-driven weighting procedure.

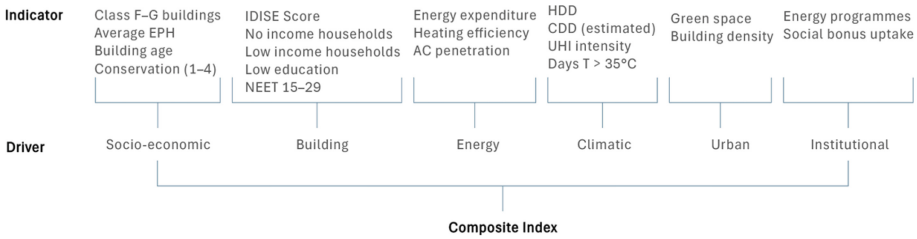


**Fig. 4.** Hierarchical structure for the aggregation of indicators

### 3.1 Data Collection from European and Local Sources

The construction of the composite index relies on a structured data collection process that integrates harmonised European indicators with high-resolution local datasets. This multi-scalar approach ensures both conceptual alignment with EU-level frameworks on energy poverty and an accurate representation of the socio-spatial specificities of Catania's neighbourhoods. At the European level, the study draws on the Energy Poverty Advisory Hub (EPAH) and EU-SILC-based indicators, which provide the foundation for identifying primary and secondary dimensions of energy poverty. These sources offer a framework for interpreting income deprivation, energy expenditure and household vulnerability across Member States, and serve as the reference for structuring the six analytical drivers adopted in this study. While European indicators are not available at intra-urban scale, they provide the methodological baseline against which local data are contextualised. Local data constitutes the core of the dataset and allow for a fine-grained characterisation of the selected districts. ISTAT sub-municipal indicators, including the IDISE index (Index of Socio-economic Disadvantage of Individuals and Households), provide detailed information on income deprivation, educational attainment, unemployment, and the incidence of NEETs aged 15–29. These indicators capture the socio-economic dimension of vulnerability and reveal pronounced disparities between historic-centre districts, peripheral public-housing areas and consolidated neighbourhoods. Building-related information was derived from municipal and regional datasets, including the Regional Energy Cadastre (SIAPE), which provides data on the distribution of energy performance classes (F–G), average energy performance (EPH), building age and conservation status. These variables reflect the structural fragility of the building stock and its limited compliance with contemporary energy-efficiency standards, particularly in pre-1945 historic fabrics and in large public-housing estates constructed before national energy regulations. Climatic exposure was assessed through locally validated indicators, including heating degree days (HDD), estimated cooling degree days (CDD), urban heat island (UHI) intensity and the number of days with temperatures exceeding 35 °C. These variables reflect the climatic pressures that shape energy needs in Mediterranean cities and highlight the relevance of cooling-related vulnerability, which is often underestimated in conventional European monitoring frameworks. Urban and environmental conditions were characterised through municipal datasets describing green-space availability, building density and service accessibility. These indicators capture the morphological and environmental constraints that influence both thermal comfort and exposure to climatic stress. Finally, institutional indicators, including the uptake of national

social energy bonuses and the presence of local energy programmes, were collected from municipal and regional administrative sources. These variables provide insight into the capacity of households to access support mechanisms and into the effectiveness of local policy responses. By integrating European conceptual frameworks with detailed local data, the study constructs a territorially sensitive dataset capable of capturing the multi-dimensional nature of urban energy vulnerability. This integrated approach ensures both methodological coherence with EU-level definitions and the spatial resolution required for intra-urban analysis.

### 3.2 Territorial Drivers

Six analytical drivers are identified, each capturing a specific dimension of urban energy vulnerability: (1) Socio-economic driver: encompassing income levels, unemployment rates, educational attainment and demographic vulnerability indicators derived from ISTAT sub-municipal data (IDISE index); (2) Building-related driver: capturing building age, conservation status, energy performance class (APE), construction materials and building typology from the Regional Energy Cadastre (SIAPE); (3) Energy driver: including estimated energy consumption, heating/cooling system type and efficiency, thermal demand, and energy expenditure share; (4) Climatic driver: measuring exposure to thermal stress through temperature extremes, urban heat island intensity, heating degree days (HDD) and cooling degree days (CDD); (5) Urban driver: accounting for building density, urban green availability, and service accessibility; (6) Institutional driver: assessing local policy effectiveness and presence of energy programmes including Renewable Energy Communities.

### 3.3 Entropy-Based Weighting System

A key methodological innovation is the adoption of a territorial weighting system calibrated to the specific context under analysis. Unlike conventional composite indicators that assume equal weights for all dimensions, the proposed approach recognises that the relative importance of vulnerability drivers varies across territorial contexts [15, 16]. To ensure transparency, replicability and the absence of subjective assumptions in the construction of the composite index, indicator weights were derived through an entropy-based data-driven procedure. Entropy weighting is widely used in composite indicator literature as it assigns higher weights to indicators that exhibit greater variability across territorial units, reflecting their higher informational content.

Let $x_{ij}$ denote the normalised value (0–1) of indicator $i$ in neighbourhood $j$. For each indicator, the proportion $p_{ij}$ is computed as:

$$p_{ij} = \frac{x_{ij}}{\sum_{j=1}^{m} x_{ij}}$$

where $m$ is the number of neighbourhoods. The entropy value of indicator $i$ is then calculated as:

$$e_i = -k \sum_{j=1}^{m} p_{ij} \ln(p_{ij})$$

with $k = \frac{1}{\ln(m)}$ ensuring $0 \leq e_i \leq 1$. Higher entropy values indicate that the indicator is relatively uniform across neighbourhoods and therefore carries limited discriminatory power.

The degree of diversification (or information utility) of each indicator is defined as:

$$d_i = 1 - e_i$$

Indicators with higher variability across neighbourhoods exhibit higher $d_i$ values and thus contribute more to the composite index. Final weights are obtained through normalisation:

$$w_i = \frac{d_i}{\sum_{i=1}^{n} d_i}$$

where $n$ is the total number of indicators. This ensures that all weights are positive and sum to one.

The entropy-based procedure allows the weighting structure to emerge directly from the data, avoiding normative or arbitrary assumptions and ensuring that indicators with greater spatial differentiation exert a proportionally larger influence on the final index.

### 3.4 Composite Index Computation

The indicators within each driver have been normalised using min-max and max-min normalisation, on a scale from 0 to 1. Instead of assigning equal weights to the six drivers, the study adopts an entropy-based weighting procedure to derive objective, data-driven weights. The entropy method quantifies the amount of information carried by each indicator across the four neighbourhoods: indicators showing higher variability contribute more to the composite index, while more uniform indicators receive lower weights. For each indicator, entropy $e_i$, diversity $d_i = 1 - e_i$, and normalised weights $w_i$ were computed. Driver-level weights $W_k$ were then obtained by aggregating the weights of the indicators belonging to each driver. The composite urban energy poverty index ($I_{uep}$) is calculated as a weighted sum of normalised indicators:

$$I_{uep} = \sum_{i=1}^{n} w_i x_i \text{ where } 0 \leq \text{ Iuep } \leq 1 \quad (1)$$

$w_i$ is the entropy-derived weight of each indicator i; $x_i$ = normalised value of indicator i for the given neighbourhood; n = total number of indicators included in the composite index.

The index ranges from 0 (no vulnerability) to 1 (maximum vulnerability).

In addition, four thresholds have been identified for the energy poverty vulnerability index: Critical, High, Medium and Low.

### 3.5 Vulnerability Thresholds

A schematic spatial representation of local vulnerability to energy poverty was produced using the four vulnerability classes derived from the empirical distribution of the composite index values. The classification is based on quartile thresholds (Q1, Q2, Q3), ensuring a fully data-driven and non-arbitrary definition of vulnerability levels.

# 4 Results

This section presents the results of the composite urban energy poverty index as applied to the selected study areas. Index values, driver-level scores and spatial distributions are reported to illustrate the internal variability and multidimensional characteristics of the urban context under analysis.

## 4.1 Territorial Drivers in Four Neighbourhoods of Catania

The variables that characterise the six specific dimensions of energy vulnerability have been identified in the four districts. Table 1 shows the values of all the considered variables. Table 2 shows the normalised values of IDISE score.

**Table 1.** The territorial drivers' indicators in four neighbourhoods of Catania (our elaboration)

| Category | Indicator | Unit | Angeli Custodi | Librino | Zia Lisa | Corso Italia |
|---|---|---|---|---|---|---|
| Socio-economic | IDISE Score | index | 114.2 | 112.2 | 107.5 | 85 |
| Socio-economic | No income households | % | 52.7 | 45 | 35 | 8 |
| Socio-economic | Low income households | % | 75.8 | 70 | 60 | 20 |
| Socio-economic | Low education | % | 76.5 | 79.1 | 65 | 40 |
| Socio-economic | NEET 15-29 | % | 66.9 | 55 | 45 | 15 |
| Building | Class F-G buildings | % | 70 | 75 | 60 | 45 |
| Building | Average EPH | kWh/m$^2$/y | 200 | 220 | 180 | 120 |
| Building | Building age | years | 60 | 50 | 45 | 65 |
| Building | Conservation (1–4) | score | 3.5 | 4 | 2.5 | 1.5 |
| Energy | Energy expenditure | % income | 12 | 14 | 10 | 5 |
| Energy | Heating efficiency | % | 65 | 60 | 70 | 85 |
| Energy | AC penetration | % | 25 | 20 | 35 | 75 |
| Climatic | HDD | degree-days | 833 | 833 | 833 | 833 |
| Climatic | CDD (estimated) | degree-days | 900 | 950 | 920 | 850 |
| Climatic | UHI intensity | °C | 2.5 | 3.5 | 2.5 | 1.5 |
| Climatic | Days T > 35 °C | days/year | 95 | 110 | 100 | 85 |
| Urban | Green space | m$^2$/capita | 2 | 5 | 8 | 15 |

(*continued*)

**Table 1.** (*continued*)

| Category | Indicator | Unit | Angeli Custodi | Librino | Zia Lisa | Corso Italia |
|---|---|---|---|---|---|---|
| Urban | Building density | $m^3/m^2$ | 4.5 | 3.8 | 2.5 | 3.2 |
| Institutional | Energy programmes | count | 1 | 2 | 1 | 3 |
| Institutional | Social bonus uptake | % | 35 | 40 | 30 | 5 |

**Table 2.** The normalised indicators for the territorial drivers in four neighbourhoods of Catania (our elaboration)

| Category | Indicator | Unit | Angeli Custodi | Librino | Zia Lisa | Corso Italia |
|---|---|---|---|---|---|---|
| Socio-economic | IDISE Score | index | 1 | 0.93 | 0.77 | 0 |
| Socio-economic | No income households | % | 1 | 0.83 | 0.6 | 0 |
| Socio-economic | Low income households | % | 1 | 0.9 | 0.72 | 0 |
| Socio-economic | Low education | % | 0.93 | 1 | 0.64 | 0 |
| Socio-economic | NEET 15-29 | % | 1 | 0.77 | 0.58 | 0 |
| Building | Class F-G buildings | % | 0.83 | 1 | 0.5 | 0 |
| Building | Average EPH | $kWh/m^2/y$ | 0.8 | 1 | 0.6 | 0 |
| Building | Building age | years | 0.75 | 0.25 | 0 | 1 |
| Building | Conservation (1–4) | score | 0.8 | 1 | 0.4 | 0 |
| Energy | Energy expenditure | % income | 0.78 | 1 | 0.56 | 0 |
| Energy | Heating efficiency | % | 0.8 | 1 | 0.6 | 0 |
| Energy | AC penetration | % | 0.91 | 1 | 0.73 | 0 |
| Climatic | HDD | degree-days | 0.5 | 0.5 | 0.5 | 0.5 |
| Climatic | CDD (estimated) | degree-days | 0.5 | 1 | 0.7 | 0 |
| Climatic | UHI intensity | °C | 0.5 | 1 | 0.5 | 0 |
| Climatic | Days T > 35 °C | days/year | 0.4 | 1 | 0.6 | 0 |

(*continued*)

**Table 2.** (*continued*)

| Category | Indicator | Unit | Angeli Custodi | Librino | Zia Lisa | Corso Italia |
|---|---|---|---|---|---|---|
| Urban | Green space | $m^2$/capita | 1 | 0.77 | 0.54 | 0 |
| Urban | Building density | $m^3/m^2$ | 1 | 0.65 | 0 | 0.35 |
| Institutional | Energy programmes | count | 1 | 0.5 | 1 | 0 |
| Institutional | Social bonus uptake | % | 0.86 | 1 | 0.71 | 0 |

### 4.2 Composite Index Values

The estimation of the composite energy poverty vulnerability index is based on the weighting system that was identified and described in the "Methods" section.

The application of the framework to four representative urban areas in Catania reveals substantial intra-urban disparities. Table 3 presents the composite index values. Librino exhibits the highest vulnerability ($I_{uep} = 0{,}74$), classified as critical, followed by Angeli Custodi/San Cristoforo ($I_{uep} = 0{,}69$). In contrast, Corso Italia shows low vulnerability ($I_{uep} = 0{,}04$). The difference between the most and least vulnerable neighbourhoods is 0.70 on a 0–1 scale, indicating extremely pronounced intra-urban disparities.

**Table 3.** Composite Index Values (our elaboration)

| | Angeli Custodi | Librino | Zia Lisa | Corso Italia |
|---|---|---|---|---|
| Iuep | 0,69 | 0,74 | 0,48 | 0,04 |

### 4.3 Vulnerability Thresholds

The quartile thresholds derived from the distribution of Iuep values are: Q1 = 0,37, Q2 = 0,59, Q3 = 0,71. These thresholds define four vulnerability classes: Low (0,04–0,37), Medium (0,37–0,59), High (0,59–0,71), Critical (0,71 –0,74).

A schematic spatial representation of local vulnerability to energy poverty was produced using the four vulnerability classes derived from the empirical distribution of the composite index values. Figure 5 presents the composite index values ordered by decreasing vulnerability, classification is based on quartile thresholds, ensuring a fully data-driven and non-arbitrary definition of vulnerability levels. The classification into four vulnerability thresholds is as follows: Librino in the critical vulnerability category, Angeli Custodi in the high category, Zia Lisa in the medium category and Corso Italia in the low category.

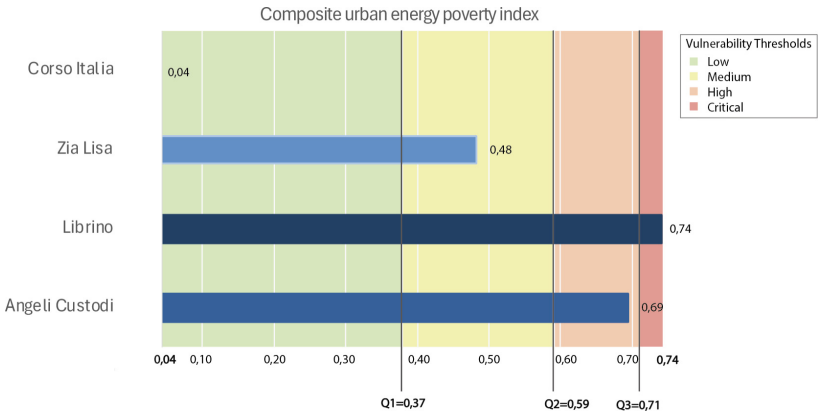


**Fig. 5.** Composite urban energy poverty index values with vulnerability classification thresholds. (our elaboration).

## 4.4 Spatial Distribution

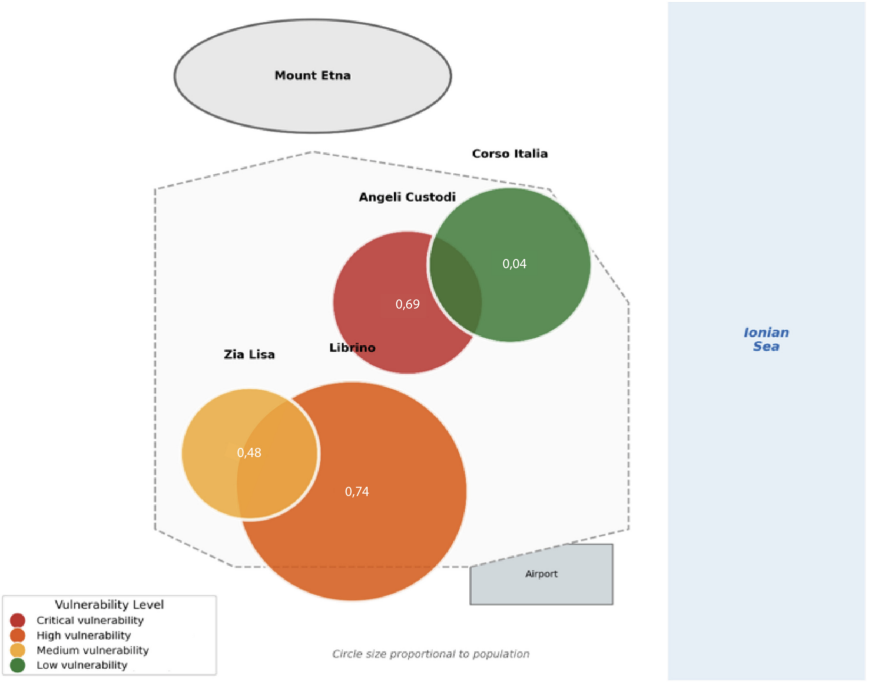


**Fig. 6.** Schematic spatial representation of energy poverty vulnerability in Catania. Circle size proportional to population; colour indicates vulnerability level.

Figure 6 presents the spatial distribution of vulnerability. A clear geographical pattern emerges critical vulnerability concentrates in the south-western periphery (Librino) and

degraded historic centre (Angeli Custodi), while low vulnerability characterises eastern coastal areas (Corso Italia). This polarisation reflects historical development patterns, with social housing isolated from central services. Circle size represents population, while colour encodes the vulnerability class.

### 4.5 Driver Decomposition Analysis

Figure 7 shows the value for each driver of local vulnerability and presents the decomposition of composite indices into weighted driver contributions. In Angeli Custodi, there is the highest value of the socio-economic driver.

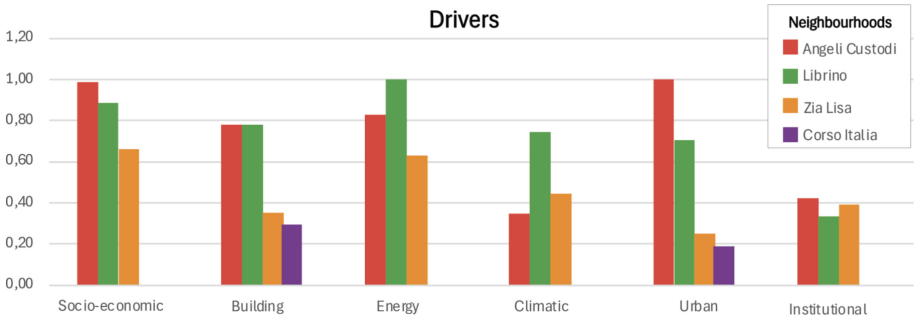


**Fig. 7.** Decomposition of composite index by weighted driver contribution.

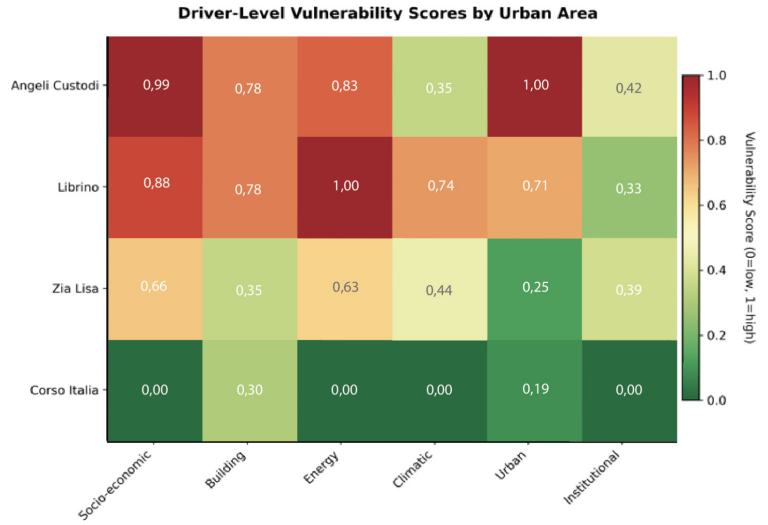


**Fig. 8.** Heatmap of driver-level vulnerability scores. Values range from 0 (green) to 1 (red).

In Librino and Angeli Custodi, there is the highest value of the building driver. Librino presents also the highest value of the energy driver. Corso Italia has the highest value in the building driver. The heatmap in Fig. 8 visualises raw driver scores, enabling rapid identification of critical hotspots.

### 4.6 Sensitivity Analysis

To assess the robustness of the index, a sensitivity analysis was performed by testing alternative weighting scenarios. Table 5 shows the baseline scenario that uses entropy-based weights. In Scenario A, the weight of the IDISE index score increased by 10%, while the remaining weights were kept unchanged (Table 6). In Scenario B the weight of the CDD index score was increased by 10% (Table 7). In Scenario C the weight of the green space score was increased by 10% (table 9). The results confirmed the stability of the index and the consistency of neighbourhood rankings across scenarios (Table 7).

**Table 5.** Baseline scenario (our elaboration)

| | Socio-economic | Building | Energy | Climatic | Urban | Institutional |
|---|---|---|---|---|---|---|
| Angeli Custodi | 0,99 | 0,78 | 0,83 | 0,35 | 1,00 | 0,42 |
| Librino | 0,88 | 0,78 | 1,00 | 0,74 | 0,71 | 0,33 |
| Zia Lisa | 0,66 | 0,35 | 0,63 | 0,44 | 0,25 | 0,39 |
| Corso Italia | 0,00 | 0,30 | 0,00 | 0,00 | 0,19 | 0,00 |

**Table 6.** Scenario A, weight of the IDISE index score increased by 10% (our elaboration)

| | **Socio-economic** | **Building** | **Energy** | **Climatic** | **Urban** | **Institutional** |
|---|---|---|---|---|---|---|
| **Angeli Custodi** | 0,99 | 0,78 | 0,83 | 0,35 | 1,00 | 0,42 |
| **Librino** | 0,88 | 0,78 | 1,00 | 0,74 | 0,71 | 0,33 |
| **Zia Lisa** | 0,66 | 0,35 | 0,63 | 0,44 | 0,25 | 0,39 |
| **Corso Italia** | 0,00 | 0,30 | 0,00 | 0,00 | 0,19 | 0,00 |

**Table 7.** Scenario B, weight of the CDD index score increased by 10% (our elaboration)

| | **Socio-economic** | **Building** | **Energy** | **Climatic** | **Urban** | **Institutional** |
|---|---|---|---|---|---|---|
| **Angeli Custodi** | 1,01 | 0,78 | 0,83 | 0,35 | 1,00 | 0,42 |
| **Librino** | 0,90 | 0,78 | 1,00 | 0,74 | 0,71 | 0,33 |
| **Zia Lisa** | 0,68 | 0,35 | 0,63 | 0,44 | 0,25 | 0,39 |
| **Corso Italia** | 0,00 | 0,30 | 0,00 | 0,00 | 0,19 | 0,00 |

**Scenario A**

**Table 8.** Scenario C, weight of the Green Space index score increased by 10% (our elaboration)

| | Socio-economic | Building | Energy | Climatic | Urban | Institutional |
|---|---|---|---|---|---|---|
| **Angeli Custodi** | 0,99 | 0,78 | 0,83 | 0,36 | 1,00 | 0,42 |
| **Librino** | 0,88 | 0,78 | 1,00 | 0,77 | 0,71 | 0,33 |
| **Zia Lisa** | 0,66 | 0,35 | 0,63 | 0,46 | 0,25 | 0,39 |
| **Corso Italia** | 0,00 | 0,30 | 0,00 | 0,00 | 0,19 | 0,00 |
| | | | | **Scenario B** | | |

## 5 Discussion

### 5.1 Intra-urban Disparities and the Limits of Aggregate Statistics

The results provide compelling evidence that energy poverty in Mediterranean cities is characterised by profound intra-urban disparities invisible in aggregate statistics. The composite index differential between Librino (0,74) and Corso Italia (0,04) exceeds 100%, revealing spatial inequality within a single municipality that rivals disparities typically observed between European countries. This corroborates research highlighting spatial heterogeneity of energy poverty [14, 26] while providing quantitative evidence of urban-scale disparity magnitude. The ISTAT IDISE data confirm the socio-economic dimension: Angeli Custodi records 114.2 versus 85.0 for Corso Italia a 34% differential. Our composite framework demonstrates that incorporating building, energy, climatic, urban and institutional dimensions amplify these disparities, as vulnerable populations concentrate in areas with multiple overlapping risk factors. This aligns with environmental justice literature emphasising cumulative and intersectional urban vulnerabilities [27, 28].

### 5.2 Building Stock as Primary Driver

The decomposition analysis reveals that the 'building driver' factor is highest in disadvantaged areas, indicating that it contributes to vulnerability in these areas (Librino 0,78; Angeli Custodi 0,78). These carries significant policy implications, as building-related vulnerability is amenable to intervention through retrofitting. SIAPE data indicate 52.1% of Catania's stock in classes F-G, with average consumption exceeding 166 kWh/m$^2$/year. In Librino, buildings consist predominantly of 1970s social housing (IACP/ATER) with estimated consumption exceeding 220 kWh/m$^2$/year, constructed before energy efficiency requirements, featuring uninsulated concrete walls, single-glazed windows and centralised heating with no cooling provision. The PNRR-funded 'Librino Città Moderna' project (€10 million) represents a positive development, though existing stock requiring renovation vastly exceeds current investment. These findings corroborate research demonstrating that fiscal incentives (Superbonus 110%) disproportionately benefited higher-income households capable of advancing costs, while energy-poor households in social housing were largely excluded [29, 30]. This regressive outcome underscores the need for targeted programmes directly addressing vulnerable housing without requiring upfront resident investment.

### 5.3 Summer Thermal Stress: The Mediterranean Gap

The climatic driver reveals a distinctive pattern in Mediterranean cities. Although summer heat stress is severe across the entire municipality, characterised by recurrent heatwaves exceeding 45 °C, more than 110 days per year with perceived temperatures above 35 °C, and CDD values between 850 and 950, the indicator displays substantial intra-urban variability. Climatic scores range from 0,74 in Librino to 0,00 in Corso Italia, reflecting marked differences in urban heat island intensity, built-form density, surface materials and ventilation conditions. Urban heat island effects compound these conditions, with + 3–4 °C differentials in Librino. These conditions have documented health impacts: recent research estimates significant excess heat-related mortality in comparable contexts [31]. These results indicate that thermal exposure is not spatially uniform: disadvantaged neighbourhoods experience significantly higher microclimatic stress than affluent coastal areas. Despite this variability, the climatic driver contributes less to the composite index than socio-economic or building-related factors. This is not due to low climatic relevance, but to the relative magnitude of inequalities: socio-economic deprivation and building obsolescence exhibit even stronger spatial contrasts, thus receiving higher entropy-based weights. The climatic driver therefore captures a widespread environmental stressor that amplifies vulnerability where adaptive capacity is limited but does not dominate the multidimensional profile. The results highlight that Mediterranean energy vulnerability emerges from the interaction between severe climatic exposure and unequal adaptive capacity, rather than from climatic conditions alone. By incorporating a cooling-related climatic indicator, the framework addresses a well-documented gap in European monitoring systems, which remains centred on winter heating. This inclusion provides a more complete representation of thermal vulnerability in cooling-stressed contexts and strengthens the capacity of the index to reflect the specific challenges faced by Mediterranean cities [15, 22]. The territorial weighting system further departs from equal-weight assumptions, recognising that driver importance varies across contexts [32].

### 5.4 Policy Implications

The institutional driver is highest in Angeli Custodi, indicating that the area is already targeted by public interventions; however, the persistence of high vulnerability across all other drivers suggests that current strategies may not be sufficient to address structural conditions. Interventions must combine retrofitting with social support: energy poverty advisory services, enhanced social bonuses and integration with urban regeneration under ‘Decreto Caivano’ The sharp contrast in the energy driver between Librino and Corso Italia reflects differences in building efficiency, access to modern heating and cooling systems, and the relative weight of energy expenditure on household income. High absolute energy spending in affluent areas does not translate into vulnerability when it represents a small share of disposable income. These patterns are consistent with the higher building and urban vulnerability observed in the most deprived neighbourhoods, highlighting the need for targeted renovation and urban adaptation policies. Several limitations should be acknowledged: (i) IDISE data refer to 2021; (ii) climatic indicators are modelled estimates; (iii) single case study limits generalizability. Future research

should address these through finer spatial scales, temporal dynamics and linkage with consumption data.

### 5.5 Sensitivity Analyses

The sensitivity analysis confirms the robustness of the composite index under moderate perturbations of key drivers. Across all scenarios, the relative ranking of neighbourhoods remains unchanged, with Librino consistently showing the highest vulnerability, followed by Angeli Custodi, Zia Lisa and Corso Italia. This stability indicates that the multidimensional structure of the index is not driven by single-driver fluctuations but by persistent structural differences across neighbourhoods. Scenario A, which increases the socio-economic indicator (IDISE) by 10%, produces only marginal variations (+0.02 in Angeli Custodi and Librino; +0.02 in Zia Lisa), confirming that socio-economic deprivation is already a dominant component of vulnerability. The limited numerical change reflects the fact that these neighbourhoods already score very high in the baseline scenario (0.66–0.99), leaving little room for further escalation.Scenario B, which increases the climatic indicator (CDD) by 10%, generates slightly larger variations, particularly in Librino (from 0.74 to 0.77) and Zia Lisa (0.44 to 0.46). This confirms that climatic exposure is an amplifying factor: it increases the magnitude of vulnerability in already disadvantaged areas but does not alter their relative position. Corso Italia remains unaffected, reflecting its higher adaptive capacity. Scenario C, which increases green space by 10%, produces small reductions in the urban driver (e.g., Angeli Custodi from 1.00 to 0.86; Librino from 0.71 to 0.60), but again without modifying the overall ranking. This suggests that improvements in environmental quality can mitigate vulnerability. Overall, the sensitivity analysis demonstrates that the index is structurally stable. The scenarios intensify or alleviate vulnerability but do not determine the spatial hierarchy.

## 6 Conclusions

This study has proposed and applied a multidimensional composite index for urban energy vulnerability assessment. The Catania case demonstrates that integrating six drivers at high spatial resolution reveals substantial intra-urban disparities that remain hidden in conventional indicators. The methodological contributions are threefold: (i) the integration of high-resolution local data enabling neighbourhood-scale analysis; (ii) the use of entropy-based weighting to reflect context-specific variability; and (iii) the explicit incorporation of summer thermal stress, addressing a persistent Mediterranean gap in existing monitoring frameworks. These innovations provide a flexible and transferable approach for assessing energy vulnerability in diverse urban contexts. By identifying the dominant drivers in each neighbourhood, the framework supports the design of targeted interventions that address the structural and environmental mechanisms shaping vulnerability. As European cities face the dual challenge of decarbonisation and climate adaptation, spatially explicit and climate-sensitive tools such as the one proposed are essential to ensure that the energy transition reduces, rather than reinforces, existing urban inequalities.

**Disclosure of Interests.** The authors have no competing interests to declare that are relevant to the content of this article.

## References


1. Bouzarovski, S., Petrova, S.: A global perspective on domestic energy deprivation: overcoming the energy poverty–fuel poverty binary. Energy Res. Soc. Sci. **10**, 31–40 (2015). https://doi.org/10.1016/j.erss.2015.06.007
2. Thomson, H., Bouzarovski, S., Snell, C.: Rethinking the measurement of energy poverty in Europe: a critical analysis of indicators and data. Indoor Built Environ. **26**(7), 879–901 (2017). https://doi.org/10.1177/1420326X17699260
3. Primc, K., Slabe-Erker, R.: Social policy or energy policy? Time to reconsider energy poverty policies. Energy Sustain. Dev. **55**, 32–36 (2020). https://doi.org/10.1016/j.esd.2020.01.001
4. Santamouris, M.: Cooling the buildings past, present and future. Energy Build. **128**, 617–638 (2016). https://doi.org/10.1016/j.enbuild.2016.07.034
5. Middlemiss, L., et al.: Energy poverty and social relations: a capabilities approach. Energy Res. Soc. Sci. **55** (2019). https://doi.org/10.1016/j.erss.2019.05.002
6. Castaño-Rosa, R., Solís-Guzmán, J., Rubio-Bellido, C., Marrero, M.: Towards a multiple-indicator approach to energy poverty in the European Union: a review. Energy Build. **193**, 36–48 (2019). https://doi.org/10.1016/j.enbuild.2019.03.039
7. Boardman, B.: Fixing Fuel Poverty: Challenges and Solutions. Earthscan, London (2010)
8. Hills, J.: Getting the Measure of Fuel Poverty: Final Report of the Fuel Poverty Review. CASE Report 72, London School of Economics, London (2012)
9. Thomson, H., Snell, C.: Quantifying the prevalence of fuel poverty across the European Union. Energy Policy **52**, 563–572 (2013). https://doi.org/10.1016/j.enpol.2012.10.009
10. European Commission: Energy Poverty Advisory Hub Monitoring Framework and Indicator Handbook. Publications Office of the European Union, Luxembourg (2023)
11. Gouveia, J.P., Palma, P., Bessa, S., Mahoney, K., Sequeira, M.: Energy Poverty National Indicators: Insights for a More Effective Measuring. Energy Poverty Advisory Hub, European Commission, Brussels (2022)
12. Herrero, S.T.: Energy poverty indicators: a critical review of methods. Indoor Built Environ. **26**(7), 1018–1031 (2017). https://doi.org/10.1177/1420326X17718054
13. Jenkins, K., McCauley, D., Heffron, R., Stephan, H., Rehner, R.: Energy justice: a conceptual review. Energy Res. Soc. Sci. **11**, 174–182 (2015). https://doi.org/10.1016/j.erss.2015.10.004
14. Mashhoodi, B., Stead, D., van Timmeren, A.: Spatial variation of residential building energy efficiency in the Netherlands. Energy Policy **165**, 112950 (2022). https://doi.org/10.1016/j.enpol.2022.112950
15. Santamouris, M.: Recent progress on urban overheating and heat island research. Energy Build. **224**, 110238 (2020). https://doi.org/10.1016/j.enbuild.2020.110238
16. Bouzarovski, S., Thomson, H., Cornelis, M.: Confronting energy poverty in Europe: a research and policy agenda. Energies **14**(4), 858 (2021). https://doi.org/10.3390/en14040858
17. Nastos, P.T., Vassilakis, E., Nastos, M.P.: Climate change impacts on urban heat islands and energy poverty in Mediterranean cities: a systematic review. Int. J. Climatol. (2024). https://doi.org/10.1002/joc.8546
18. Sánchez-Guevara Sánchez, C., Sanz Fernández, A., Núñez Peiró, M., Gómez Muñoz, G.: Energy poverty in Madrid: data exploitation at the city and district level. Energy Policy **144** (2020). https://doi.org/10.1016/j.enpol.2020.111653
19. Ürge-Vorsatz, D., Cabeza, L.F., Serrano, S., Barreneche, C., Petrichenko, K.: Heating and cooling energy trends and drivers in buildings. Renew. Sustain. Energy Rev. **41**, 85–98 (2015). https://doi.org/10.1016/j.rser.2014.08.039
20. Di Rocco, A.R., Trovato, M.R., Caponetto, R.G., Nocera, F.: Energy Poverty and territorial resilience: an integrative review and an inclusive governance model. Sustainability **17**, 8555 (2025). https://doi.org/10.3390/su17198555

21. Romanello, M., et al.: The 2022 report of the Lancet countdown on health and climate change. Lancet **400**(10363), 1619–1654 (2022). https://doi.org/10.1016/S0140-6736(22)01540-9
22. Pavanello, F., et al.: Air-conditioning and the adaptation cooling deficit in emerging economies. Nat. Commun. **12**, 6460 (2021). https://doi.org/10.1038/s41467-021-26592-2
23. ISTAT: Report Comune di Catania. Commissione parlamentare di inchiesta sulle condizioni di sicurezza e sullo stato di degrado delle città e delle loro periferie. ISTAT, Roma (2024)
24. Colloca, C., Pantaleo, V.: Diseguaglianze socio-spaziali e progetti di rigenerazione urbana: il caso di Catania. Rivista Trimestrale di Scienza dell'Amministrazione 1/2025 (2025). https://doi.org/10.32049/RTSA.2025.1.07
25. Comune di Catania: Deliberazione della Giunta Comunale n. 200 del 2 ottobre 2024. Atto di indirizzo per il Piano Urbanistico Generale (PUG). Comune di Catania, Catania (2024)
26. Bouzarovski, S., Simcock, N.: Spatializing energy justice. Energy Policy **107**, 640–648 (2017). https://doi.org/10.1016/j.enpol.2017.03.064
27. Walker, G., Day, R.: Fuel poverty as injustice: integrating distribution, recognition and procedure in the struggle for affordable warmth. Energy Policy **49**, 69–75 (2012). https://doi.org/10.1016/j.enpol.2012.01.044
28. Sovacool, B.K., Lipson, M.M., Chard, R.: Temporality, vulnerability, and energy justice in household low carbon innovations. Energy Policy **128**, 495–504 (2019). https://doi.org/10.1016/j.enpol.2019.01.010
29. Martini, C.: Assessing Ecobonus as energy poverty mitigation policy: is energy efficiency for all?. In: Bardazzi, R., Pazienza, M.G. (eds.) Vulnerable Households in the Energy Transition. SEREE, pp. 207–233. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-35684-1_9
30. Faccioli, M., Lucarelli, C., Mazzoli, C. et al.: What are the policy drivers to undertake green retrofitting investments? The role of tax incentives and communication in Italian households' decision-making. Ital. Econ. J. **11**, 1211–1237 (2025). https://doi.org/10.1007/s40797-024-00283-5
31. Wedler, M., Pinto, J.G., Hochman, A.: More frequent, persistent, and deadly heat waves in the 21st century over the Eastern Mediterranean. Sci. Total Environ. **870** (2023). https://doi.org/10.1016/j.scitotenv.2023.161883
32. Fusco, E., Vidoli, F., Sahoo, B.K.: Spatial heterogeneity in composite indicator: a methodological proposal. Omega **77**, 1–14 (2018). https://doi.org/10.1016/j.omega.2017.04.007



# Holistic Sustainability Evaluation: Preliminary Phases for a Methodology Application in Docks Dora, Turin (Italy)

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**Abstract.** The increasing complexity of urban transformation processes requires decision-support tools capable of integrating the different dimensions of sustainability. Traditional evaluation models, often based on single-dimensional indicators, are becoming increasingly inadequate for representing the multidimensional nature of urban regeneration interventions and building transformations. This contribution integrates life cycle–based approaches, namely Life Cycle Costing (LCC) and Life Cycle Assessment (LCA), with the Social Return on Investment (SROI) method to assess the social dimension.

The harmonization of economic, environmental, and social indicators is supported through the application of Saaty's Analytic Hierarchy Process (AHP), which enables the structuring of the decision problem and the weighting of the different sustainability criteria. The research focuses on the definition of the indicator system and, particularly, on the development of the social dimension, which still presents a limited level of methodological standardization compared to the economic and environmental components.

In order to contextualize the methodological framework, the study identifies the Docks Dora complex in Turin (Northern Italy) as a reference case study, a significant example of industrial heritage currently involved in urban regeneration processes. The integration of LCA, LCC, SROI, and AHP, still scarcely explored in the literature, may represent a relevant methodological support for the multidimensional evaluation of urban transformation processes and for the comparison of alternative design scenarios related to building retrofit and adaptive reuse.

**Keywords:** Holistic Sustainability · Social – Economic – Environmental Indicators · AHP · Docks Dora

## 1 Introduction

The increasing complexity of urban development processes, characterized by the presence of multiple stakeholders and often divergent objectives, requires the adoption of evaluation tools capable of harmonizing heterogeneous dimensions and different analytical languages and tools. In this regard, multidimensional approaches represent a

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fundamental support for understanding the effects generated by interventions and for structuring decision-making processes. Traditional decision-support models often rely on unidimensional indicators, which are increasingly inadequate to represent the complexity of urban transformation and regeneration processes that simultaneously involve economic, environmental, and social systems.

This contribution aims to clarify the assumptions underlying the research with reference to sustainability assessment in urban and building transformation processes, with particular attention to the need to integrate environmental and social components alongside the economic and financial aspects traditionally considered in investment analysis.

The study represents an advancement of the research conducted by [1], in which a methodological framework for the holistic assessment of sustainability in real estate projects was proposed, based on the integration of Life Cycle approaches, the AHP and SROI. Within this perspective, evaluation plays a central role in the decision-making processes that accompany urban regeneration interventions and building retrofit, supporting the definition and comparison of alternative project scenarios. This contribution builds upon that research with the aim of further integrating and developing the proposed framework. Starting from the overall methodological structure defined in [1], this paper examines the first three steps of the research path, with particular attention to the application and role of SROI. In particular, the focus is placed on deepening the definition of the indicators associated with sustainability criteria, with specific reference to social indicators and to the methods used to assess the social impacts generated by urban interventions.

Within the theoretical framework developed in the research by [1], among the approaches used for sustainability assessment in the construction and real estate sectors are those based on the life-cycle perspective. LCA allows the analysis of environmental impacts associated with the different phases of the life cycle of a product or building, while LCC enables the evaluation of costs incurred throughout the entire life cycle of the intervention. These dimensions are complemented by tools aimed at assessing the social value generated by projects, including SROI, which is used to estimate and monetize the social impacts of initiatives [2].

The presence of heterogeneous indicators requires the use of tools capable of integrating them. In this context, Multi-Criteria Decision Analysis (MCDA) plays a significant role in supporting decision-making processes and in enabling the comparison of alternative project scenarios. Among these, the AHP represents one of the most widely used tools for the hierarchical structuring of decision problems and for determining the weights associated with different evaluation criteria [3].

In order to frame the proposed methodological framework within a specific territorial context, this study identifies the Docks Dora complex and area in Turin as a reference case study. The site is an industrial archaeology complex characterized by the coexistence of multiple cultural and productive functions and is currently subject to potential urban regeneration strategies. The selection of this case study is motivated by its emblematic nature with respect to urban transformation processes and by the opportunity to explore the scalability of the proposed model, enabling analysis at both the urban and individual asset.

Considering these premises, the paper is structured as follows. Section 2 presents the proposed methodological framework and the main analytical assumptions. Section 3 describes the case study. Section 4 illustrates the preliminary stages of applying the methodology, precisely the alternative scenarios definition and the system of indicators to be used for the evaluation. Finally, Sect. 5 presents the study's discussion, further research developments and conclusions.

## 2 Methodology Framework

The proposed methodological framework aims to support decision-making processes in contexts of urban transformation and regeneration in the presence of alternative design scenarios. The model is consistent with the theoretical framework outlined in [1] and involves applying Life Cycle approaches, multi-criteria analysis, and the SROI method. The methodological approach is based on the concept of "complementary methodology" [4, 5], which, as the United Nations Environment Programme (UNEP) indicates, requires analysing the different dimensions of sustainability using distinct but parallel approaches.

The framework is structured in the conventional six main steps, as illustrated in Fig. 1.

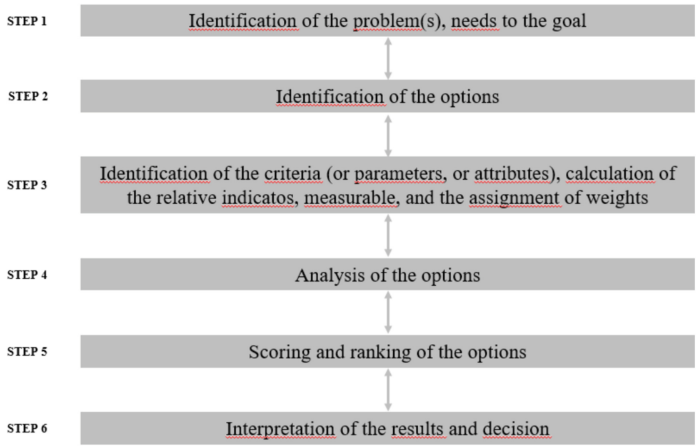


**Fig. 1.** Evaluation process: iterative workflow. Source: authors' elaboration.

The first step is to define the evaluation objective, identify the case study, and analyse the competitive analysis. In this phase, the decision-making problem is formalized, defined as the identification of the preferred design option.

The second operational step involves defining the alternative options to be evaluated. Within the methodological workflow, a limited set of mutually exclusive design scenarios is assumed, defined to ensure comparability across possible configurations of the intervention. The alternatives represent different design options, technological solutions, management strategies, or operational configurations related to the system being

analysed. These are selected based on technical, scientific, regulatory, and strategic criteria, with consideration of the study's objectives and the stakeholders involved in the decision-making process.

The third step involves identifying the criteria and related indicators for the three dimensions of sustainability. The economic and environmental dimensions are assessed using LCC and LCA approaches, which enable analysis of the costs and environmental impacts across the life cycle. The social dimension, on the other hand, is investigated using the SROI method, which estimates the social value generated by interventions by monetizing the impacts and benefits produced for stakeholders. Assessing sustainability criteria enables us to develop a set of indicators that holistically represent the performance of the various alternatives.

The fourth step involves harmonizing the selected specific indicators. To this end, we adopt the AHP [6] which enables us to structure the decision-making problem and assign relative weights to the criteria through pairwise comparisons of the hierarchy's elements. This allows comparison of heterogeneous indicators.

The fifth step consists of the option ranking phase, which involves selecting the most advantageous alternative or defining a ranking of preferences among the selected options. This step is closely linked to the preferences of the various stakeholders involved in the decision-making process.

The process concludes with the sixth and final step, which interprets the results from the previous steps and leads to a final decision.

## 3 Case Study

The urban regeneration and architectural redevelopment project of the Docks Dora complex, located in Turin (Northern Italy) in the Barriera di Milano district, within the Circoscrizione n°6 (Fig. 2), is assumed as a case study for the methodology application. The area where the Docks Dora are located is part of an urban transformation zone [7], characterized by a strong concentration of industrial activities and production infrastructure, representative also for the potential impacts on the Turin's property market values in the area [8, 9].

The Docks Dora complex (Fig. 3) was built between 1912 and 1914 as a general warehouse for the storage and conservation of duty-free goods, fitting into a territorial context that, in the first half of the twentieth century, established itself as one of the main hubs of Turin's industrial development.

From an architectural and construction point of view, the complex, designed by the engineer Ernesto Fantini and built by the company of Giovanni Antonio Porcheddu [10], constitutes a significant example of the use of the Hennebique system in reinforced concrete, an innovative technology for the time, which allowed for large structural spans and greater distribution flexibility.

The buildings, characterised by exposed brick facades and a modular structure organised into several functional pavilions, were equipped with internal railway connections that enabled the direct transfer of goods from wagons to warehouses.

Beginning in the second half of the twentieth century, functions as logistics systems were progressively reorganized, warehouses' original functions gradually diminished, and the area entered a phase of disuse and underuse.




**Fig. 2.** Localization of the Docks Dora in the Barriera di Milano neighborhood (Turin, Italy). Source: authors' elaboration from Piano Urbano della Mobilità Sostenibile (PUMS) (www.cittametropolitana.torino.it).




**Fig. 3.** Docks Dora complex. Source: authors' photos.

Since the 1980s, the Docks Dora complex, owned by private individuals available to accommodate scenarios with public implications, has been progressively reoccupied by commercial activities, creative studios, and cultural spaces, establishing itself as one of the city's main venues for artistic and cultural experimentation.

The complex today represents an emblematic example of the adaptive reuse of industrial heritage and the transformation of abandoned production infrastructure within the broader urban regeneration processes affecting the Barriera di Milano neighbourhood.

The complex borders the public green space of Peccei Park, one of the most strategic public spaces for use and socialization by neighbourhood residents.

## 4 Preliminary Phases for the Methodology Application

This contribution, as shown in Fig. 4, focuses on the first three operational steps of the methodological process, with particular attention to the social dimension of sustainability, while the subsequent steps will be further explored in future research.

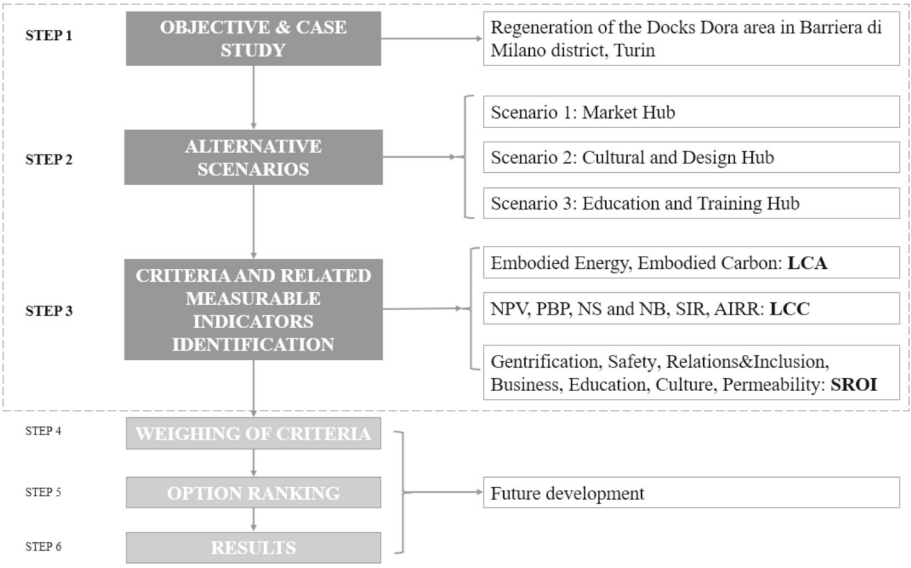


**Fig. 4.** Methodological process. Source: authors' elaboration.

### 4.1 Alternative Scenarios

The use of well-established methods, such as competitive analysis and SWOT analysis, led to the identification of the main sensitive issues and design strategies. Three alternative scenarios have been defined for the selected case study, which include interventions at urban and building level, with the aim of restoring the entire area to collective use and with attention to a potential permeability between private spaces with free access and public spaces bordering the complex. All alternatives require synergy between the private sector, private third-sector organizations, and public bodies. The scenarios are as follows:

- Market Hub: the alternative enhances the site's historical heritage, highlighting its commercial vocation through the creation of a market with indoor and outdoor spaces, complemented by a dedicated restaurant area. This alternative is expected to be completed in the short term, as it does not require any major architectural interventions.

- Cultural and Design Hub: the approach combines conservation-oriented enhancement with a contemporary reinterpretation of the site's historic character. The site is designed as a multifunctional hub capable of integrating new cultural and professional functions, while maintaining the creative activities already present in the area. Through targeted architectural interventions aimed at improving urban permeability, the redevelopment includes the creation of shared open spaces for artistic expression, including street art in the near Peccei Park, and an open-air theatre accessible to the community. The alternative envisages medium-term construction as it requires targeted architectural interventions.
- Education and Training Hub: the scenario defines a clear and structured functional structure. On the ground floor of the buildings, the current purpose of the spaces as open and permeable areas is maintained and enhanced, intended for workshops, commercial activities, creative studios, and light manufacturing. The upper floor houses training facilities, with particular attention to programs aimed at the international population. The proposal also includes the creation of co-working spaces, designed to foster professional activities and dynamic collaboration. The alternative envisions long-term construction as it requires significant architectural interventions.

The alternative scenarios proposed above have been developed on the basis of ISTAT data [11] (e.g. resident population, birth and death rates, business register, per capita income etc.), of Statistical yearbooks of the municipality of Turin [12], of the Territorial Projects of the National Metro Plus Programme 2021–2027 [13], of the Turin Metro project – Line 2 [14] and Circoscrizione n°6 and neighborhood dataset [15].

### 4.2 Identification of Criteria and Related Measurable Indicators

The assessment of sustainability criteria is based on specific indicators across the three dimensions of environmental, social, and economic sustainability.

The set of criteria identified for the study are the following:

- economic sustainability: NPV, PBP, NS, NB, SIR, AIRR;
- environmental sustainability: embodied energy and embodied carbon,
- social sustainability: Gentrification, Safety, Relations&Inclusion, Business, Education, Culture, Permeability

The related indicators represent the status of a specific area, phase, or process in the life cycle [16] and can be qualitative, semi-quantitative, or quantitative in nature. They can also be classified as specific or generic, primary or secondary.

Assuming that "*An indicator is a synthetic measure, generally expressed in quantitative form, coinciding with a variable or composed of multiple variables, capable of summarizing the trend of the phenomenon to which it refers"* [17], the following paragraphs outline and discuss the indicators associated with the LCC and LCA approaches, as required by the relevant regulations and guidelines.

By contrast, the SROI method does not rely on standardized regulations or predefined indicators applicable across all contexts. For this reason, the present study focuses on identifying and selecting social indicators, aiming to address this methodological limitation and strengthen the analytical robustness of the approach.

**Economic Indicators.** The economic sustainability criterion is assessed using LCC, a methodology normed in the international standard ISO 15686-5:2017 [18], which serves as the reference framework for evaluating costs incurred throughout the life cycle of a building or construction system.

The LCC approach introduces the concept of sustainability by applying economic indicators, expressed in monetary, percentage, or time units, to evaluate different design scenarios, particularly technological ones [1].

For the Docks Dora case study, selected for this research, the indicators considered most suitable for assessing economic sustainability are described in the following Table 1, based on [19, 20]. Notice that the indicators calculation implies delicate steps, specifically in relation to the financial input data selection and the discount rate definition [21].

**Table 1.** Economic Indicators. Source: authors' elaboration from [20]

| Indicators | Description | Aims | Applicability condition |
|---|---|---|---|
| Net Present Value (NPV) | It represents the discounted value of costs over the entire time horizon considered. "Non-cost" components such as operational savings, strategic benefits, residual value, and economic incentives are also considered | – Comparison of alternative solutions through the application of the LCC;<br>– Production of a ranking of alternatives based on cost-effectiveness principles;<br>– Identification of the best alternative;<br>– Verification of the economic acceptability of an alternative | As low as possible |
| Pay-Back Period (PBP) | Represents the number of periods necessary for the savings achieved to compensate for the initial costs of the initial investment | – Acceptance/rejection of alternative projects on the basis of a cost-effectiveness principle | Less than the useful life of the product |
| Net Saving (NS) and Net Benefits (NB) | Allow us to quantify the net economic margin of an alternative scenario compared to the reference one, by comparing their respective discounted costs. A positive value highlights the greater economic convenience of the alternative solution | – Single-option evaluation to rank alternative technology scenarios based on the lowest life cycle cost;<br>– Selection of the most cost-effective products/processes/components;<br>– Selection of optimal system/scenario combinations | Acceptable if $>0$ Rejectable if $<0$ |

(*continued*)

The calculation of the selected indicators will be developed subsequently, based on primary data collected through direct interviews with stakeholders and secondary data derived from scientific literature and available documentary sources.

**Table 1.** (*continued*)

| Indicators | Description | Aims | Applicability condition |
|---|---|---|---|
| Saving to Investment Ratio (SIR): | It is a cost-effectiveness indicator that expresses the ratio between the savings achieved during the operational phase and the additional investment required, excluding residual value. Specifically, it compares the operational savings achieved with the incremental costs incurred for the adoption of improved technological solutions | – Acceptance/rejection of technological scenarios;<br>– Ranking of alternative options | Acceptable if >0<br>Ascending order of values |
| Adjusted Internal Rate of Return (AIRR) | It measures a project's overall return by considering the reinvestment of intermediate cash flows over the analysis horizon and is determined using a specific financial mathematical formula. The AIRR expresses the project's effective annual rate of return, incorporates the effect of intermediate reinvestments, and allows for the identification of alternatives with the highest net returns | – Acceptance/rejection of technological scenarios;<br>– Ranking of alternative options | >r (discount rate)<br>Ascending order of values |

**Environmental Indicators.** The evaluation of the environmental sustainability criterion is based on the use of specific indicators, understood as parameters or values derived from parameters capable of describing the state of the environment, the pressures exerted on it, the dynamics that influence its evolution and the effects produced on human health, ecosystems and materials [22–24].

Environmental impact refers to the modification of the quality of one or more environmental elements resulting from an action or activity, i.e., the alteration of an environmental aspect susceptible to interaction with the natural system. Impact represents the phase preceding the effect and can generate consequences at local, regional, or global scales, often resulting from the combination of multiple contributions distributed across space and time. Its assessment involves analyzing emissions, diffusion, and transformation processes in the environment, and final concentrations or deposition [25].

The choice of impact categories must be consistent with the study's objectives and relevant to the subject being analyzed; the main ones include climate change, acidification, eutrophication, stratospheric ozone depletion, resource consumption, land use,

and toxicity. Environmental indicators are divided into midpoints, which quantify the contributions to specific environmental phenomena along the cause-effect chain using characterization factors, and endpoints, which express the final damage to the environment and human health through further aggregation and normalization processes [5].

The selection of indicators is a crucial step and must ensure methodological consistency, scientific validity, transparency, and compatibility with any standardization and weighting procedures, in line with ISO recommendations and the guidance provided by [17].

In this study, the environmental indicators suggested are Embodied Energy (EE) and Embodied Carbon (EC), considered particularly representative of the impacts associated with materials and construction systems throughout their life cycle [26].

Embodied Energy (EE) is the total primary energy incorporated into a product, including the phases of extraction, production, transport, construction, and end-of-life.

Embodied Carbon (EC) measures the overall greenhouse gas emissions generated along the same phases and is expressed in kg of $CO_2$ equivalent. The reference indicator for climate change is the Global Warming Potential (GWP), expressed in kg $CO_2$eq, while $CO_2$ indicates only carbon dioxide, $CO_2$ equivalent includes all greenhouse gases weighted according to their global warming potential.

Notice that the calculation of the environmental indicators will be the subject of a subsequent in-depth study during which the concrete possibility of proceeding with their quantification will also be verified in relation to the availability and quality of the data collected. Alternatively, data from the literature will be assumed as a proxy for the simulation.

**Social Indicators.** The social criterion explicitly refers to the SROI index, a quantitative metric calculated using a numerical value that functions as an "efficiency" indicator. It assesses an entity or organization's capacity to convert invested resources into initiatives that generate measurable social impact [1].

As per the methodology, SROI is developed in six stages: (i) establishing scope and identifying stakeholders; (ii) mapping outcomes; (iii) evidencing outcomes and giving them a value; (iv) establishing impact; (v) calculating the SROI; (vi) reporting, using, and embedding. In this contribution, which is an in-depth analysis of the methodology with respect to the article [1], we have reached stage iv.

One of the core elements of the SROI method, particularly in the "Theory of Change" phase, is the involvement of stakeholders from the earliest stages of the analysis through to the final phase of reporting and disclosing results. As Jeremy Nicholls's guide highlights, SROI seeks to foster accountability to stakeholders [27].

A primary objective of SROI, whether evaluative or forecast, is to assess the extent to which a project generates change for the stakeholders involved, namely those who "experience change, whether positive or negative, as a result of the activity being analysed" [27 p. 20]. For methodological consistency, these actors must therefore be fully integrated into the evaluation process, contributing to the identification of outcomes and indicators, as well as to the definition and valuation of the impact generated.

However, although the importance of stakeholder involvement is repeatedly emphasized, Nicholls [27] does not provide detailed operational guidance on specific engagement methods. As a result, practical applications have led to the development of heterogeneous approaches: "practitioners developed the SROI framework according to their specific needs" [28].

On this basis, stakeholder identification was conducted by combining the CIA method [29] and the Salience Model [30] to obtain a more comprehensive assessment of each key actor. The Salience Model classifies stakeholders according to the combination of three core attributes: (i) power, defined as the stakeholder's capacity to influence decisions, processes, or project outcomes; (ii) legitimacy, understood as the perception that a stakeholder's actions or claims are appropriate and socially accepted within the project context; and (iii) urgency, referring to the degree to which stakeholder claims require immediate attention, based on their criticality and time sensitivity. The integration of these two approaches enabled a more robust mapping and prioritization process.

In the case study of Docks Dora in Turin, the analysis (see Sect. 3) identified the stakeholders most directly involved in and affected by the transformation process across the three alternative scenarios (Fig. 5).

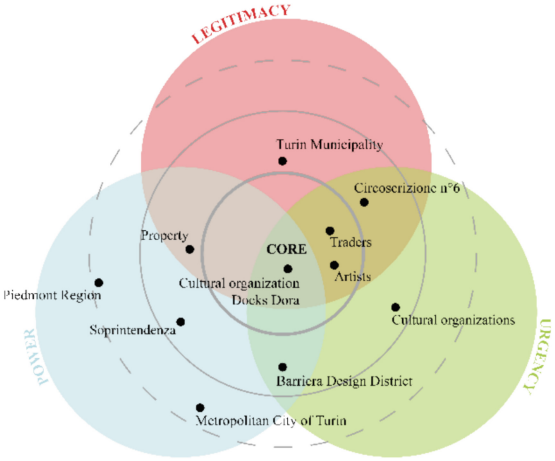


**Fig. 5.** Stakeholders mapping: Salience Model application. Source: authors' elaboration

This has led to the involvement of stakeholders of different types and backgrounds, since "research shows that how social value is understood and operationalized, is shaped by subjective interests, professional norms, and broader ideological positions" [31, p. 1]. The stakeholders involved are: users, comprising artists with studios within the complex as well as commercial operators (including restaurant and bar owners); the property owners; and the local government, encompassing the Municipality of Turin, Circoscrizione n°6, the Piedmont Region, and the Soprintendenza Archeologia Belle Arti e Paesaggio for Turin (Superintendency for Archaeology, Fine Arts and Landscape), given the site's protected status.

Tourists, who may access the site through private tours, and residents of the Borgata Montebianco subarea were excluded from the present analysis. This decision was made because these groups are not directly involved in the specific transformation process under examination and because the study focuses primarily on the individual asset rather than the broader territorial impacts. Moreover, both categories constitute large and internally heterogeneous groups whose systematic engagement would have required substantial financial and time resources. This constraint reflects one of the principal criticalities of the SROI methodology: "resources are not only monetary costs but also time of people, expertise of the practitioners, and the required information which is not always available (e.g., inexistent standardized indicators, or financial proxies)" [32, p. 4].

Table 2 highlights the stakeholders, the reasons for their inclusion and their characteristics in the Salience Model.

**Table 2.** Stakeholders included. Source: authors' elaboration.

| Stakeholders | Reasons for inclusion | Salience Model |
|---|---|---|
| Users | Those who will be most affected by the change | Legitimacy: ++<br>Urgency: +++<br>Power: + |
| Local Government | Those who make decisions and money | Legitimacy: ++<br>Urgency: +<br>Power: ++ |
| Property | Those who make decisions and money | Legitimacy: ++<br>Urgency: ++<br>Power: +++ |
| Cultural organizations | Those who actively operate in the area | Legitimacy: +<br>Urgency: +++<br>Power: + |

Once stakeholders had been identified, participants were engaged through a master's degree program at the Politecnico di Torino, informal semi-structured interviews, and a series of participatory workshops. The workshops, organized as discussion sessions involving artists, commercial tenants, property representatives, and local institutional actors, were designed to facilitate collective reflection on the expected effects of the regeneration process and to elicit shared and divergent perspectives [33].

Consistent with the SROI methodology, these activities enabled the systematic mapping of the outcomes that the various scenarios aim to achieve. The engagement process revealed that each identified outcome is relevant to multiple stakeholder clusters, indicating a shared interest in transforming the area under analysis despite the differing roles, expectations, and institutional positions of the actors involved.

The outcomes identified are: (i) limiting the phenomenon of gentrification; (ii) improvement in perceived safety; (iii) intensification of social relations; (iv) development of business activities; (v) improvement in the quality of educational provision; and (vi) permeability of the site.

Finally, as explained in the methodology section, specific indicators were defined for each outcome, along with corresponding financial proxies (Table 3). This stage is pivotal because it enables monetizing outcomes that are inherently qualitative. At the same time, it constitutes one of the principal methodological limitations of the approach. The absence of a universal standardized database of financial proxies limits comparability across studies and reduces the degree of international standardization of SROI applications [34, 35]. As a result, practitioners are often required to develop contextualized proxies grounded in their own assumptions, perceptions, and professional judgment [36–38] further argue that SROI analyses should place greater emphasis on including a control group (a group not affected by the intervention) to measure and compare outcomes at baseline, during implementation, and upon project completion, to ensure accurate attribution of effects. This issue could be further addressed through the Delphi method, which brings together a panel of experts to assess and refine project scenarios through structured consultation [39–42].

Furthermore, since many of the outcomes under consideration are intangible and not directly market-valued, identifying appropriate proxies is particularly complex. This often requires integrating complementary valuation techniques, such as contingent valuation methods or structured stakeholder surveys. In the case of perceived safety, for example, focus group-based data collection was used to estimate stakeholders' willingness to pay for improvements in safety, thereby assigning monetary values to the corresponding indicators. Another applicable approach is cost comparison, using the market value of a comparable activity as a proxy. This method was employed to calculate the indicators "Use of public spaces and gathering places" and "New activity courses". Table 3 presents the identified outcomes along with their respective indicators and financial proxies.

The final impact (the impact map) associated with a given benefit does not always correspond to the value derived from the financial proxy, as in some cases the latter may result in an overestimation. To mitigate this risk, four adjustment factors can be applied: (i) deadweight defined as the measure of the quantity of outcome that would have occurred even if the activity had not taken place; (ii) attribution, i.e., the evaluation of how much of the outcome comes from the contribution of other organizations or people; (iii) displacement, i.e., how much what is a benefit for a given group of stakeholders may have the opposite effect on another group of stakeholders; (iv) drop-off, i.e., the quantity of the outcome will likely decrease over time [43].

In the case study presented here, the deadweight factor was applied to the indicators "Housing price trends in the area", "Identification of elements of degradation", and "Increase in events during nighttime opening hours". The drop-off factor was applied to the indicators "Housing price trends in the area," "Use of public spaces and gathering places", "Opening of new businesses", "Number of people enrolled", and "Quantity and type of cultural events".

In this contribution, the specific adjustment percentages for each factor are not reported; they will be further developed and discussed in a future study.

**Table 3.** Identification of outcomes, indicators, and financial proxies. Source: authors' elaboration.

| Stakeholders | Outcome | Indicators | Financial proxy | Sources |
|---|---|---|---|---|
| Users, Cultural organizations | Limiting the phenomenon of gentrification | – Housing price trends in the area | – Market value (€/sqm) | – OMI data (Agenzia delle Entrate)<br>– OICT_ricerche |
| Users, Local Government | Improvement in perceived safety | – Identification of elements of degradation<br>– Number of complaints | – WTP | – Survey<br>– Municipality of Turin |
| Users, Cultural organizations | Intensification of social relations and inclusion | – Use of public spaces and gathering places<br>– Quantity of events | – Average household expenditure on recreational activities<br>– Opportunity cost | – ISTAT<br>– Municipality of Turin - Green Division, Parks and Animal Protection<br>– Survey |
| Users, Local Government, Property | Development of business activities | – New type of businesses<br>– New jobs | – Quantity of new business<br>– Average salary | – Chamber of Commerce of Turin/Industrial Union of Turin<br>– ISTAT |
| Local Government, Cultural organizations | Improvement in the quality of educational provision | – New activity courses<br>– Number of people enrolled<br>– New jobs | – Cost of private training courses<br>– Average household expenditure on educational activities<br>– Average salary | – ISTAT<br>– Barriera Design District (BDD) association data |

(*continued*)

**Table 3.** (*continued*)

| Stakeholders | Outcome | Indicators | Financial proxy | Sources |
|---|---|---|---|---|
| Users, Cultural organizations, Property | Promotion and growth of cultural activities | – Quantity and type of cultural events | – Average household expenditure on cultural activities | – Osservatorio Culturale del Piemonte (Cultural Observatory of Piedmont) - Barriera Design District (BDD) association data<br>– VivoIn dataset |
| Users, Cultural organizations, Local Government, Property | Permeability of the site | – Increase in events during nighttime opening hours | – WTP | – Survey |

## 5 Discussion, Further Research Developments and Conclusions

This contribution examines the methodological aspects involved in developing multidimensional evaluation tools for urban and building transformation processes. Specifically, the study focuses on selecting the case study and defining alternative scenarios, along with the sustainability criteria and indicators identified.

The analysis shows that integrating life cycle-based approaches (LCC and LCA) with tools designed to assess the social dimension (SROI) can provide a more comprehensive understanding of the impacts generated by urban transformation interventions. In this context, the AHP enables the integration of heterogeneous indicators and supports structuring the decision-making process by defining a weighting system for the different sustainability criteria.

Several methodological challenges arise, primarily due to the heterogeneity of the indicators adopted. This heterogeneity complexifies the comparability of results and the definition of shared units of measurement, particularly about the social dimension [44]. In this area, the definition of proxies used to monetize social benefits remains limitedly standardized, resulting in a certain level of subjectivity in evaluation procedures. By contrast, relatively consolidated methodological references exist for the economic and environmental components. Additional challenges arise from the operational complexity of integrating heterogeneous datasets, which can affect the replicability of the proposed models, the long timescales required for developing individual approaches, and the large number of stakeholders involved. Within this framework, the selection and structuring of the indicator system play a crucial role, as they directly influence the model's ability to consistently represent the different dimensions of sustainability. In this context, particular attention is given to the selection of indicators, the use of financial proxies within the SROI component, and the transferability of the framework to other contexts, which are

addressed consistently with the methodological scope of the study while acknowledging the need for context-specific adaptations.

Despite these challenges, integrating Life Cycle approaches, AHP, and SROI is particularly effective in supporting complex decision-making processes. By simultaneously considering the three dimensions of sustainability, the framework enables explicit consideration of trade-offs among competing project objectives and greater transparency in selecting alternative scenarios.

Based on these findings, several directions for future research can be identified. A first area concerns the operational application of the methodological framework to the selected case study through the calculation of the identified indicators and the implementation of the AHP, with the aim of validating the methodology and assessing its replicability. Moreover, the integrated framework proposed here (combining LCA, LCC, SROI, and AHP) remains relatively underexplored in the literature and has been applied only to a limited extent in this research field. In this perspective, integrating these tools may provide a valuable methodological contribution to addressing the growing complexity of project-related decisions, enabling a multidimensional, holistic assessment of urban and building transformation processes and facilitating comparisons of alternative scenarios.

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## References

1. Fregonara, E., Senatore, C., Coscia, C., Pasquino, F.: A holistic sustainability evaluation for heritage upcycling vs. building construction projects. Real Estate **2**(4), 17 (2025). https://doi.org/10.3390/realestate2040017
2. Coscia, C., Rubino, I.: Fostering new value chains and social impact-oriented strategies in urban regeneration processes: what challenges for the evaluation discipline?. In: Bevilacqua, C., Calabrò, F., Della Spina, L. (eds.) NMP 2020. SIST, vol. 178, pp. 983–992. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-48279-4_92
3. Opher, T., Friedler, E., Shapira, A.: Comparative life cycle sustainability assessment of urban water reuse at various centralization scales. Int. J. Life Cycle Assess. **24**, 1319–1332 (2019). https://doi.org/10.1007/s11367-018-1469-1
4. Valdivia, S., Ugaya, C.M.L., Hildenbrand, J., Traverso, M., Mazijn, B., Sonnemann, G.: A UNEP/SETAC approach towards a life cycle sustainability assessment—our contribution to Rio+20. Int. J. Life Cycle Assess. **18**, 1673–1685 (2013). https://doi.org/10.1007/s11367-012-0529-1
5. Thiebat, F.: Life Cycle Design: An Experimental Tool for Designers. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-11497-8
6. Saaty, T.L.: The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation. McGraw-Hill, Columbus (1980)
7. Piano Regolatore Generale di Torino. http://www.torinofacile.it/esturbgw/swhttpesturbgewerNew.do. Accessed 04 Mar 2026

8. Curto, R., Fregonara, E.: Monitoring and analysis of the real estate market in a social perspective: results from the Turin's (Italy) experience. Sustainability **11**(11), 3150 (2019). https://doi.org/10.3390/su11113150
9. Coscia, C., Fregonara E., Rolando, D.: Project management, briefing and territorial planning. The case of military properties disposal. TERRITORIO **73**, 135–144 (2015). https://doi.org/10.3280/TR2015-073020
10. Magnaghi, A., Tosoni, P.: La città smentita. Torino: ricerca tipologica in ambiti urbani di interesse storico. Cortina, Torino (1996)
11. ISTAT data. https://esploradati.istat.it/databrowser/#/it/dw/categories. Accessed 21 Feb 2026
12. Annuario Statistico Città di Torino. https://www.comune.torino.it/media/8351. Accessed 19 Feb 2026
13. PN METRO plus e città medie Sud 2021-2027 - Piano Operativo Città di Torino. https://www.comune.torino.it/media/7579. Accessed 01 Mar 2026
14. INFRA.TO Infrastrutture per la mobilità. https://infrato.it/linea-2/. Accessed 01 Mar 2026
15. Geoportale Regione Piemonte. https://www.geoportale.piemonte.it/geonetwork/srv/api/records/c_l219:ab400347-2c50-4573-a3a2-15e18ef4253c. Accessed 28 Feb 2026
16. Vanclay, F.: Conceptualising social impacts. Environ. Impact Assess. Rev. **2**(3), 183–211 (2002). https://doi.org/10.1016/s0195-9255(01)00105-6
17. UNEP: Guidelines for social life cycle assessment of products and organization 2020. United Nations Environment Programme (UNEP) (2020). https://www.lifecycleinitiative.org/wp-content/uploads/2021/12/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2021-ITA.pdf. Accessed 7 Feb 2026
18. ISO 15686-5:2017; Buildings and Constructed Assets Service Life Planning—Part 5: Life-Cycle Costing. ISO: Geneva, Switzerland (2017). https://www.iso.org/standard/61148.html. Accessed 22 Jan 2026
19. Boussabaine, H., Kirkham, R.: Whole Life-Cycle Costing: Risk and Risk Responses. Blackwell Publishing Ltd. (2004). https://doi.org/10.1002/9780470759172
20. Langdon, D.: Life Cycle Costing (LCC) as a Contribution to Sustainable Construction: A Common Methodology—Final Methodology. https://www.tmb.org.tr/uploads/publications/6065d0814e2c483e72ff9009/1617285248294-lccdraft-methodology.pdf. Accessed 10 Feb 2026
21. Fregonara, E., Ferrando, D.G.: The discount rate in the evaluation of project economic-environmental sustainability. Sustainability **15**(3), 2467 (2023). https://doi.org/10.3390/su15032467
22. EEAGlossary: European Union (2024). http://glossary.eea.europa.eu/EEAGlossary. Accessed 02 Feb 2026
23. UNI EN ISO 14044:2021: Gestione ambientale - Valutazione del ciclo di vita - Requisiti e linee guida. https://store.uni.com/uni-en-iso-14044-2021. Accessed 10 Feb 2026
24. UNI EN ISO 14040:2006: Gestione ambientale - Valutazione del ciclo di vita - Principi e quadro di riferimento. https://store.uni.com/uni-en-iso-14040-2006. Accessed 10 Mar 2026
25. UNI EN ISO 14001:2015: Sistemi di gestione ambientale - Requisiti e guida per l'uso. https://store.uni.com/uni-en-iso-14001-2015. Accessed 10 Mar 2026
26. European Committee for Standardization (CEN). Standard EN ISO 16627: 2015. Sustainability of Construction Works—Assessment of Economic Performance of Buildings—Calculation Methods; European Committee for Standardization: Brussels, Belgium (2015). https://standards.iteh.ai/catalog/standards/cen/873a2524-808c-4843-b1db-35520c48146a/en-16627-2015?srsltid=AfmBOooD2bBHk0lONDwRaoLKtS-u13oyJTxqJ9QcUAd-lHjzsad4PTFH. Accessed 10 Mar 2026
27. Nicholls, J., Lawlor, E., Neitzert, E., Goodspeed, T.: A Guide to Social Return on Investment (SROI) (Revised), socialvalueselfassessmenttool.org. Accessed 29 Jan 2026

28. Klein, C.: The scientific discussion of stakeholder involvement in social return on investment analysis? A systematic literature review. Eval. Program Plann. (2025). https://doi.org/10.1016/j.evalprogplan.2025.102678
29. Coscia, C., Gron, S., Vercellino, E.: Decision-making CIA process (DeMaCIA) to support SNAI strategies: the case of Castelluccio Inferiore in Basilicata, Italy. In: Gervasi, O., et al. (eds.) ICCSA 2025. LNCS, vol. 15889, pp. 250–267. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97603-2_16
30. Mitchell, R., Bradley, A., Wood, D.: Toward a theory of stakeholder identification and salience: defining the principle of who and what really counts. Acad. Manag. Rev. **22**(4), 853–886 (1997). https://doi.org/10.2307/259247
31. Kady, N.: What happens afterwards? Navigating social value in a fragmented property-led planning landscape—a systematic literature review. J. Plan. Lit. (2026). https://doi.org/10.1177/08854122251410185
32. Maldonado, M., Corbey, M.: Social return on investment (SROI): a review of the technique. Manag. Account. **90**, 79–86 (2016). https://doi.org/10.5117/mab.90.31266
33. Coscia, C., Gron, S., Primavera, A., Viotto, I.: Tra spazio e rigenerazione. Percorsi di ricerca, strategie, pratiche per la trasformazione urbana di un quartiere ex industriale: borgata Montebianco a Torino. Maggioli Editore, Santarcangelo di Romagna (2025)
34. Nielsen, J.G., Lueg, R., Van Liempd, D.: Challenges and boundaries in implementing social return on investment: an inquiry into its situational appropriateness. Nonprofit Manag. Leadersh. **31**, 413–435 (2021). https://doi.org/10.1002/nml.21439
35. Vasiliu, E.-E., Torabi Moghadam, S., Bisello, A., Lombardi, P.: Visionary nature-based solutions evaluated through social return on investment: the case study of an Italian urban green space. Smart Cities **7**(2), 946–972 (2024). https://doi.org/10.3390/smartcities7020040
36. Maier, F., Schober, C., Simsa, R., Millner, R.: SROI as a method for evaluation research: understanding merits and limitations. Voluntas Int. J. Volunt. Nonprofit Organ. **26**, 1805–1830 (2015). https://doi.org/10.1007/s11266-014-9490-x
37. Pathak, P., Dattani, P.: Social return on investment: three technical challenges. Soc. Enterp. J. **10**, 91–104 (2014). https://doi.org/10.1108/SEJ-06-2012-0019
38. Krlev, G., Münscher, R., Mülbert, K.: Social return on investment (SROI): state-of-the-art and perspectives - a meta-analysis of practice in social return on investment (SROI) studies published 2002-2012. Centre for Social Investment, Heidelberg University (2013)
39. Kim, D.-J., Ji, Y.-S.: The evaluation model on an application of SROI for sustainable social enterprises. J. Open Innov. Technol. Mark. Complex. **6**(1), 7 (2020). https://doi.org/10.3390/joitmc6010007
40. Nieto, I., Mayo, X., Davies, L., Reece, L.J., Strafford, B., Jimenez, A.: Toward an international consensus on a social return on investment model of recreational physical activity and sport participation: a Delphi study. J. Phys. Act. Health **22**, 1–19 (2026). https://doi.org/10.1123/jpah.2025-0362
41. Fregonara, E., Coscia, C.: Multi criteria analyses, life cycle approaches and Delphi method: a methodological proposal to assess design scenarios. Valori e Valutazioni **23**, 107–117 (2019)
42. Coscia, C., Dalpiaz, P.E., Giacopelli, E., Infortuna, G.M.: The case of the Unità Residenziale Est - Ex-Hotel La Serra. The Delphi Method to support intervention scenarios to "re-Type" the City of Ivrea. Valori e Valutazioni **22** (2019)
43. Solórzano-García, M., Navío-Marco, J., Ruiz-Gómez, L.M.: Ambiguity in the attribution of social impact: a study of the difficulties of calculating filter coefficients in the SROI method. Sustainability **11**, 386 (2019). https://doi.org/10.3390/su11020386
44. Gutiérrez-Nieto, B., Camón-Cala, J., Cuéllar-Fernández, B., et al.: A bibliometric analysis of the social return on investment. Humanit. Soc. Sci. Commun. **12**, 1189 (2025). https://doi.org/10.1057/s41599-025-05529-w

# Balancing Sustainability and Performance: A Multi-criteria Comparison of Recycled, Bio-Based and Low-Carbon Materials Using the Analytic Hierarchy Process (AHP)

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**Abstract.** Material selection in engineering and manufacturing increasingly requires balancing technical performance, economic feasibility and environmental sustainability. This paper presents a structured multi-criteria decision-making (MCDM) framework based on the AHP to compare three broad classes of materials: Recycled (A), Bio-based (B), and Low-carbon virgin (C). Each representing a family of real-world alternatives that share a defining sourcing or production characteristic. Five key criteria are considered: carbon footprint, availability, cost, technical performance and circularity. Baseline input values are drawn from established life-cycle assessment databases and published industry benchmarks, and are intended to represent typical class-level performance. Raw indicator values are transformed into benefit scores, used to construct consistent pairwise comparison matrices, and aggregated into global priority scores. Results show recycled materials ranking highest under balanced baseline weights, while sensitivity analysis reveals critical trade-offs when environmental or technical priorities dominate. The proposed framework offers repeatability and clear managerial guidance for sustainable procurement decisions, and is designed to be parameterised as organisation-specific data become available.

**Keywords:** Sustainable material selection · Analytic Hierarchy Process · Circularity

## 1 Introduction

Material selection is a critical activity in engineering and manufacturing, as it directly influences product performance, cost structure, supply-chain resilience, regulatory compliance and environmental footprint. Traditional approaches, such

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as Ashby charts (Fig. 1) and performance indices [2], excel at trading off mechanical, thermal and chemical properties but often overlook sustainability and circular economy dimensions [30].

The growing demand for low-impact materials has highlighted the need for integrated decision-support tools, capable of handling quantitative indicators (e.g. life-cycle emissions, cost) and qualitative aspects (e.g. supply reliability, strategic alignment). MCDM methods, particularly the AHP, have proven effective in reconciling such objectives [6,42].

Despite increasing emphasis on the circular economy, organizations face difficulty comparing heterogeneous material alternatives that differ in economic, environmental, and operational attributes. Existing evaluation approaches address these dimensions separately, limiting consistent decision-making.

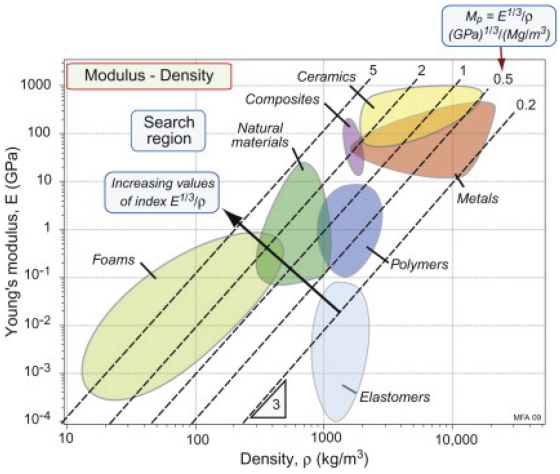


**Fig. 1.** Distribution of material classes plotted by Young's modulus ($E$) versus density ($\rho$) [2].

Consequently, there is a need for a framework capable of integrating quantitative and qualitative criteria to support robust comparison. This study addresses the following research question: How can heterogeneous material alternatives be quantitatively and qualitatively compared within a unified decision-support framework that supports circular economy objectives?

This study aims to develop a decision-support framework to compare recycled, bio-based, and low-carbon virgin materials. The primary objective is to demonstrate an AHP-based template for ranking material alternatives across sustainability, economic, and technical criteria, with a sensitivity analysis to assess its robustness.

## 2 Literature Review

Engineering material selection has relied on tools such as Ashby-type charts and performance indices, which trade off properties including mechanical strength, thermal behaviour, and chemical resistance [30]. More recent sustainability-oriented extensions of these approaches have begun to incorporate life-cycle assessment (LCA) indicators, such as recyclability, allowing environmental performance to be considered alongside traditional criteria [1,29].

Among multi-criteria decision-making methods applied to materials, the AHP continues to enjoy widespread use thanks to its hierarchical structure, its capacity to handle both qualitative and quantitative criteria, and its built-in mechanism for checking the consistency of judgments [42]. While other techniques, such as TOPSIS, VIKOR, and PROMETHEE, are employed for final ranking tasks, AHP is particularly valued for its ability to derive consistent criteria weights directly from expert judgments or quantitative indicators [6] (Fig. 2).

In the context of the circular economy, material strategies emphasise high reuse, recycling, and recovery rates. Contemporary decision-support models therefore tend to integrate data from established LCA databases (Ecoinvent, GaBi) and regional trade statistics, creating real-world evaluation frameworks [16].

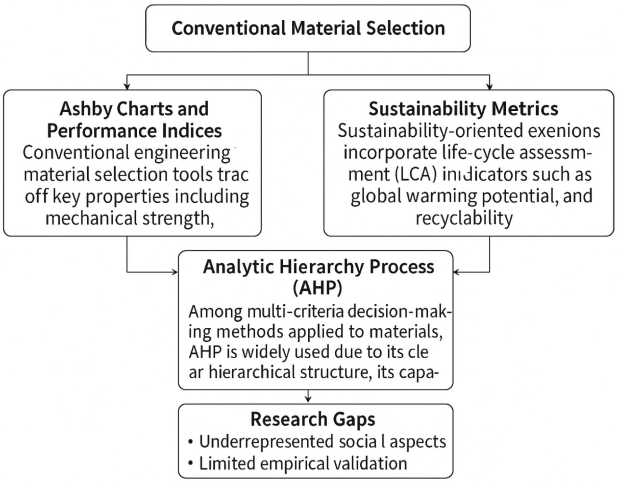


**Fig. 2.** Conceptual framework linking conventional material selection, sustainability metrics, and AHP.

Despite advancements in integrating sustainability methods, such as LCA and MCDM, into material selection processes, several critical research gaps remain in the literature. Many studies focus predominantly on environmental

and economic dimensions while underrepresenting social aspects (e.g., labor conditions and community impacts) within circular economy frameworks for engineering materials [3,36].

Additionally, although hybrid MCDM approaches address uncertainty criteria, there is limited empirical validation of these models in real-world, sustainable procurement scenarios that incorporate regional material availability and comprehensive circularity indicators [28,37].

Persistent methodological challenges and insufficient integration of normalized mechanisms for comparable evaluations across diverse material types, highlight the need for more robust and practically oriented frameworks that bridge these limitations to support consistent decision-making in pursuing circular material strategies [27,37].

### 2.1 Research Hypotheses

The following hypotheses guide the development of the framework:

- **H1:** Defining clear material alternatives enhances consistency in MCDM judgements [13].
- **H2:** Integrating quantitative life-cycle indicators with qualitative expert inputs yields more robust prioritization [43].
- **H3:** Normalised indicators and ratio-based pairwise comparisons enable comparability across heterogeneous materials [25,42].

The research hypotheses are formulated to address persistent gaps in the existing literature on sustainable material selection within circular economy contexts. While recent advancements have expanded MCDM applications, particularly through hybrid methods (e.g., fuzzy AHP-TOPSIS), to better incorporate uncertainty, many studies still prioritize economic criteria at the expense of integrated social dimensions, comprehensive circularity metrics, and practical validation [36,37].

Moreover, methodological limitations such as rank reversal in TOPSIS, subjectivity in weighting, and insufficient emphasis on normalized mechanisms for cross-material comparability hinder the development of adaptive frameworks that can support decision-making across engineering applications [3,27]. By testing H1 through enhanced alternative definition, H2 via balanced quantitative-qualitative integration, and H3 with improved normalization techniques, the proposed framework aims to bridge these gaps, contributing to more holistic MCDM tools aligned with circular economy goals.

## 3 Methodology

### 3.1 Material Alternatives and Evaluation Criteria

Three classes of materials are evaluated in Table 1. Each class is defined as a category of alternatives, representing a family of real-world materials that share a

defining sourcing or production characteristic. Recycled materials (A) encompass secondary-stream inputs such as recycled aluminium and post-consumer plastics; bio-based materials (B) include plant-derived and agricultural by-product inputs; and low-carbon virgin materials (C) refer to primary materials produced through low-emission processes, including hydrogen-based steels. The class-level framing is intentional, enabling procurement decision-makers to screen strategic material categories, and aligns with how sustainability strategies are formulated at the portfolio level [32].

**Table 1.** Classification of materials by source and carbon intensity.

| Class of Materials | Explanation | Examples |
|---|---|---|
| Recycled materials (A) | Obtained from secondary raw materials, recovered from waste streams. | Recycled aluminium; post-consumer recycled plastics |
| Bio-based materials (B) | Derived from renewable biomass such as plants or agricultural by-products. Reduce dependence on fossil inputs and may be biodegradable. | PLA; natural-fibre composites |
| Low-carbon virgin materials (C) | Primary materials produced via low-emission processes. Incorporate renewable energy, electrification, or hydrogen. | Low-emission steel; green aluminium |

The comparison is structured around five key criteria, with the direction of preference and data sources summarised in Table 2. Data are drawn from LCA databases (Ecoinvent [9], GaBi [14]), industry cost benchmarks [21], and circularity certification frameworks [38].

**Table 2.** Main criteria, preference direction and data sources

| Criterion | Preference | Example data sources |
|---|---|---|
| Carbon footprint | lower better | LCA (kg $CO_2$e/kg) |
| Availability | higher better | % local/reliable supply |
| Cost | lower better | \$/kg (CAPEX + OPEX) |
| Technical performance | higher better | normalised index (0–1) |
| Circularity | higher better | % recyclable/recoverable |

### 3.2 AHP Framework

Figure 3 illustrates the fundamental steps and mathematical structure of the AHP applied in this study. The diagram presents the hierarchical decomposi-

tion of the decision problem into goal, criteria, and alternatives, alongside the corresponding pairwise comparison matrices.

The calculation of the priority vector as the normalized principal eigenvector of the comparison matrix is shown, as well as the evaluation of judgment consistency through the consistency ratio (CR). This representation clarifies the workflow from qualitative judgments to quantitative priority weights, providing a foundation for the multi-criteria evaluation of circular material alternatives.

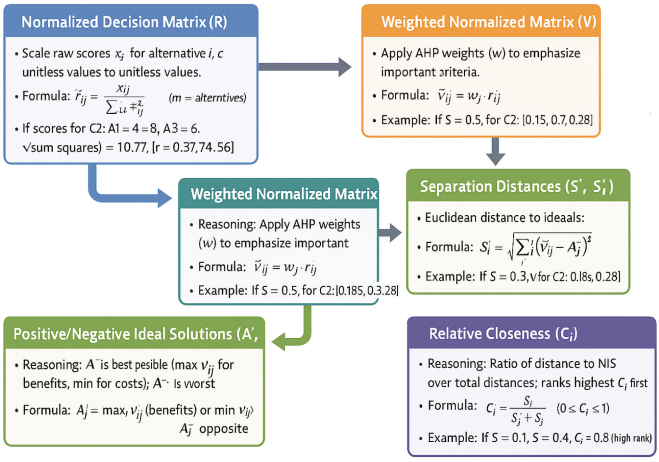


**Fig. 3.** Mathematical structure of the AHP

### 3.3 AHP Procedure

The AHP procedure consists of five steps (Fig. 4). Raw values are first transformed into benefit scores: the raw value is used directly for higher-better criteria (*Availability, Technical performance, Circularity*), while the reciprocal (benefit = inverse of raw value) is applied for lower-better criteria (*Carbon footprint, Cost*).

Each benefit vector is then normalised to obtain local priorities. Pairwise comparison matrices are constructed using ratios of benefit scores ($a_{ij} = b_i/b_j$), resulting in consistent matrices by design. Global priorities ($G_k$) are computed as the weighted sum of local priorities:

$$G_k = \sum_{j=1}^{5} w_j \cdot p_{k,j}, \tag{1}$$

where $w_j$ is the criterion weight and $p_{k,j}$ is the local priority of alternative $k$ on criterion $j$. Finally, sensitivity analysis is performed by varying criterion weights to assess ranking stability.

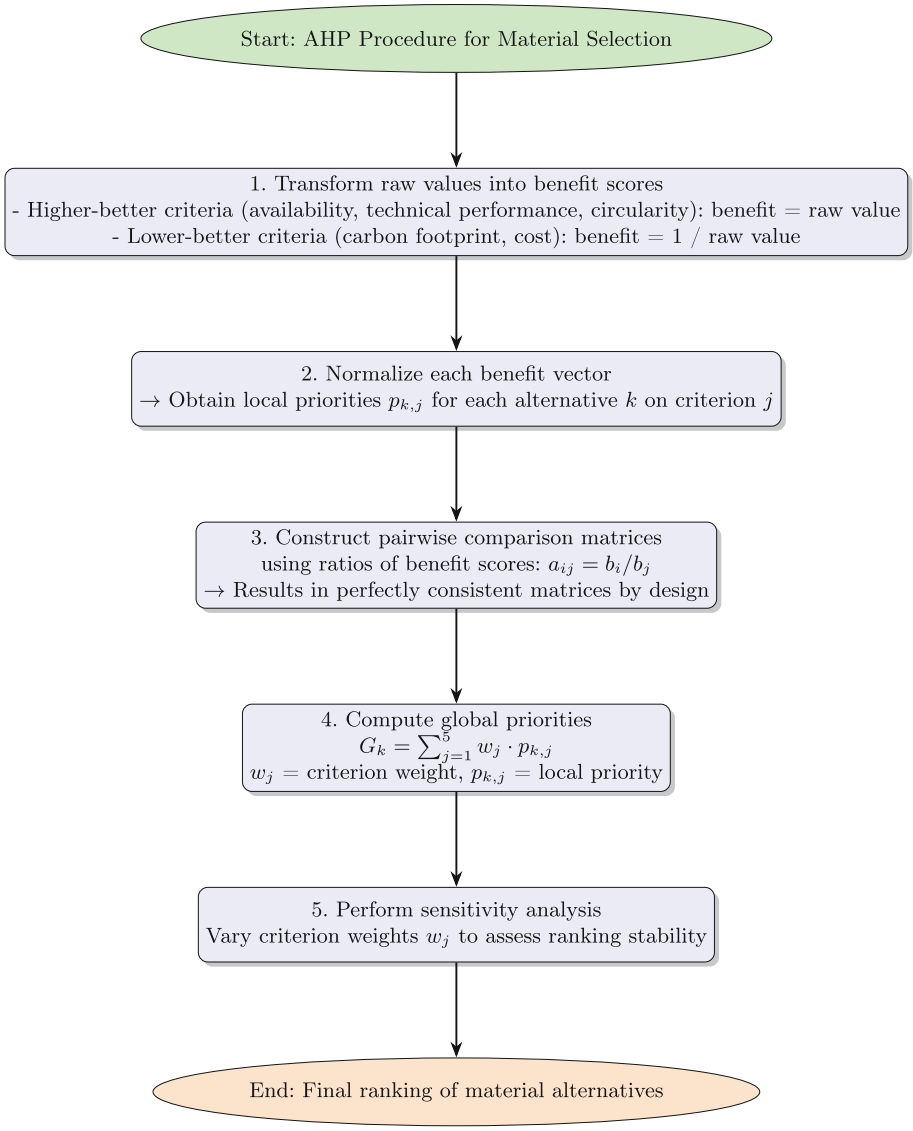


**Fig. 4.** Flowchart of the adapted AHP procedure.

## 4 Quantitative Model and Results

### 4.1 Selection of Baseline Input Values

The analysis uses raw performance values for the three material alternatives: Recycled (A); Bio-based (B), and Low-carbon virgin (C). Table 3 reports class-representative values aligned with LCA databases. Carbon footprints are

2.0kg,$CO_2$e/kg (recycled), 3.5kg,$CO_2$e/kg (bio-based), and 1.5kg,$CO_2$e/kg (low-carbon virgin), consistent with Ecoinvent and GaBi ranges for secondary aluminium/plastics, PLA biopolymers, and hydrogen or renewable-electricity-based primary production [9,14].

Recycled aluminium typically ranges from 0.5–3.0kg, $CO_2$e/kg, making 2.0kg, $CO_2$e/kg a reasonable mid-range value. The 1.5kg,$CO_2$e/kg low-carbon virgin estimate aligns with emerging routes such as Hybrit, whose near-zero pilot results support a broader 1.0–2.0kg,$CO_2$e/kg range [19,33]. Availability scores (60%, 40%, 30% for A–C) reflect EU procurement and secondary market evidence. Recycled materials benefit from mature collection systems; bio-based supply is limited by seasonality and processing capacity; low-carbon virgin depends on early-stage hydrogen and carbon capture infrastructure [5,39].

Cost benchmarks (2.5, 3.0, 4.0 $/kg for A–C) reflect industry surveys showing secondary materials' cost advantage and packaging [5,26]. Technical scores (0.7, 0.6, 0.8) capture performance: low-carbon virgin aligns with virgin specs; bio-based is limited in strength [22,35]. Circularity (85%, 60%, 50%) reflects recovery rates from certification frameworks [38]. Criterion weights (Carbon: 0.30; Cost: 0.25; Technical: 0.20; Availability: 0.15; Circularity: 0.10) define a balanced baseline where no criterion dominates. This reflects multi-stakeholder settings prioritising cost and emissions, and serves as a reference for sensitivity analysis. The baseline criterion weights, which sum to 1.00, are as follows: *Carbon footprint* is assigned a weight of 0.30, *Cost* 0.25, *Technical performance* 0.20, *Availability* 0.15, and *Circularity* 0.10. To enable consistent comparison across criteria with different directions of preference, the raw values are first transformed into benefit scores.

**Table 3.** Baseline raw values and preference direction for each criterion

| Criterion | Unit | Recycled (A) | Bio-based (B) | Low-carbon virgin (C) |
|---|---|---|---|---|
| Carbon footprint | kg $CO_2$e/kg | 2.0 | 3.5 | 1.5 |
| Availability | % local | 60 | 40 | 30 |
| Cost | $/kg | 2.5 | 3.0 | 4.0 |
| Technical performance | index (0–1) | 0.7 | 0.6 | 0.8 |
| Circularity | % recyclable | 85 | 60 | 50 |

For criteria where lower values are preferred (*Carbon footprint* and *Cost*), the benefit score is computed as the reciprocal of the raw value. For criteria where higher values are preferred (*Availability*, *Technical performance*, and *Circularity*), the benefit score is set equal to the raw value itself. The resulting approximate benefit scores after transformation are presented in the Table 4. These benefit values are then normalised within each criterion by dividing each individual benefit score by the sum of the benefit scores for that criterion, yielding

local priority weights that reflect the relative attractiveness of each alternative with respect to the specific criterion.

**Table 4.** Benefit scores for each criterion and alternative

| Criterion | A (Recycled) | B (Bio-based) | C (Low-carbon virgin) |
|---|---|---|---|
| Carbon footprint | 0.50 | $\approx 0.286$ | $\approx 0.667$ |
| Availability | 60 | 40 | 30 |
| Cost | 0.40 | $\approx 0.333$ | 0.25 |
| Technical performance | 0.7 | 0.6 | 0.8 |
| Circularity | 85 | 60 | 50 |

Under the baseline weights, the resulting global priority scores are approximately 0.385 for Recycled materials (A), 0.338 for Low-carbon virgin materials (C), and 0.278 for Bio-based materials (B). This yields a clear ranking of A > C > B. Recycled materials (A) achieve the highest overall priority primarily due to their strong performance in *Availability*, *Cost competitiveness*, and *Circularity*, even though they do not lead in direct carbon reduction or technical performance index.

### 4.2 Sensitivity and Robustness Analysis

Sensitivity analysis indicates that the ranking structure is primarily driven by the relative weight allocation between *Carbon footprint*, *Technical performance*, and the jointly reinforcing operational criteria (*Cost* and *Availability*). The model exhibits a non-linear response to changes in environmental prioritisation.

A sensitivity analysis on the *Carbon footprint* weight reveals a switching point at $w_{CO_2} \approx 0.50$, beyond which Low-carbon virgin materials (C) overtake Recycled materials (A) in priority. This threshold is not symmetric: reductions in $w_{CO_2}$ below the baseline (0.30) strengthen the dominance of A only marginally, while increases above the threshold induce a rank reversal, reflecting the convex structure of the weighted aggregation.

A one-way sensitivity analysis on *Technical performance* shows a weaker but consistent effect. Even when the weight of this criterion is increased up to 0.40 (double its baseline value), Low-carbon virgin materials (C) narrow the gap with A but do not overtake it unless accompanied by a increase in environmental weight. This indicates that technical superiority alone is insufficient to compensate for the cost–availability disadvantage of C under current parametrisation.

To formalise interaction effects, a two-dimensional sensitivity region analysis was conducted over $(w_{CO_2}, w_{TP})$ while rescaling remaining weights proportionally. The results define three stable regions:

- **Region I (Operational dominance)**: A remains optimal when $w_{CO_2} < 0.45$ and $w_{TP} < 0.35$. This region reflects procurement regimes dominated by cost efficiency, supply security, and circularity objectives.

- **Region II (Transitional regime)**: C becomes competitive but not dominant when $0.45 \leq w_{CO_2} \leq 0.55$, provided $w_{TP} \leq 0.35$. In this region, ranking inversion is sensitive and small perturbations in weights can lead to rank reversal between A and C.
- **Region III (Decarbonisation dominance)**: C dominates when $w_{CO_2} > 0.50$ jointly with $w_{TP} \geq 0.30$, reflecting policy-driven procurement settings with binding emissions constraints.

Across all configurations, Bio-based materials (B) remain rank-stable in third position. This result is robust even to extreme weight scenarios, indicating structural inferiority under industrial performance parameters rather than sensitivity to weighting assumptions.

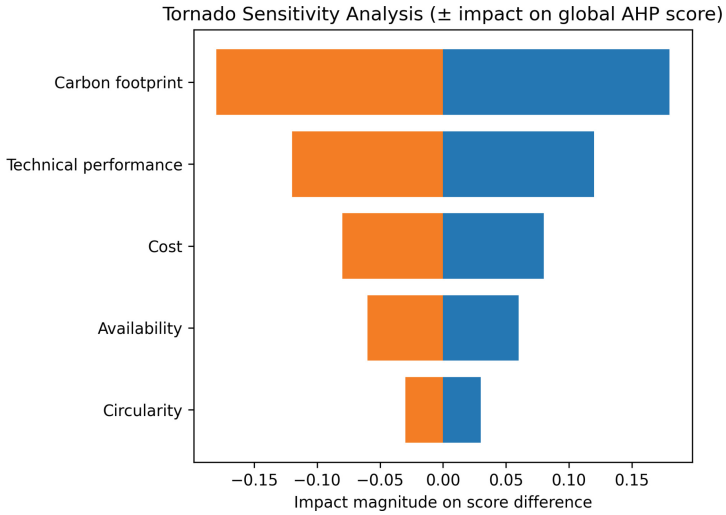


**Fig. 5.** Tornado sensitivity analysis of global AHP scores under ±10% variation in criterion weights. Bars represent the impact range of each criterion on the global priority difference between alternatives. Criteria are ordered by decreasing influence on ranking stability.

The tornado diagram in Fig. 5 provides a one-way sensitivity decomposition of the AHP-based global priority scores under bounded perturbations of ±10% in each criterion weight. The analysis quantifies the marginal effect of each criterion on the stability of the ranking structure A $\succ$ C $\succ$ B.

The results show that the *Carbon footprint* is the main sensitivity driver, generating the largest score variation between Recycled (A) and Low-carbon virgin (C). This confirms that environmental weighting drives rank reversals, consistent with the identified switching threshold at $w_{CO_2} \approx 0.50$. Increasing the carbon weight favors C, while decreasing it reinforces the dominance of A.

*Technical performance* is the second most influential criterion. Its effect is asymmetric: higher weights improve C's position but do not overturn the baseline

ranking without stronger carbon emphasis, indicating a complementary rather than substitutive role.

By contrast, *Cost* and *Availability* stabilise the ranking. Changes in their weights consistently reinforce the dominance of Recycled materials (A), reflecting their strong performance on both criteria and anchoring the ranking against environmental reweighting.

Finally, *Circularity* shows the lowest marginal impact among all criteria. While it contributes positively to the score of Recycled materials, its limited dispersion across alternatives results in low leverage over ranking outcomes. This suggests that circularity, as operationalised in the present model, functions primarily as a secondary reinforcing criterion rather than a decisive differentiator.

The tornado analysis confirms that the decision model exhibits a structured sensitivity hierarchy, with environmental and technical criteria acting as primary volatility drivers, and economic and logistical criteria acting as stabilising forces. This asymmetric sensitivity structure explains the observed robustness of Recycled materials (A) under most weight perturbations, while simultaneously highlighting the conditional dominance of Low-carbon virgin materials (C) under carbon-intensive policy regimes.

### 4.3 Discussion and Managerial Implications

The results underscore a trade-off that decision-makers in procurement and circularity must carefully manage. Recycled materials (A) demonstrate clear advantages in operational efficiency, supply-chain resilience, and circularity metrics, consistent with prior studies emphasizing the energy and material savings associated with secondary raw material loops [15,23]. These materials reduce dependence on primary extraction, lowering both environmental impact and exposure to raw-material price volatility.

Empirical evidence from industrial practice reinforces these findings. In the steel sector, Electric Arc Furnace (EAF) production based on scrap inputs has been shown to reduce energy consumption by approximately 60–75% and $CO_2$ emissions by 70–90% relative to blast furnace routes [26]. Similarly, in aluminium production (e.g., Hydro's recycling operations in Europe [18], secondary aluminium exhibits energy savings of up to 95% compared to primary smelting, significantly improving both cost efficiency. In the construction sector, recycled aggregates in road sub-bases have been documented in Dutch infrastructure projects to replace up to 30–50% of virgin aggregates without compromising structural performance [12] (Table 5. Strategic recommendations therefore depend on the organisation's primary objectives:

1. Choose Recycled (A) when supply-chain robustness and circular economy alignment represent strategic priorities. This is relevant in metals, packaging, and construction materials sectors, where industrial evidence shows cost reductions of 10–25% and volatility hedging benefits in input markets.
2. Choose Low-carbon virgin (C) when regulatory carbon-reduction targets are non-negotiable; in such cases, the combined weight of Carbon footprint and

**Table 5.** Synthesis of material classes with empirical industrial evidence and observed trade-offs across sectors.

| Material Class | Industrial Evidence | Trade-offs |
|---|---|---|
| Recycled (A) | Steel [20]: 60–75% energy reduction and 70–90% $CO_2$ reduction vs. BF route; Aluminium recycling: up to 95% energy savings; Construction aggregates: 30–50% substitution in infrastructure projects [7,8,11,12]. | Quality variability in feedstock; dependency on collection systems; limited suitability for high-spec aerospace-grade applications |
| Low-carbon virgin (C) | Hybrit steel: 90–95% $CO_2$ reduction [19]; CCS cement: 80–90% reduction potential [31]; Renewable-powered aluminium: ∼75% lower footprint vs. global average production [18]. | High CAPEX and infrastructure dependence (hydrogen/renewables); limited scalability in short term; residual reliance on virgin extraction |
| Bio-based (B) | PLA bioplastics: limited composting infrastructure coverage (<30%) [8]; Bio-composites in automotive interiors: 10–15% weight reduction but hybrid reinforcement required [41]; packaging pilots in FMCG sector [12]. | Mechanical performance constraints; higher unit cost and supply instability; end-of-life treatment limitations; need for hybridisation with synthetic materials |

Technical performance should exceed approximately 60% of the total weighting to shift the ranking in C's favour. This reflects observed adoption patterns in steel and aerospace supply chains, where compliance requirements dominate procurement decisions.

3. Bio-based materials (B) should be considered only after development efforts have demonstrably improved their performance on cost and availability. Current evidence suggests their optimal use is limited to packaging and consumer goods unless supported by subsidies or technological breakthroughs in biorefining and composite engineering.

A novelty of the present work lies in the application of a ratio-based AHP structure to circular-economy procurement decisions. By constructing consistent pairwise comparison matrices directly from transformed benefit scores, the approach provides a fully quantifiable risk assessment for a multi-faceted sourcing choice. This is consistent with decision-support frameworks adopted in consulting practice [5,26], where multi-criteria scoring systems are increasingly used to map material substitution pathways under carbon and supply constraints.

## 5 Conclusions and Future Work

The AHP-based framework developed in this study offers a structured and replicate method for comparing heterogeneous sustainable material alternatives under environmental, technical, and economic objectives. Under balanced baseline weights, Recycled materials (A) provide the most attractive compromise.

However, when environmental performance, particularly greenhouse-gas reduction, is assigned substantially higher priority, Low-carbon virgin materials (C) emerge as the best choice.

Moreover, methodological limitations such as rank reversal in TOPSIS and subjectivity in weighting, ratio-based mechanisms for cross-material comparability hinder the development of robust, adaptive frameworks capable of supporting decision-making across diverse management and engineering applications [3,27]. By testing H1 with a stronger definition, H2 with a better mix of quantitative and qualitative methods, and H3 with improved comparison, the framework fills gaps and supports more reliable MCDM tools for circular economy goals.

Several directions for future refinement are proposed. These include implementing dynamic weighting mechanisms to better reflect evolving regulatory pressures and technology maturity curves; integrating full Life Cycle Costing into the cost criterion to account for end-of-life management expenses from secondary material recovery; extending the model to handle uncertainty using fuzzy AHP or Monte Carlo simulation of weights; and conducting validation through procurement case studies, thereby strengthening confidence in the framework's practical utility.

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## References

1. Anelli, D., Ranieri, R.: Resilience of complex urban systems: a multicriteria methodology for the construction of an assessment index. In: International Symposium: New Metropolitan Perspectives, pp. 690–701. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-06825-6_65
2. Ashby, M.F.: Materials Selection in Mechanical Design, 4th edn. Butterworth-Heinemann, Oxford, UK (2011). ISBN: 978-1-85617-663-7
3. Bajwa, A.U.R., Siriwardana, C., Shahzad, W.M., Naeem, M.A.: Material selection in the construction industry: a systematic literature review on multi-criteria decision making. Environ. Syst. Decis. **45**(1), 8 (2025). https://doi.org/10.1007/s10669-025-10001-w
4. Balali, A., Hakimelahi, A., Jahangiri, M.H.: Multi-criteria ranking of green materials according to the goals of sustainable development. Sustainability **12**(22), 948 (2020). https://doi.org/10.3390/su12229482
5. Feth, M., Healy, G., Polunin, K., von Szczepanski, K., Van Der Weck, M.: A Faster Path to Sustainability in the Materials and Process Industries. Boston Consulting Group (BCG) (2023). https://www.bcg.com/publications/2023/path-to-sustainability-in-materials-process-industries
6. Bhaskar, A.S., Khan, M.A.: Comparative analysis of hybrid MCDM methods in material selection for dental applications. Expert Syst. Appl. **209**, 11826 (2022). https://doi.org/10.1016/j.eswa.2022.118268

7. Høibye, L., Sand, H.: Circular Economy in the Nordic Construction Sector: Identification and Assessment of Potential Policy Instruments. Nordic Council of Ministers, TemaNord 2018:517 (2018). https://norden.diva-portal.org/smash/get/diva2:1188884/FULLTEXT01.pdf
8. European Commission. A European Strategy for Plastics in a Circular Economy. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, COM(2018) 28 final, Brussels, 16 January 2018 (2018). https://www.europarl.europa.eu/RegData/docs_autres_institutions/commission_europeenne/com/2018/0028/COM_COM(2018)0028_EN.pdf
9. Ecoinvent Association. Ecoinvent Database, version 3.x. Zürich, Switzerland (2025). https://ecoinvent.org/
10. European Environment Agency (EEA). Resource Efficiency and the Circular Economy in Europe 2019 – Even More from Less. EEA Report No 26/2019. Publications Office of the European Union, Luxembourg (2020). https://circulareconomy.europa.eu/platform/sites/default/files/26_2019_resource_efficiency_2019_th-al-20-007-en-n.pdf
11. European Environment Agency. Construction and demolition waste: Challenges and opportunities in a circular economy. EEA (2020). https://www.eea.europa.eu/publications/construction-and-demolition-waste-challenges
12. Ellen MacArthur Foundation. Completing the picture: How the circular economy tackles climate change. Ellen MacArthur Foundation (2019). https://www.ellenmacarthurfoundation.org/completing-the-picture
13. Emovon, I., Oghenenyerovwho, O.S.: Application of MCDM method in material selection for optimal design: a review. Results Mater. **7**, 10011 (2020). https://doi.org/10.1016/j.rinma.2020.100115
14. Sphera Solutions. GaBi Database. Leinfelden-Echterdingen, Germany (2025). https://sphera.com/
15. Geyer, R., Jambeck, J.R., Law, K.L.: Production, use, and fate of all plastics ever made. Sci. Adv. **3**(7), e170078 (2017). https://doi.org/10.1126/sciadv.1700782
16. Hafner, A., Ott, S., Winter, S.: Recycling and end-of-life scenarios for timber structures. In: Materials and Joints in Timber Structures: Recent Developments of Technology, pp. 89–98. Springer (2014). https://doi.org/10.1007/978-94-007-7810-8
17. Hosseinijou, S.A., Mansour, S., Shirazi, M.A.: Social life cycle assessment for material selection: a case study of building materials. Int. J. Life Cycle Assess. **19**(3), 620–64 (2014). https://doi.org/10.1007/s11367-013-0658-1
18. Norsk Hydro. Environmental product declaration: Hydro REDUXA 4.0 aluminium extrusion ingot (NEPD-1840-768-EN). Norsk Hydro ASA (2020). https://www.hydro.com/globalassets/download-center/certificates/nepd-1840-768-hydro-4.0-aluminium-extrusion-ingot.pdf
19. Hybrit Development AB. HYBRIT: Fossil-free steel initiative. SSAB, LKAB, & Vattenfall (2021). https://www.hybritdevelopment.se/en/
20. International Energy Agency. Aluminium. IEA (2022). https://www.iea.org/energy-system/industry/aluminium
21. International Organization for Standardization. ISO 59020:2024: Circular economy — Measuring and assessing circularity performance, 1st edn. ISO (2024). https://www.iso.org/standard/80650.html
22. Jha, S., Akula, B., Enyioma, H., Novak, M., Amin, V., Liang, H.: Biodegradable biobased polymers: a review of the state of the art, challenges, and future directions. Polymers **16**(16), 226 (2024). https://doi.org/10.3390/polym16162262

23. Kirchherr, J., Reike, D., Hekkert, M.: Conceptualizing the circular economy (revisited): an analysis of 221 definitions. Resour. Conserv. Recycl. **194**, 10700 (2023). https://doi.org/10.1016/j.resconrec.2023.107001
24. Mardina, Z., et al.: CM3D: a circular materials multi-criteria decision-making tool for medical devices. Mater. Des. **254**, 11401 (2025). https://doi.org/10.1016/j.matdes.2025.114015
25. Mardina, Z., Turnbull, R.P., Rahimifard, S., Bibb, R., Culmer, P.: CM3D: a circular materials multi-criteria decision-making tool for medical devices. Mater. Des. **254**, 11401 (2025). https://doi.org/10.1016/j.matdes.2025.114015
26. McKinsey & Company. Decarbonizing the world's industries: A net-zero guide for nine key sectors. McKinsey & Company (2023). https://www.mckinsey.com/capabilities/sustainability/our-insights/decarbonizing-the-world-industries-a-net-zero-guide-for-nine-key-sectors
27. Meng, L., Osmani, M., Glass, J.: A probabilistic multi-criteria framework for assessing circularity and sustainability in modern methods of construction. Smart Sustain. Built Environ. (2025). https://doi.org/10.1108/SASBE-04-2025-0185
28. Mlybari, E.A.: Smart sustainability in construction: an integrated LCA-MCDM framework. Sustainability **17**(21), 965 (2025). https://doi.org/10.3390/su17219650
29. Morano, P., Tajani, F., Guarnaccia, C., Anelli, D.: An optimization decision support model for sustainable urban regeneration investments. WSEAS Trans. Environ. Dev. **17**, 1245–1251 (2021)
30. Mussatto, A., Bradley, D., Toso, G., Bártolo, P.J., O'Halloran, S.: Advanced production routes for metal matrix composites. Eng. Rep. **3**(5), e1233 (2021). https://doi.org/10.1002/eng2.12330
31. Norcem. Brevik CCS Project: Carbon Capture and Storage in Cement Production. Brevik, Norway (2020). https://www.norcem.no/en/brevikccs/
32. Pagell, M., Wu, Z.: Building a more complete theory of sustainable supply chain management using case studies of 10 exemplars. J. Supply Chain Manag. **45**(2), 37–5 (2009). https://doi.org/10.1111/j.1745-493X.2009.03162.x
33. Pei, M., Petäjäniemi, M., Regnell, A., Wijk, O.: Toward a fossil free future with HYBRIT: development of iron and steelmaking technology in Sweden and Finland. Metals **10**(7), 97 (2020). https://doi.org/10.3390/met10070972
34. Poulikidou, S., et al.: Material selection for minimizing life cycle environmental impact of vehicles. Mater. Des. **83**, 704–71 (2015). https://doi.org/10.1016/j.matdes.2015.06.079
35. Shelly, D., et al.: Mechanical performance of bio-based fiber reinforced polymer composites: a review. Polym. Compos. (2025). https://doi.org/10.1002/pc.30000
36. Soliman, M.H., Mohammed, A.B., Zaki, A.A.: Sustainable building materials: a critical literature review. Discov. Mater. **6**(1), 3 (2026). https://doi.org/10.1007/s43939-025-00485-3
37. Tighnavard Balasbaneh, A., Aldrovandi, S., Sher, W.: MCDM approaches for circular economy and cost assessment. Sustainability **17**(11), 500 (2025). https://doi.org/10.3390/su17115007
38. World Business Council for Sustainable Development & One Planet Network. Global Circularity Protocol for Business (Version 1.0). WBCSD & UNEP (2025). https://www.wbcsd.org/resources/a-global-framework-to-measure-manage-and-communicate-business-circularity/
39. World Economic Forum. The Net-Zero Industry Tracker. Geneva, Switzerland (2022). https://www.weforum.org/reports/the-net-zero-industry-tracker

40. World Steel Association. Sustainability Indicators 2023. Brussels, Belgium: World Steel Association (2023). https://worldsteel.org/wp-content/uploads/Sustainability-indicators-report-2023.pdf
41. Yan, L., Xu, H.: Lightweight composite materials in automotive engineering: state-of-the-art and future trends. Alex. Eng. J. **118**, 1 (2025). https://doi.org/10.1016/j.aej.2024.12.002
42. Zakeri, S., et al.: A decision analysis model for material selection. J. Eng. Appl. Sci. **70**(1), 5 (2023). https://doi.org/10.1038/s41598-023-35405-z
43. Zambujal-Oliveira, J., Fernandes, C.: Sustainable packaging in circular food supply chains. Packag. Technol. Sci. **37**(6), 443–45 (2024). https://doi.org/10.1002/pts.2802
44. Zambujal-Oliveira, J., Duque, J.: Stochastic carbon taxes and capital turnover. Results Eng. (2026). https://doi.org/10.1016/j.rineng.2026.109902
45. Zou, R.X., Mayfield, E.N.: Lifecycle greenhouse gas emissions of raw steel production plants in the US. Environ. Sci. Technol. (2026). https://doi.org/10.1021/acs.est.5c01504

# An Integrated Framework for ESG Assessment and Action Planning in Eco-Industrial Parks

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**Abstract.** Eco-Industrial Parks (EIPs) are increasingly regarded as important instruments for promoting more sustainable forms of industrial development. Their performance, however, cannot be understood only in terms of environmental efficiency, since it also depends on social conditions, governance arrangements, shared infrastructures, and the quality of coordination among multiple actors. This makes the assessment of EIPs particularly challenging and highlights the need for approaches capable of integrating environmental, social, and governance (ESG) dimensions within a single analytical framework. This paper proposes a two-phase methodological framework for assessing and improving ESG performance in EIPs. The first phase is diagnostic and measures deviations between observed performance and predefined targets derived from regulations, institutional benchmarks, and best practices. The second phase is prescriptive and uses Goal Programming to identify the most effective improvement strategies under economic, technical, and organizational constraints. In this way, the framework links sustainability assessment with the definition of intervention priorities and the selection of feasible actions. The main contribution of the paper lies in adapting ESG logic to the territorial and multi-actor nature of eco-industrial parks, while also connecting performance evaluation with decision support. The framework is presented as a methodological proposal that may support more operational and integrated forms of sustainability governance in industrial areas, although its usefulness still requires empirical testing in different EIP contexts.

**Keywords:** Eco-Industrial Parks · ESG assessment · Goal Programming · sustainability assessment · industrial symbiosis

## 1 Introduction

In recent years, Eco-Industrial Parks (EIPs) have gained increasing attention as a sustainability-oriented model for rethinking industrial areas. Unlike conventional industrial parks, EIPs are not simply clusters of firms located in the same area, but organized systems in which environmental and economic performance also depends on shared

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infrastructures, coordinated management of energy, water, and waste, and structured relationships among firms, park managers, and public actors [1]. Their functioning therefore reflects not only firm-level behavior, but also wider territorial and organizational conditions, including the capacity to activate industrial synergies and to connect industrial development with local sustainability goals [2, 3].

This broader understanding has important implications for assessment. The sustainability of an eco-industrial park cannot be reduced to eco-efficiency alone, since it also depends on organizational arrangements, working conditions, governance capacity, stakeholder relations, and the park's interaction with the surrounding territory. Recent studies have in fact shown that EIPs may contribute not only to resource efficiency and impact reduction, but also to green innovation, resilience, and more integrated forms of territorial development [4, 5]. Consequently, the evaluation of EIPs requires approaches that can jointly take into account the different dimensions involved [6, 7].

In this respect, the Environmental, Social and Governance (ESG) perspective offers a useful conceptual basis. Originally developed in responsible investment and later extended to sustainability reporting and accountability systems, ESG provides an integrated framework for considering environmental impacts, social implications, and governance mechanisms together. This orientation is also consistent with recent developments in the European reporting framework, which increasingly emphasize integrated sustainability approaches [8, 9].

However, applying ESG logic to EIPs is not straightforward. Most ESG tools were designed for individual firms, financial markets, or investment portfolios, whereas eco-industrial parks are collective and territorial systems in which performance emerges from shared assets, interdependencies, and multi-actor governance processes [10, 11]. This makes direct transfer difficult and requires methodological adaptation. A further issue concerns the broader ESG literature itself, where the heterogeneity of indicators, measurement approaches, and weighting systems often limits comparability across results [12, 13]. If this is already problematic for individual firms, it becomes even more so in the case of EIPs, where sustainability performance depends on system-level relationships that exceed the boundaries of any single organization.

Against this background, the key methodological challenge is not only to build ESG indicator systems at park scale, but also to understand how assessment can support decision-making. In the case of eco-industrial parks, this means linking the measurement of performance to the identification of priorities and to the selection of feasible intervention strategies under economic, technical, and organizational constraints [14].

## 2 Aim

This contribution proposes a two-phase methodological framework for the assessment and improvement of Environmental, Social and Governance (ESG) performance in Eco-Industrial Parks (EIPs). Its aim is to address a gap that is still present in the literature, namely the limited availability of approaches capable of explicitly linking sustainability assessment with the selection of intervention strategies consistent with economic, technical, and organizational constraints.

To this end, the paper develops an approach based on Goal Programming, which is considered suitable for managing multiple and heterogeneous objectives expressed through explicit targets. The framework performs a dual function:

1. a passive phase, aimed at assessing ESG performance by measuring deviations from targets defined on the basis of regulatory references, institutional benchmarks, and best practices;
2. an active phase, aimed at identifying the most effective intervention strategies for reducing such deviations through an optimization model that incorporates costs, priorities, budget constraints, minimum performance thresholds, and dependency relationships among actions.

Within this perspective, the originality of the proposed framework does not lie in the development of a new optimization technique, but in the integrated adaptation of ESG logic to the territorial and multi-actor nature of EIPs. Compared with existing indicator-based approaches, the framework does not limit the assessment to the construction of a sustainability profile or a composite score. Instead, it explicitly measures deviations from predefined ESG targets and uses these diagnostic results as inputs for a constrained decision-support model. In this sense, the contribution is both methodological and operational: it connects ESG performance assessment, priority identification, and action selection within a single structured procedure.

In this way, ESG assessment is interpreted as a decision-support tool for the sustainable governance of territorial production systems.

The remainder of the paper is structured as follows. Section 3 reviews the main strands of literature on EIPs, sustainability assessment, and Goal Programming. Section 4 presents the proposed methodology, describing both the passive and the active phases of the framework. Finally, Sect. 5 concludes by discussing the main implications, limitations, and possible directions for future research.

## 3 Background

The literature on Eco-Industrial Parks (EIPs) initially developed around the concept of industrial symbiosis, understood as a set of cooperative relationships through which co-located firms exchange energy, materials, by-products, and services, thereby improving the overall efficiency of the system. Early studies were mainly concerned with clarifying the concept itself and identifying the conditions under which symbiotic relationships emerge and persist. Over time, attention shifted towards the role of exchange networks, shared infrastructures, and coordination among actors, showing that EIPs should not be understood as simple agglomerations of firms, but as more complex territorial systems [15–17]. More recently, this view has been further expanded by studies that interpret EIPs as socio-technical transition processes, in which infrastructures, organizational capabilities, collective learning, and policy conditions evolve together [2, 19]. This evolution in the literature has gradually moved the debate beyond symbiotic exchanges alone and towards the broader issue of how the sustainability of these systems can be assessed.

This question has been addressed by a growing body of work on EIP performance assessment. Several studies have proposed environmental, economic, and social indicators to evaluate park sustainability and to support the construction of more coherent

monitoring frameworks. Felicio and Amaral (2013) [20], for instance, applied environmental indicators to eco-industrial parks, while Lütje and Wohlgemuth (2020) [21] developed a quantitative system to monitor progress towards sustainability targets in industrial symbiosis contexts. Koch et al. (2022) [22] used performance assessment as a strategic support tool for energy and waste recovery in an eco-industrial park. Taken together, these contributions suggest a gradual shift from descriptive accounts of symbiotic practices towards more structured approaches to sustainability measurement.

At the same time, EIP research has increasingly incorporated optimization models to support the design of industrial park configurations, exchange networks, and restructuring strategies. Many of these studies rely on MILP (Mixed-Integer Linear Programming) formulations or integrated network models to balance economic costs, environmental gains, and, in some cases, social impacts. Genc et al. (2019) [19], for example, proposed a socio-ecological approach to support the transition of industrial zones towards eco-industrial configurations, and Genc et al. (2020) [23] later developed an integrated optimization, location, and food-web analysis model inspired by natural systems for circular eco-industrial park design. Despite their relevance, however, recent reviews point out that these modelling approaches still tend to focus on material and energy flows, network structure, and environmental efficiency, while much less attention is paid to fully integrated ESG-oriented frameworks [24].

In this context, Goal Programming (GP) deserves more attention than it has so far received in EIP studies. As an extension of linear programming for multi-objective problems, GP makes it possible to define each objective in terms of a target and to measure deviations from that target while incorporating priorities, weights, and resource constraints [25–28]. Its potential has already been recognized in several fields related to sustainable planning and environmental management. Reviews have highlighted its use in sustainable energy planning, where economic, environmental, and social goals must be balanced within a consistent decision framework [29]. Other studies have shown its relevance in resource management and multicriteria decision-making contexts characterized by competing objectives and explicit constraints [30]. In fields closer to territorial planning and sustainable investment, optimization-based decision-support models have also shown how these techniques can help connect sustainability criteria with the selection of feasible alternatives [31]. Although GP has not yet been widely applied to eco-industrial parks, it appears particularly suitable when sustainability is interpreted both as distance from explicit targets and as a problem of choosing interventions under economic, technical, and organizational constraints.

## 4 Methodology

The proposed methodological approach is structured in two phases and is designed to connect ESG performance assessment with the identification of improvement priorities in Eco-Industrial Parks. The first phase is diagnostic: it measures the extent to which observed performance differs from a set of reference targets. The second phase is prescriptive: it supports the selection of the most effective improvement strategies under economic, technical, and organizational constraints. Figure 1 summarizes the overall structure of the proposed methodological framework.

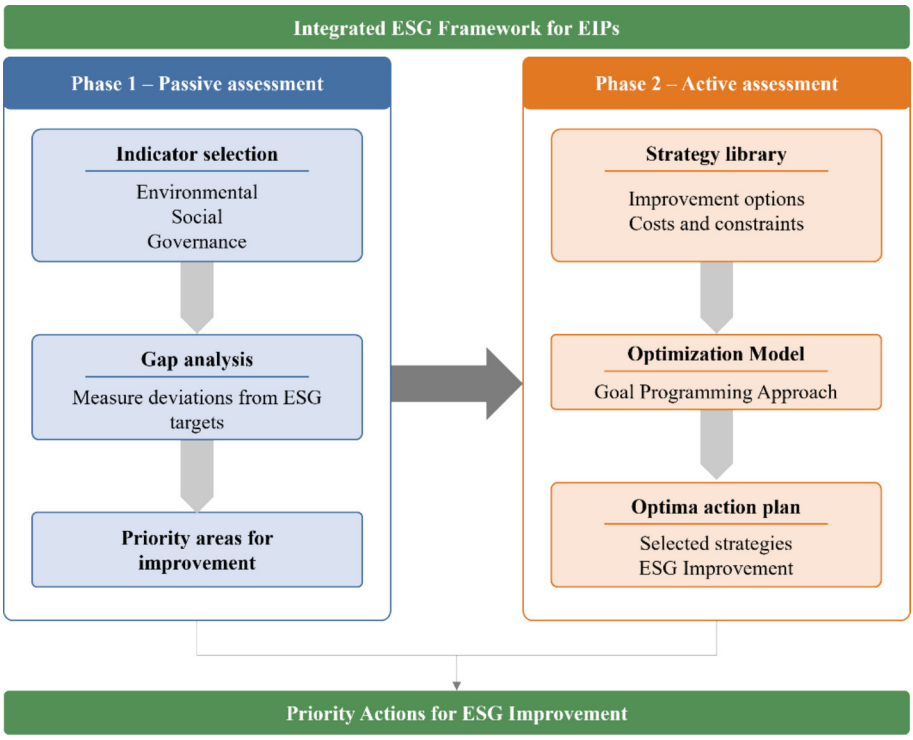


**Fig. 1.** Overview of the proposed two-phase framework for ESG assessment and improvement in Eco-Industrial Parks.

The framework is based on Goal Programming (GP), a mathematical programming technique developed to address multi-objective problems in which each objective is expressed as the achievement of a predefined target. Unlike traditional linear programming, which is oriented towards the optimization of a single objective function, GP makes it possible to deal simultaneously with heterogeneous objectives by measuring deviations from desired levels. In its classical formulation, for each objective $j$, the relationship between observed value, target, and deviations can be expressed as:

$$f_j(\mathrm{x}) + d_j^- - d_j^+ = g_j$$

where $f_j(\mathrm{x})$ represents the value of the objective function, $g_j$ the desired target, and $d_j^-$ and $d_j^+$ the negative and positive deviations from that target, respectively. In the present framework, this logic is adapted to ESG assessment by taking the individual indicator as the unit of analysis; accordingly, the index $j$ denotes the ESG indicator under consideration, each associated with a corresponding reference target.

On this basis, the methodology is divided into two phases. The first is intended to measure the distance between observed ESG performance and predefined sustainability targets. The second uses those results to identify the most appropriate intervention strategies within a constrained decision space.

### 4.1 Phase 1 – Passive Assessment

The passive phase is aimed at identifying ESG gaps with respect to predefined targets. It includes two main steps: the construction of the indicator system and the formalization of the assessment model.

The first step consists in selecting a set of indicators capable of representing, in an integrated way, the environmental, social, and governance dimensions of the industrial park. From a methodological point of view, these indicators may be divided into two groups. The first includes mandatory indicators, associated with targets derived from binding regulations, recognized standards, or institutional references. The second includes strategic voluntary indicators, which do not necessarily correspond to mandatory thresholds but are useful for capturing aspects that are relevant to the overall ESG quality of the park.

As shown in Table 1, the indicator system may include variables related to environmental performance, social conditions, and governance arrangements. The examples reported in the table should not be interpreted as a fixed or exhaustive set, but rather as an operational template that can be adapted to different contexts depending on data availability, local priorities, and decision needs.

For each selected indicator $j$, three elements are defined: the observed value $x_j$, the reference target $g_j$, and the weight $w_j$. Targets may derive from regulatory sources, institutional benchmarks, international standards, or best practices. In order to ensure transparency and replicability, indicator selection should follow explicit criteria. In particular, indicators should be selected according to: i) relevance to the environmental, social, or governance dimension under analysis; ii) measurability and data availability at the park scale; iii) comparability across parks or over time; and iv) actionability, namely the possibility of linking the indicator to concrete improvement strategies.

Normalization is required because the selected indicators may be expressed in different units and scales. Depending on the nature of the indicator, benefit-type variables can be normalized so that higher values correspond to better ESG performance, while cost-type or pressure indicators can be transformed so that lower original values correspond to higher normalized scores. When regulatory thresholds or institutional benchmarks are available, normalized values may also be expressed in relation to the corresponding target. Observed values are therefore normalized onto a common scale, for example within the interval [0, 1], so that originally heterogeneous variables can be treated jointly.

Weights should be assigned through a transparent procedure, such as expert judgement, stakeholder consultation, pairwise comparison, or a combination of these approaches. They reflect the relative importance attributed to the different indicators within the overall evaluation framework. In order to test the robustness of the results, alternative weighting scenarios or sensitivity analyses may also be considered.

Once the indicator system has been defined, the passive assessment is formalized through a classical GP model. At this stage, the purpose is not to reward performance beyond the target, but to measure shortfalls with respect to regulatory thresholds, institutional benchmarks, or best practices. For this reason, the model considers only negative deviations. For each indicator $j$, the observed normalized value $x_j$ is compared with the corresponding normalized target $g_j$; the variable $d_j^-$ measures the residual gap with

**Table 1.** Illustrative examples for constructing the ESG indicator system in the passive assessment phase.

| Dimension | Category | Examples of indicators | Possible target references |
|---|---|---|---|
| Environmental | Mandatory | Share of energy from renewable sources; energy efficiency measures; presence of renewable energy plants; waste recovery in a circular economy perspective; reduction of $CO_2$ emissions; active water-saving systems | EU directives and regulations; institutional benchmarks; applicable technical standards |
| Environmental | Strategic voluntary | Park territorial extension; environmental certifications; sustainable facilities; hydrogen production systems from waste; sustainable mobility initiatives; monitoring of indirect emissions; $CO_2$ capture and reuse projects | Sectoral best practices; international guidelines; internal improvement targets |
| Social | Mandatory | Corporate welfare services; training, equality, and inclusion programmes; collaboration with schools and universities; average employee tenure; community relations; onboarding and professional development programmes | International standards; EIP guidelines; ESG/social reporting references |
| Social | Strategic voluntary | Number of firms located in the park; number of direct employees; hosted events; territorial engagement initiatives | Comparative benchmarks; organizational targets; territorial development objectives |
| Governance | Mandatory | Risk management structure; anti-corruption training; code of conduct; whistleblowing procedures | Existing regulation; compliance standards; corporate governance references |
| Governance | Strategic voluntary | Sustainability board; transparent governance systems; voluntary sustainability reporting; governance-related recognitions and certifications | Voluntary standards; UNIDO/GRI/OECD guidelines; accountability and reputation goals |

respect to that target, while the weight $w_j$ expresses the relative importance attributed to the indicator within the overall evaluation framework.

The objective function is therefore:

$$\min \sum_{j=1}^{n} w_j \cdot d_j^-$$

Subject to:

$$x_j + d_j^- \geq g_j \qquad \forall j$$

with:

$$d_j^- \geq 0 \qquad \forall j$$

In this formulation, the larger the value of $d_j^-$, the greater the distance of indicator $j$ from its target. The objective function therefore provides a synthetic measure of the overall distance of the system from a condition of full alignment with ESG objectives. No logical interdependency constraints are introduced at this stage, since the model is exclusively evaluative and does not yet simulate intervention scenarios.

For clarity, Table 2 summarizes the main variables and parameters used in the passive assessment phase.

**Table 2.** Variables and parameters of the passive assessment model

| Symbol | Description | Domain |
|---|---|---|
| $j$ | Index of ESG indicator | $j = 1, \ldots, n$ |
| n | Total number of ESG indicators considered | Positive integer |
| $x_j$ | Observed and normalized value of indicator $j$ | $x_j \in [0, 1]$ |
| $g_j$ | Normalized target value of indicator $j$ | $g_j \in [0, 1]$ |
| $d_j^-$ | Negative deviation of indicator $j$ from its target | $d_j^- \geq 0$ |
| $w_j$ | Weight assigned to indicator $j$ | $w_j \in [0, 1]$ |

The output of the passive phase consists of a synthetic measure of ESG performance, the identification of the indicators showing the largest deviations from their targets, and, consequently, the identification of priority areas for improvement.

### 4.2 Phase 2 – Active Assessment

The second phase is prescriptive and aims to transform the diagnostic results into a coherent set of priority actions. If the first phase measures the distance from ESG targets, the second phase is concerned with identifying which strategies should be implemented in order to reduce those distances as effectively and realistically as possible.

To make this phase operational, a library of improvement strategies must first be constructed on the basis of the gaps emerging from the passive phase. Each strategy should be described at least in terms of its expected ESG improvement, its total implementation cost, and any dependency, precedence, or compatibility relationship with other strategies. In practical terms, strategies may concern energy and environmental infrastructures, welfare and training measures, governance and control mechanisms, or actions aimed at strengthening relations with the surrounding territory and stakeholders.

The construction of the strategy library represents a key operational step of the active phase. Strategies should be derived from the priority gaps identified in the passive assessment and should be defined in collaboration with park managers, firms, public authorities, and technical experts. For each strategy, the expected ESG improvement may be estimated through technical assessments, benchmarking of similar interventions, expert elicitation, feasibility studies, or evidence from previous projects. Implementation costs should include not only direct investment costs, but also operating, maintenance, coordination, and transaction costs where relevant. Dependency relationships should also be made explicit. Some actions may require preliminary enabling measures, while others may be mutually exclusive or complementary. For example, the installation of advanced monitoring systems may be a prerequisite for more complex energy optimization measures. Including these relationships in the model allows the strategy selection process to better reflect real implementation conditions.

The model is formulated as a selection problem with binary variables, in which each strategy represents an option that may or may not be activated depending on available resources. More specifically, for each strategy *j,* the parameter $DESG_j$ represents the expected improvement in ESG performance associated with its implementation, while $C_j^{tot}$ denotes the total cost of the intervention. The decision variable $y_j$ takes value 1 when the strategy is selected and 0 otherwise. The set of selected strategies must also satisfy an overall available budget $B$.

The objective function is therefore aimed at maximizing the overall ESG improvement associated with the selected strategies:

$$max \sum_{j=1}^{m} \Delta ESG_j y_j$$

subject to the budget constraint:

$$\sum_{j=1}^{m} C_j^{tot} y_j \leq B$$

where $m$ denotes the total number of strategies considered. Additional logical interdependency constraints may also be introduced, for example:

$$y_i \leq y_k$$

whenever intervention $i$ requires the prior implementation of intervention $k$. This formulation makes it possible to represent conditions that are typical of real contexts, where not all desirable actions can be implemented simultaneously and where some strategies are feasible only if accompanied by enabling measures or preliminary investments.

Table 3 summarizes the main variables and parameters used in the active assessment phase.

**Table 3.** Variables and parameters of the active assessment model

| Symbol | Description | Domain |
|---|---|---|
| $j$ | Index of the improvement strategy | $j = 1, \ldots, m$ |
| $m$ | Total number of strategies considered | Positive integer |
| $DESG_j$ | Expected ESG performance improvement associated with strategy $j$ | Normalized value, [0, 1] |
| $C_j^{tot}$ | Total implementation cost of strategy $j$ | Non-negative monetary value |
| $yj$ | Binary decision variable associated with strategy $j$ | $y_j \in \{0, 1\}$ |
| $B$ | Overall available budget | Non-negative monetary value |

To clarify the interaction between the two phases, a simplified illustrative example may be considered. Suppose that the passive phase identifies the largest ESG gaps in three areas: renewable energy production, employee training, and governance transparency. The active phase would then translate these gaps into a set of possible strategies, such as installing photovoltaic systems, introducing training and inclusion programmes, or strengthening whistleblowing and reporting procedures. Each strategy would be associated with an expected ESG improvement, an implementation cost, and possible dependency conditions. Under a limited budget, the optimization model would select the combination of actions that maximizes the overall ESG improvement while respecting the available resources and any logical constraints.

The output of the active phase consists of the optimal set of selected strategies, the overall improvement achievable under the given constraints, and, more broadly, an argued basis for defining intervention priorities. In this way, ESG assessment is no longer confined to a descriptive exercise, but becomes part of a decision-support process that is more closely aligned with the operational conditions of eco-industrial parks.

## 5 Conclusions

Assessing sustainability in Eco-Industrial Parks (EIPs) requires tools that can reflect their territorial, multi-actor, and multidimensional nature. Because EIPs operate through the interaction of firms, shared infrastructures, governance arrangements, and local dynamics, their performance cannot be adequately understood through descriptive assessments alone.

This paper has proposed a two-phase framework based on Goal Programming. The first phase is designed to measure deviations from predefined ESG targets, while the second uses those results to support the selection of improvement strategies under explicit economic, technical, and organizational constraints. In this way, the framework connects assessment and intervention within a single methodological structure.

The main contribution of the proposed approach lies in its adaptation to the specific characteristics of eco-industrial parks. By combining ESG indicators, reference targets, weighted priorities, and constrained action selection, the framework offers a more operational perspective on sustainability assessment. ESG evaluation is therefore treated not only as a reporting exercise, but also as a potential support tool for governance and decision-making.

From a practical perspective, the framework may support different stakeholders involved in the governance of EIPs. Park managers can use it to identify priority ESG gaps and to allocate resources among competing interventions. Firms located within the park can benefit from a clearer understanding of collective sustainability objectives and of the actions required to achieve them. Public authorities may use the framework to define transparent criteria for incentives, monitoring procedures, or policy support measures. Finally, investors and financial actors may rely on the model to better connect ESG performance with feasible improvement plans.

The operationalization of the framework requires reliable data collection procedures, agreement on shared targets, transparent weighting mechanisms, and a periodically updated strategy library. For this reason, the model should be understood not only as an assessment tool, but also as a structured process for supporting dialogue, coordination, and decision-making among the actors involved in EIP development.

At the same time, the framework should be regarded as a methodological proposal that still requires empirical application and refinement. Its effectiveness depends on several factors, including data availability and quality, the definition of context-sensitive targets, the transparent assignment of weights, and the realistic estimation of costs, expected improvements, and dependencies among strategies. For this reason, further research should test the model in different EIP contexts and assess its robustness through comparative applications and sensitivity analyses [31–33].

Overall, the paper suggests that a closer connection between performance assessment and action planning may represent a useful direction for advancing ESG-oriented approaches to eco-industrial parks and, more broadly, for supporting more integrated forms of sustainability governance in territorial production systems.

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## References

1. UNIDO: International Framework for Eco-Industrial Parks. United Nations Industrial Development Organization, Vienna (2021)
2. Susur, E., Hidalgo, A., Chiaroni, D.: A strategic niche management perspective on transitions to eco-industrial park development: a systematic review of case studies. Resour. Conserv. Recycl. **140**, 338–359 (2019)
3. World Bank: Leveraging Eco-Industrial Parks for a Sustainable Transition of Industries. World Bank Group (2025)

4. Zhang, H., Xu, B.: Eco-industrial parks construction and industrial chain resilience. Front. Sustain. Cities **7**, 1663273 (2025)
5. Wu, Y., Gao, X.: Can the establishment of eco-industrial parks promote urban green innovation? Evidence from China. J. Clean. Prod. **341**, 130855 (2022)
6. Perrucci, D.V., Aktaş, C.B., Sorentino, J., Akanbi, H., Curabba, J.: A review of international eco-industrial parks for implementation success in the United States. City Environ. Interact. **16**, 100086 (2022)
7. Lo, S.F., Lu, W.M., Chang, C.W., Hung, S.W., Yang, L.L.: An efficiency-driven approach for global ecological industrial parks. J. Clean. Prod. **424**, 138837 (2023)
8. European Union: Directive (EU) 2022/2464 of the European Parliament and of the Council of 14 December 2022 amending Regulation (EU) No 537/2014, Directive 2004/109/EC, Directive 2006/43/EC and Directive 2013/34/EU, as regards corporate sustainability reporting. Official Journal of the European Union L 322, 15–80 (2022)
9. EFRAG: ESRS workstreams. https://www.efrag.org/en/sustainability-reporting/esrs-workstreams. Accessed 31 Mar 2026
10. Anelli, D., Morano, P., Fariello, F., Sabatelli, E.: Environmental, social and governance (ESG) assessment with a two-phase goal-programming-based optimization model: a comparative study of Envipark and Kalundborg eco-industrial parks. Front. Built Environ. **12**, 1731282
11. Quaranta, D.: Strategies to improve the carbon footprint of industrial zones and their competitiveness: implications of the adoption of an ESG framework to measure performances of industrial zones and identify potential interventions. A study of two industrial zones in Morocco (2024)
12. Berg, F., Kölbel, J.F., Rigobon, R.: Aggregate confusion: the divergence of ESG ratings. Rev. Finance **26**(6), 1315–1344 (2022)
13. Capizzi, V., Gioia, E., Giudici, G., Tenca, F.: The divergence of ESG ratings: an analysis of Italian listed companies. J. Financ. Manag. Mark. Inst. **9**(02), 2150006 (2021)
14. Guarini, M.R., D'Addabbo, N., Morano, P., Tajani, F.: Multi-criteria analysis in compound decision processes: the AHP and the architectural competition for the chamber of deputies in Rome (Italy). Buildings **7**(2), 38 (2017)
15. Lowe, E.A.: Creating by-product resource exchanges: strategies for eco-industrial parks. J. Clean. Prod. **5**(1–2), 57–65 (1997)
16. Chertow, M.R.: Industrial symbiosis: literature and taxonomy. Annu. Rev. Energy Env. **25**, 313–337 (2000)
17. Chertow, M.R.: "Uncovering" industrial symbiosis. J. Ind. Ecol. **11**(1), 11–30 (2007)
18. Boons, F., Spekkink, W., Mouzakitis, Y.: The dynamics of industrial symbiosis: a proposal for a conceptual framework based upon a comprehensive literature review. J. Clean. Prod. **19**(9–10), 905–911 (2011)
19. Genc, O., van Capelleveen, G., Erdis, E., Yildiz, O., Yazan, D.M.: A socio-ecological approach to improve industrial zones towards eco-industrial parks. J. Environ. Manag. **250**, 109507 (2019)
20. Anelli, D., Ranieri, R.: Resilience of complex urban systems: a multicriteria methodology for the construction of an assessment index. In: Calabrò, F., Della Spina, L., Piñeira Mantiñán, M.J. (eds.) NMP 2022. LNNS, vol. 482, pp. 690–701. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-06825-6_65
21. Lütje, A., Wohlgemuth, V.: Tracking sustainability targets with quantitative indicator systems for performance measurement of industrial symbiosis in industrial parks. Adm. Sci. **10**(1), 3 (2020)
22. Koch, C., Tomasin, L., Lolli, F., Butturi, M., Sellitto, M.: Performance assessment of an eco-industrial park: a strategic tool to help recovering energy and industrial waste. Chem. Eng. Trans. **91**, 481–486 (2022)

23. Genc, O., Kurt, A., Yazan, D.M., Erdis, E.: Circular eco-industrial park design inspired by nature: an integrated non-linear optimization, location, and food web analysis. J. Environ. Manag. **270**, 110866 (2020)
24. Demartini, M., Tonelli, F., Govindan, K.: An investigation into modelling approaches for industrial symbiosis: a literature review and research agenda. Clean. Logist. Supply Chain **3**, 100020 (2022)
25. Charnes, A., Cooper, W.W.: Management models and industrial applications of linear programming. Manag. Sci. **4**(1), 38–91 (1957)
26. Ignizio, J.P.: Goal programming and extensions (1976)
27. Anelli, D., Morano, P., Tajani, F., Sabatelli, E.: Impacts of urban decay on the residential property market: an application to the City of Rome (Italy). In: Gervasi, O., Murgante, B., Garau, C., Taniar, D., Rocha, A.M.A.C., Faginas Lago, M.N. (eds.) ICCSA 2024. LNCS, vol. 14822, pp. 36–48. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-65318-6_3
28. Jones, D., Tamiz, M.: Practical Goal Programming. Springer, New York (2010). https://doi.org/10.1007/978-1-4419-5771-9
29. Pohekar, S.D., Ramachandran, M.: Application of multi-criteria decision making to sustainable energy planning—a review. Renew. Sustain. Energy Rev. **8**(4), 365–381 (2004)
30. Diaz-Balteiro, L., Romero, C.: Making forestry decisions with multiple criteria: a review and an assessment. For. Ecol. Manag. **255**(8–9), 3222–3241 (2008)
31. Morano, P., Tajani, F., Guarnaccia, C., Anelli, D.: An optimization decision support model for sustainable urban regeneration investments. WSEAS Trans. Environ. Dev. **17**, 1245–1251 (2021)
32. Canesi, R.: Urban policy sustainability through a value-added densification tool: the case of the South Boston Area. Sustainability **14**(14), 8762 (2022)
33. Zambujal-Oliveira, J., Duque, J.: Stochastic carbon taxes and capital turnover: a real options model for decarbonization investment. Results Eng. **109902** (2026). https://doi.org/10.1016/j.rineng.2026.109902

# A Methodological Framework for Identifying Compromise Solutions in Complex Urban Squatting Conditions

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**Abstract.** Complexity, uncertainty, and the coexistence of multiple stakeholders with divergent interests increasingly characterize contemporary urban contexts, making traditional decision-making approaches often inadequate.

This study aims to develop a structured methodological framework to support decision-making processes in complex urban environments, with particular attention to the identification of compromise solutions among conflicting actors.

The proposed approach integrates Social Multi-Criteria Evaluation (SMCE), the Best–Worst Method (BWM), and a MACBETH-inspired procedure within a coherent six-phase framework, guiding the process from problem structuring to the evaluation and comparison of alternative scenarios.

The framework enables the explicit representation of stakeholder preferences, the analysis of convergence and divergence among actors, and the identification of potential rejection conditions. From this perspective, evaluation is not only a technical tool, but also a support for transparent negotiation processes.

A key contribution of the study lies in its ability to distinguish between theoretically optimal solutions and those that are practically implementable, by explicitly addressing trade-offs and compromise conditions in multi-actor decision contexts.

The proposed framework contributes to advancing decision-support approaches in urban planning by providing a structured and replicable method for identifying context-sensitive and implementable solutions.

**Keywords:** Multi-criteria Decision Analysis · Decision Support Systems · Compromise Solutions

## 1 Introduction

Today, challenges related to the environment, economy, and society are changing cities in a rapid way. The conditions characterizing the new kind of urban development are ever more redefining climate-related risks, growing resource constraints, as well as shifting and modifying demographic patterns [1].

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At the same time, planning systems – required to respond to multiple and often competing expectations – are pressed by the increasing demand for more sustainable and resilient forms of expansion. In many contexts, these changes are not only quantitative but also qualitative, and influence the way urban areas are generated, exploited and managed [2].

There are no linear or predictable processes driving these changes. Rather, complex interactions between factors operating at different spatial and temporal levels [3] increasingly characterize urban systems. Local dynamics are influenced by worldwide processes, while short-term decisions may produce long-term and sometimes accidental and/or unintentional consequences.

In this respect, cities can be considered as evolving systems; environment is subjected to never-ending transformations whereas effects and consequences may be sometimes out of control. In such a context, reliance on usual and tested planning approaches built on stability, predictability and simplified representations of reality [4] becomes surely much more demanding and problematic.

This questions the validity of the efficacy and success of models which adopt a distinct separation between causes and effects, emphasizing instead the need to take into consideration feedback devices and collective and combining impacts [5].

Another relevant aspect to be considered concerns the gradual assimilation of various dimensions within urban policies. Nowadays environmental, economic and social questions are no longer managed as unconnected domains, but there is an ever more research-backed approach within the same frameworks [6]. On one side this integration is indispensable, on the other it clearly launches new challenges.

Objectives can be desirable from a certain point of view but they may clash with others; moreover, actions aimed at improving particular aspects of urban systems may generate negative outcomes on others [7]. For this reason, interventions on urban scenarios are often subjected to operations under conditions of tension and pressure, so it is inevitable finding a balance among several priorities. This is particularly manifest in spaces where resource constraints, environmental risks and social vulnerabilities intersect; this important factor requires a kind of coordinated responses, but these ones are seldom neat and direct [8].

The need for more flexible and integrated approaches has become greatly evident in this context. Rather than concentrating on isolated or single components, there is increasing attention towards structures able to seize the intrinsic and interconnected nature of urban systems, and to reinforce a more comprehensive understanding and knowledge of current transformations [9].

The good results of planning processes may be negatively influenced by two aspects: (i) if the multiplicity of factors implied is not focused, (ii) if the presence of uncertainty, partial information and changing variables is not recognized. Actually, these dynamics often arouse the necessity for flexible strategies, able to be revised and modified over time as new information becomes available or when previous conditions change [10].

Simultaneously, urban transformations are essentially built thanks to the interaction of multiple actors; the roles of these actors and general expectancies may vary significantly across contexts.

It is notorious that government institutions, private operators and local groups or communities give different contributions to the definition and implementation of urban strategies, as they bring with them different priorities and perspectives. This plurality has a twofold-aspect: it may be both a resource and a source of complexity, because it may produce good opportunities for cooperation but also states of rigidity and disagreement.

For the most part, the achievement of a successful intervention derives from the capacity to navigate these dynamics, rather than on the real qualitative value of the proposed solution [11].

The study of this wider scenario shows that the focus of urban analysis is progressively moving from the search for ideal solutions towards the detection of practicable and context-sensitive results.

Very often, the success of an intervention derives not only from its theoretical performance, but also from its capacity to be embraced, subject to be negotiated and improved within a given urban context. This underlines the importance of the following concept: not only what is originally planned should be considered, but also what can practically be achieved in a real scenario [12]. In complicated environments – whereas restrictions are not only technical but also social and institutional [13] – the disparity between ideal solutions and implementable ones becomes particularly significant.

These reflections suggest the necessity of devising approaches capable of promoting a more structured knowledge of complex urban problems; moreover, these approaches should be able to accommodate manifold perspectives and to sustain and favour the identification of solutions that are not only theoretically complete, but also possible in a practical way.

## 2 Aim

The present study aims at developing a structured and widely articulated methodological framework to sustain decision-making processes in complex and difficult urban contexts, characterised by multiple stakeholders, conflicting interests, and heterogeneous evaluation criteria.

Definitely, the research tries to offer a framework that favours the methodical comparison of alternative scenarios, taking into account stakeholder-specific urgent priorities as well as the multiple dimensions that affect urban decision-making processes.

According to this viewpoint, evaluation is not conceived as a simple technical strategy, but as a structured process aimed at supporting negotiation, enhancing transparency, and clarifying the implications of different choices.

The study gives a contribution to a progress in decision-support approaches in urban planning by proposing an mixed framework that merges different evaluation techniques within a coherent and rational structure. The framework is designed to capture preference heterogeneity, assess the relative performance of alternative options, and make value trade-offs explicit in a clear, traceable and observable way.

Moreover, this research aims at supporting the recognition of conciliation solutions in multi-actor contexts, where the presence of contrasting interests may lead to rejection conditions or decision-making deadlock. Special attention is given to the distinction between ideally preferable alternatives and those that are actually implementable, without underestimating the necessity of a balance between different priorities and limits.

In conclusion, the proposed approach is intended to function as a decision-support instrument able to improve the quality and strength of urban policy choices, by providing a clearer knowledge of the relationships between stakeholders, evaluation criteria, and alternative scenarios.

The structure of the paper is outlined as follows. Section 3 provides the background framework. Section 4 describes the proposed methodological approach, detailing the different phases to be carried out. In Sect. 5 the conclusions are explained, discussing the main methodological implications and outlining possible future developments.

## 3 Background

In light of these challenges, the limitations of traditional evaluation approaches have been widely documented, particularly in contexts characterised by multiple stakeholders and conflicting objectives.

Conventional tools often fail to capture the multidimensional nature of decision problems and to adequately represent the diversity of stakeholder perspectives. In such settings, the coexistence of heterogeneous value systems and competing priorities makes it difficult to identify solutions that are both analytically strong and socially acceptable.

These challenges are further reinforced in governance arrangements marked by the interaction between public and private actors, such as public–private partnerships (PPPs), whereas decision-making processes are fundamentally shaped by the coexistence of different institutional logics, risk perceptions and investment objectives. In such settings, the different orientation of public interest and private profitability becomes a critical challenge, often requiring the definition of compromise solutions able to balance efficacy, impartiality and financial support [14].

As practical studies highlight, the success of these arrangements greatly is based on the capacity to manage conflicts, to negotiate trade-offs and to ensure the acceptability of decisions among involved actors.

In this scenario, Multi-Criteria Decision Analysis (MCDA) has been widely recognised as a successful framework for the support of complex decision-making processes. Applications in transport planning show that MCDA can structure decision problems and identify relevant criteria for infrastructure location, improving the transparency and traceability of the evaluation process [15, 16].

Likewise, studies in road safety analysis confirm that MCDA models allow the identification and ranking of multiple influencing factors, producing consistent and interpretable outputs even in highly problematic systems [17]. Multi-criteria approaches have been effectively used to compare and balance conflicting performance criteria in engineering contexts, so demonstrating the need of devising solutions that simultaneously satisfy various objectives [18, 19].

Apart from technical evaluation, a critical factor for the effectiveness of decision-making processes – clearly shown by realistic studies – is represented by the explicit incorporation of stakeholder perspectives. Multi-actor and multi-criteria frameworks demonstrate that ignoring stakeholder preferences may lead to the failure or rejection of planning solutions, in a particular way in urban contexts characterised by contrasting interests [20, 21].

In this sense, sharing approaches such as Social Multi-Criteria Evaluation (SMCE) have been widely applied in urban regeneration processes, showing that the inclusion

of stakeholder preferences can highly improve the acceptability and can legitimate decisions [22].

Case study applications confirm that the integration of technical and social evaluations allows the mediation between different stakeholder rankings, supporting the identification of more balanced and strong solutions [23, 24]. Likewise, participatory evaluation frameworks have been successfully applied in conflictual settings, where they contribute to structuring decision problems and facilitating the comparison of alternative situations [25].

Yet, empirical evidence also shows that stakeholder inclusion does not automatically generate consensus and/or a possible compromise. Decision-making processes often remain characterised by incessant struggles and divergent preferences, which may block the identification of shared solutions. In this regard, the idea of compromise plays a central role, as it enables the balancing of competing objectives and the construction of solutions that, while not optimal for all actors, are acceptable enough to allow improvements.

Studies on compromise-based decision methods show that the need to harmonise conflicting criteria is a usual and recurrent feature of complex decision problems [26, 27]. At the same time, research on stakeholder behaviour highlights that different groups may reveal heterogeneous attitudes towards compromise, ranging from willingness to negotiate to complete refusal; in some cases this factor leads to situations of conflict or decision-making gridlock [28].

To address these challenges, latest contributions have explored the integration of MCDA with conflict analysis and stakeholder-oriented approaches, showing that such integration can improve the capacity of decision-support instruments to deal with both technical and social dimensions of serious issues [29].

Hybrid models combining different multi-criteria techniques have been proposed to enhance the reliability and strength of evaluation results, particularly in contexts characterised by uncertainty and conflicting information [30].

In this framework, specific methods such as the Best–Worst Method (BWM) have been empirically validated as efficient tools for deriving consistent criteria weights with a reduced number of comparisons, while structured approaches based on pairwise comparisons contribute to the construction of transparent and reproducible evaluation models [31]. The flexibility and adaptability of multi-criteria methods in addressing heterogeneous decision-making environments [32] is further confirmed by the applications in urban and territorial contexts.

Despite the wide body of empirical and methodological contributions, an outstanding gap still emerges in the literature. In fact, limited attention has been devoted to the explicit identification of compromise solutions within integrated analytical frameworks, even if numerous studies demonstrate the effectiveness of MCDA in structuring and evaluating complex decision problems, and others emphasise the importance of stakeholder engagement.

Particularly, there is a lack of approaches able to distinguish between only theoretically valid alternatives and effectively implementable alternatives in real-world environments characterised by conflict, negotiation and institutional constraints, such as those detected in multi-actor governance arrangements and public–private partnerships. The gap underlines the need for methodological frameworks that explicitly address the

conditions under which compromise can emerge, supporting decision-makers in navigating compromise and identifying solutions able to balance competing interests while maintaining analytical consistency.

## 4 Methodology

The complexity of conflictual urban contexts, characterized by more stakeholders, heterogeneous value systems, and competing objectives, asks for the development of an integrated assessment framework able to represent divergent perspectives, multiple evaluation criteria, and the need to identify compromise solutions.

To address these challenges, the proposed model integrates three complementary methodological components:

– Social Multi-Criteria Evaluation (SMCE) as a conceptual framework;
– the Best–Worst Method (BWM) for criteria weighting;
– a MACBETH-inspired approach for the construction of value functions.

The framework is structured into six main phases described below.

The **first phase** consists in structuring the decision problem and identifying the relevant stakeholder groups involved in the evaluation process.

SMCE provides the conceptual foundation of the model, allowing the formal representation of a multiplicity of viewpoints and overcoming the constraints of one-dimensional economic evaluation.

Also, it allows incorporating different value systems, interests, and decision rationalities within a unified analytical framework.

Stakeholders are selected to represent the diversity of actors that are typically involved in questioned urban contexts, including institutional actors, private interests, and civil society groups.

Their inclusion ensures that the evaluation reflects the multiplicity of perspectives and potential conflicts underlying the decision-making process.

The **second phase** involves the definition of evaluation criteria.

Criteria are selected through a triangulation procedure that integrates insights from the scientific literature, contextual knowledge, and planned logic.

Particular attention is given to ensuring the internal coherence and non-redundancy of the selected criteria.

In this perspective, criteria are defined in such a way as to avoid overlaps or intersections and double counting effects, even if they continue to maintain their capacity to seize distinct dimensions of the decision issue.

Moreover, when necessary, criteria can be structured hierarchically into sub-criteria: in this way they allow a more detailed representation of complex evaluation dimensions.

This hierarchical organisation improves both the transparency of the evaluation process and the intelligibility of outputs; this is particularly true in contexts characterised by interdependencies among social, economic and institutional factors.

This ensures that the criteria capture the key dimensions of the decision problem—social, legal, economic, urban, and institutional—while maintaining enough discriminative capacity with respect to the alternatives.

The **third phase** focuses on the definition of alternative scenarios, ensuring consistency with the previously identified evaluation criteria.

Ensuring consistency means maintaining uniform standards to achieve reliable results. Also, it involves the creation of ordered and replicable procedures. Quality characterizes consistency.

A set of alternative scenarios is defined to represent feasible intervention options. The identification of alternatives responds to the need, inherent in the SMCE approach, to make decision options clear and comparable within a formalised evaluation structure.

These scenarios constitute an analytical translation of possible solutions typically emerging in complex urban conflicts.

The **fourth phase** focuses on the estimation of criteria weights for each stakeholder using the Best–Worst Method (BWM), a multi-criteria decision-making technique that allows for consistent and efficient elicitation of preferences.

The approach identifies the best and worst criteria and performing pairwise comparisons between them, and generates optimized weights through an optimization model.

For each stakeholder, the most important criterion considered ("Best") and the one considered least relevant ("Worst") are identified. Then, two sets of ordinal comparisons are defined: comparisons between the Best criterion and all other criteria, and comparisons between all criteria and the Worst.

In contexts where direct elicitation is not possible, preference structures can be rebuilt through the analysis of secondary sources, such as institutional documents, press articles, interviews, and public statements. These sources are collected and triangulated in order to formalise stakeholder positions within the BWM framework.

In case of ambiguity, judgments are assigned using conservative suppositions, minimising the intensity of preferences to reduce potential bias.

The produced comparisons are used to derive an optimal weight vector by solving a minimisation problem that reduces inconsistency between expressed preferences and resulting weights.

The use of BWM is particularly suitable in this context due to its capacity to reduce the cognitive weight connected to traditional pairwise comparison methods, while ensuring a high level of consistency in the derived weights.

In addition, a first-level sensitivity analysis can be performed on the weights and/or adjacent comparison intensities (e.g. $\pm$ 10%) to verify the stability of the outputs.

In the **fifth phase**, planning alternatives are evaluated through the building of value functions based on qualitative judgments, using a MACBETH-inspired approach.

This method allows for the construction of cardinal value scales (interval scales) derived from qualitative pairwise comparisons of differences in attractiveness between alternatives.

For each criterion and stakeholder, alternatives are compared in pairs and the intensity of preference is expressed using an ordered semantic scale (e.g. from "no difference" to "extreme difference").

These qualitative judgments are then translated into numerical values that preserve both the ranking and the relative intensity of differences, ensuring consistency with the logical constraints of the MACBETH approach.

In cases involving a limited number of alternatives, the problem can be reduced to the positioning of intermediate options between the most and least ideal alternatives. In such cases, a ratio-based positioning rule can be adopted, allowing the construction of a closed and reproducible value scale consistent with the expressed semantic judgments.

The internal consistency of judgments can be verified in terms of monotonicity and coherence of preference intensities, with minimal adjustments applied where it is necessary to restore logical consistency.

In the **sixth phase**, the scores derived from the value functions are aggregated using a weighted additive model, combining them with the criteria weights acquired through BWM for each stakeholder.

This process generates an actor–alternative evaluation matrix; this matrix allows for the construction of stakeholder-specific rankings, as well as the analysis of convergence and divergence among actors.

The framework enables the identification of value conflicts, potential compromise solutions (due to conflicts), and alternatives that may produce rejection conditions or de facto vetoes for specific stakeholder groups.

In this way, both the distinction between theoretically preferable solutions and those that are effectively implementable in multi-actor decision contexts are supported.

Figure 1 summarises the six phases of the proposed methodological framework.

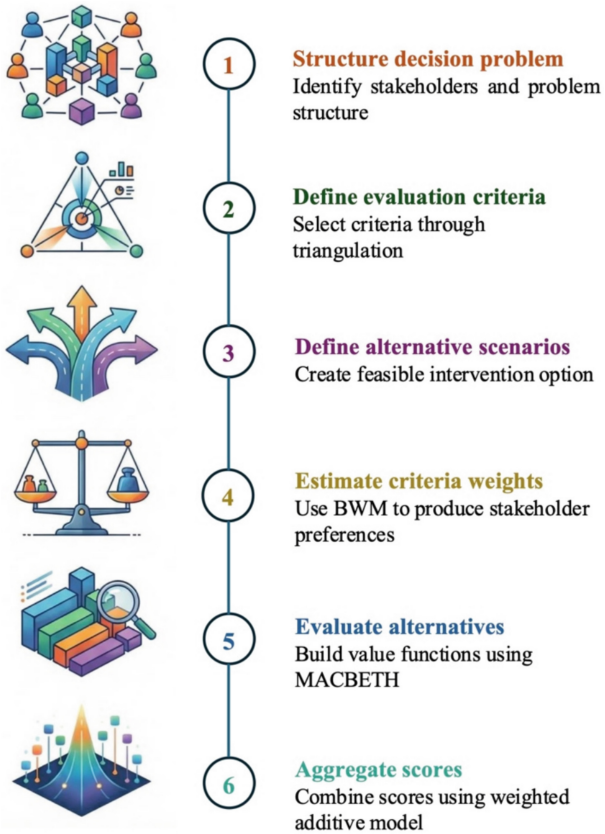


**Fig. 1.** Phases of the proposed methodological approach.

## 5 Conclusions

As stated previously, the present study confirms and strengthens the necessity for decision-support approaches that better conform to the complexity of today's urban contexts. Decision-making cannot be reduced to a simple technical practice in situations involving several stakeholders, and when everyone's interests seem not to be aligned. On the contrary, decision-making needs means that can take different perspectives into consideration, make trade-offs unambiguous, and promote the identification of possible and reasonable solutions [33].

In light of this perspective, this framework proposes a structured way to address these challenges. The integration of SMCE, BWM and a MACBETH-inspired approach allows the synchronized consideration of stakeholder inclinations, evaluation criteria and alternative settings. This makes it possible not only to arrange alternatives, but also to understand the origin of conflicts emerged (where and why), and what are the conditions that might reduce this contrast.

Among the most significant aspects of the framework one them comes out: its focus on the difference between what is theoretically desirable and what is effectively implementable. In many real-world conditions, the so-called "best" solution from an analytical point of view may not be acceptable to all stakeholders. The model openly cope with this gap, and it helps identify conciliation solutions that, even if not optimal or ideal for everyone, can be considered balanced enough to be realistically and reasonably carried out [34].

At the same time, the study shows the existence of some limits that should be acknowledged and considered. The reconstruction of stakeholder preferences and/or inclinations through secondary sources may introduce a certain degree of approximation, especially when direct interaction with actors is impossible. Also, the framework has been developed at a methodological level and would benefit from further testing through empirical applications [35].

Future developments could include a stronger integration and involvement of sharing processes, so allowing for direct stakeholder participation and responsibility, as well as the extension of the model to dynamic contexts where preferences and favourite conditions evolve over time [36].

In order to fortify the strength of the results, further work could also concentrate on the incorporation of ambiguous analysis.

In general, the proposed approach contributes to a more evident and complete decision-support paradigm, reinforcing the ability to focus on complexity and to contribute to the development and implementation of practicable and context-sensitive urban interventions and intermediations.

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## References


1. Black, R., Kniveton, D., Skeldon, R., Coppard, D., Murata, A., Schmidt-Verkerk, K.: Demographics and climate change: future trends and their policy implications for migration. Development Research Centre on Migration, Globalisation and Poverty, University of Sussex, Brighton, pp. 157–175 (2008)
2. Folke, C., Carpenter, S., Elmqvist, T., Gunderson, L., Holling, C.S., Walker, B.: Resilience and sustainable development: building adaptive capacity in a world of transformations. Ambio **31**(5), 437–440 (2002)
3. Anelli, D., Morano, P., Tajani, F., Sabatelli, E.: Impacts of urban decay on the residential property market: an application to the city of Rome (Italy). In: Gervasi, O., Murgante, B., Garau, C., Taniar, D.,C. Rocha, A.M.A., Faginas Lago, M.N. (eds.) Computational Science and Its Applications – ICCSA 2024 Workshops. ICCSA 2024. Lecture Notes in Computer Science, vol. 14822. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-65318-6_3
4. Alibašić, H.: Sustainability and Resilience Planning for Local Governments: the Quadruple Bottom Line Strategy. Springer, New York (2018)
5. Batty, M.: Cities as Complex Systems: Scaling, Interaction, Networks, Dynamics and Urban Morphologies (2009)
6. Portugali, J.: Cognition, complexity and the city. in: complexity, cognition and the City. Understanding Complex Systems. Springer, Berlin, Heidelberg (2011). https://doi.org/10.1007/978-3-642-19451-1_6
7. Bhatia, R., Pihlajamaa, M., Hyytinen, K., Jäntti, A.: Capabilities for transformative sustainability management in cities. Public Manag. Rev. **27**(4), 1179–1203 (2025)
8. Bates, G., Hasan, M.N., Barnfield, A., Bondy, K.: Urban policies and the creation of healthy urban environments: a review of government housing and transport policy documents in the United Kingdom. J. Urban Aff. **47**(6), 1942–1960 (2025)
9. Lu, Z., Wang, W., Guo, T., Li, Y., Wang, F.: Decoding urban policies: NLP-driven concise explanations. Environ. Plann. B Urban Anal. City Sci. **53**(1), 125–142 (2026)
10. Porto, M., Chester, M., Kim, Y., Mascaro, G., Srivastava, N.A.: Expanding infrastructure resilience horizons: safe-to-fail and social-ecological-technological dynamics for requisite variety. Sustainabil. Sci. 1–15 (2025)
11. Walker, R.J.: Phase change and the limits of resilience: a physics-inspired lens on societal fragility and collapse. Recoletos Multidisciplinary Res. J. **13**(2), 99–109 (2025)
12. Van Assche, K., Beunen, R., Duineveld, M.: Power of, on and in planning. In: Handbook on Planning and Power, pp. 354–366. Edward Elgar Publishing (2023)
13. Zhou, X., Lin, Y., Monstadt, J., Hooimeijer, P., Wang, S., Liu, Z.: Examining collaborative planning processes and outcomes in urban regeneration: a deliberative turn in China? Urban Stud. **62**(4), 682–699 (2025)
14. Milan, L., Kin, B., Verlinde, S., Macharis, C.: Multi-actor multi-criteria analysis for sustainable city distribution: a new assessment framework. Int. J. Multicriteria Decis. Making **5**(4), 334–354 (2015)
15. Ligtenberg, A., Wachowicz, M., Bregt, A.K., Beulens, A., Kettenis, D.L.: A design and application of a multi-agent system for simulation of multi-actor spatial planning. J. Environ. Manage. **72**(1–2), 43–55 (2004)
16. Anelli, D., Ranieri, R.: Resilience of complex urban systems: a multicriteria methodology for the construction of an assessment index. In: Calabrò, F., Della Spina, L., Piñeira Mantiñán, M.J. (eds.) New Metropolitan Perspectives. NMP 2022. Lecture Notes in Networks and Systems, vol. 482. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-06825-6_65
17. Ortega, J., Moslem, S., Palaguachi, J., Ortega, M., Campisi, T., Torrisi, V.: An integrated multi criteria decision making model for evaluating park-and-ride facility location issue: a case study for Cuenca city in Ecuador. Sustainability **13**(13), 7461 (2021)

18. Moslem, S., Farooq, D., Ghorbanzadeh, O., Blaschke, T.: Application of the AHP-BWM model for evaluating driver behavior factors related to road safety: a case study for Budapest. Symmetry **12**(2), 243 (2020)
19. Thinh, H.X., Trung, D.D.: A research on application of the measurement of alternatives and ranking according to compromise solution method for multi-criteria decision making in the grinding process. EUREKA: Phys. Eng. **2**, 101–110 (2022)
20. Marcelino, P., Antunes, M.D.L., Fortunato, E., Gomes, M.C.: Development of a multi criteria decision analysis model for pavement maintenance at the network level: application of the MACBETH approach. Front. Built Environ. **5**, 6 (2019)
21. Acosta, M., Corral, S.: Participatory multi-criteria assessment of forest planning policies in conflicting situations: the case of Tenerife. Forests **6**(11), 3946–3969 (2015)
22. Macharis, C., Baudry, G.: The multi actor multi criteria analysis framework. In: Decision-Making for Sustainable Transport and Mobility, pp. 2–27. Edward Elgar Publishing (2018)
23. De Brucker, K., Macharis, C., Verbeke, A.: Multi-criteria analysis and the resolution of sustainable development dilemmas: a stakeholder management approach. Eur. J. Oper. Res. **224**(1), 122–131 (2013)
24. Shen, L., Sun, X., Suo, W.: A MACBETH-based method for urban resilience evaluation. Proc. Comput. Sci. **214**, 456–460 (2022)
25. Rodrigues, T.C.: The MACBETH approach to health value measurement: building a population health index in group processes. Proc. Technol. **16**, 1361–1366 (2014)
26. Kundakcı, N.: Combined multi-criteria decision making approach based on MACBETH and MULTI-MOORA methods. Alphanumeric J. **4**(1), 17–26 (2016)
27. Srdjevic, B., Srdjevic, Z., Reynolds, K.M., Lakicevic, M., Zdero, S.: Using analytic hierarchy process and best-worst method in group evaluation of urban park quality. Forests **13**(2), 290 (2022)
28. Weber, J.: Gridlock in compromise, or is multi-objective optimisation possible in renewable energy planning? a stakeholder analysis using scenario-MCDA. Int. J. Sustain. Energ. **42**(1), 1538–1568 (2023)
29. Losa, F.B., Belton, V.: Combining MCDA and conflict analysis: an exploratory application of an integrated approach. J. Oper. Res. Soc. **57**(5), 510–525 (2006)
30. Pamučar, D., Ecer, F., Cirovic, G., Arlasheedi, M.A.: Application of improved best worst method (BWM) in real-world problems. Mathematics **8**(8), 1342 (2020)
31. Baja, S., Chapman, D.M., Dragovich, D.: Spatial based compromise programming for multiple criteria decision making in land use planning. Environ. Model. Assess. **12**(3), 171–184 (2007)
32. Bittencourt, M.: Sustainability assessment of university buildings: an application of a multi-criteria and multi-actor tool to help the decision-making process. Doctoral dissertation, Université de Versailles-Saint-Quentin-en-Yvelines (2017)
33. Morano, P., Tajani, F., Guarnaccia, C., Anelli, D.: An optimization decision support model for sustainable urban regeneration investments. WSEAS Trans. Environ. Dev. **17**, 1245–1251 (2021)
34. Guarini, M.R., D'Addabbo, N., Morano, P., Tajani, F.: Multi-criteria analysis in compound decision processes: the AHP and the architectural competition for the chamber of deputies in Rome (Italy). Buildings **7**(2), 38 (2017)
35. Anelli, D., Morano, P., Fariello, F., Sabatelli, E.: Environmental, social and governance (ESG) assessment with a two-phase goal-programming-based optimization model: a comparative study of Envipark and Kalundborg eco-industrial parks. Front. Built Environ. **12**, 1731282
36. Santucci, L., Cassalia, G., Calabrò, F.: Economic feasibility of a project for the reuse of the old hospital of nicotera as a center for eating disorders and for the enhancement of the mediterranean diet. In: Calabrò, F., Della Spina, L., Piñeira Mantiñán, M.J. (eds.) New Metropolitan Perspectives. NMP 2022. Lecture Notes in Networks and Systems, vol. 482. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-06825-6_225

# Rent and Buy Market Interactions: a Focus on Energy Performance and Building Technological Systems

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**Abstract.** This study investigates the relationship between the rental and sales segments of the housing market in the city of Rome (Italy), with a specific focus on the role of building energy efficiency and technological systems features. Although renting and buying are driven by distinct market drivers, both segments increasingly respond to sustainability-oriented and comfort-enhancing attributes. Understanding how these characteristics are appreciated across markets is fundamental for interpreting household choices, investor behaviour and policy effectiveness. The proposed methodological approach develops two separate econometric evaluation models, i.e. one for the sales market (BUY model) and one for the rental market (RENT model), to identify the most influential energy-related variables and building technological systems factors to quantify their marginal contribution to housing prices and rents. The two comparable datasets are constructed for properties sold and rented within the same urban context, specifically focusing on the following variables: energy performance label, central heating systems, photovoltaic installations, air conditioning systems and building automation technologies. Energy efficiency and technological factors have notable impacts on each housing segment, though with different intensities and directions. Overall, the findings highlight differentiated market appreciation of sustainable housing features and demonstrate the effectiveness of the flexible data-driven approach in capturing the cross-market dynamics.

**Keywords:** rental market · sale market · real estate · energy performance · EPC label · building automation · photovoltaic panels · influencing factors · econometric analysis

## 1 Introduction

The residential real estate sector is commonly articulated into two main components, namely the selling market and the renting market. While these segments operate according to distinct transactional logics, they are structurally interconnected and respond to a

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shared set of drivers. Changes in demand conditions, price levels and investment expectations in one segment often translate into adjustments in the other, contributing to cyclical dynamics that characterise urban housing markets. Factors such as credit availability, interest rate trends, fiscal frameworks and broader macroeconomic conditions influence households' and investors' choices between purchasing and renting, thereby shaping the relative balance between the two markets.

Alongside these general factors, the buildings attributes play an important role in the formation of prices and rents. In recent years, particular attention has been directed towards aspects related to energy performance, driven by regulatory requirements, rising energy costs and growing awareness of environmental sustainability [1, 2]. Energy efficiency is no longer perceived solely as a technical attribute, but rather as a component of overall housing quality that may affect operating expenses, comfort levels and long-term asset value. Consequently, energy-related variables are progressively incorporated into the decision-making processes of both buyers and tenants.

Within this context, features such as the energy label, the presence of central heating systems, photovoltaic installations, air conditioning and building automation technologies have the potential to influence residential market outcomes. However, the extent to which these characteristics are reflected in selling prices and rental levels may differ between the two segments, depending on the objectives, time horizons and financial constraints of market participants. While purchasers may place greater emphasis on long-term performance and capital value, tenants may prioritise immediate usability and cost efficiency, leading to differentiated market appreciations and preferences mechanisms.

Despite the growing relevance of energy performance in the real estate market, empirical evidence comparing its impact across sales and rental markets remains limited, particularly in cities characterised by heterogeneous building stocks and complex demand structures. Addressing this gap is especially relevant for urban contexts where territorial policies objectives related to energy transition intersect with housing affordability and investment dynamics.

In this background, the present paper focuses on the analysis of the relationships between residential sales and rental markets, with specific attention on the role played by energy performance variables and technological systems factors. The empirical investigation is carried out with reference to the city of Rome (Italy), providing a structured framework for examining similarities and divergences in the way these building characteristics influence prices and rents.

The structure of the paper is described below: Sect. 2 presents a review of the existing literature on the relationship between building energy performance and residential property values; Sect. 3 outlines the proposed methodological approach aimed at evaluating the impact of building energy performance and related techno-logical systems on housing prices; Sect. 4 illustrates the application of the method-ology to the case study related to the city of Rome (Italy); Sect. 5 discusses the conclusions and the further insights of the analysis.

## 2 Literature Background

During the last two decades, the academic literature has increasingly attested that building energy performance and associated technological systems are significant determinants of residential property values [3, 4], both in terms of selling prices and rental fees. Early studies by Brounen and Kok (2011) [5] and Hyland, Lyons and Lyons (2013) [6] have shown that homes with higher energy ratings (Energy Performance Certificates, EPCs) enjoy a green premium generally ranging from 2% to 10%, with positive effects also observed in the rental market, albeit often smaller than in sales. Comparable evidence has been reported in the context of Germany [7, 8], Sweden [9, 10], Wales [11] and Denmark [12], confirming that the real estate market tends to partially capitalize expected energy savings and improvements in housing comfort.

A comprehensive review of the European literature developed by Ou et al. (2025) [13] has highlighted high heterogeneity in the magnitude of premiums, attributable to i) government differences, ii) varying quality of EPC information, iii) input data included in econometric analysis and iv) stage of real estate market evolution. Similarly, Aydin, Brounen and Kok (2020) [14] have used large-scale disaggregated transaction data to show that the contribution of energy performance tends to be stronger in markets with higher buyer awareness and more transparent energy disclosure regimes.

From a methodological perspective, almost all contributions have adopted hedonic pricing approaches [15], where energy performance - measured either as EPC label or a continuous energy consumption index - is included among the structural characteristics of the property. However, research such as Fuerst, McAllister and Nanda (2015) [16] and Kahn and Kok (2014) [17] explicitly addressed potential endogeneity and omitted variable bias by applying matching techniques, fixed or spatial effects and instrumental strategies, in order to isolate the causal effect of energy performance on property prices and rental rates, separating it from other potentially correlated physical or locational characteristics.

In the Italian context, recent studies by Loberto, Mistretta and Spuri (2023) [18] and Giarda and Panarello (2025) [19] pointed out statistically significant price premiums associated with higher energy labels, with impacts that vary across regions, property types and segments of the price distribution. These findings are consistent with Chareyron (2026) [20], who have recognised similar price increments in the French housing market, and with de Ayala, Galarraga and Spadaro (2016) [21] in Spain, indicating that energy rating consistently affects property values across a wide range of European housing markets.

Beyond overall energy certification, the emerging literature has increasingly examined the role played by the presence of specific building technologies and systems in the selling and rental prices formation processes. For the U.S. market, Hoen et al. (2013) [22] have observed that homes equipped with photovoltaic systems tend to sell at significantly higher prices (on average above 3–4%), while Dastrup et al. (2012) [23] have demonstrated how these effects are moderated by tax incentives and expectations regarding future energy costs. Additional research by Wee (2016) [24] have estimated how much a solar PV system affects the price of a home on the island of O'ahu (Hawaii, U.S.), pointing out that a PV home is worth 5.4% more on average than a non-PV one, which translates to an increase of 35,000$.

Studies examining Heating, Ventilation and Air Conditioning (HVAC) systems, insulation upgrades and smart controls - such as Eichholtz, Kok and Quigley (2013) [25] - have indicated that certified green homes not only achieve higher prices but may also experience lower price volatility during market downturns, suggesting an additional risk-mitigating benefit of energy and performance-oriented investments. Newell and Siikamäki (2014) [26] concluded that disclosure of expected operating costs can strongly affect potential buyer willingness to pay, implying that information transparency - not just property physical performance and characteristics - assumes a key function in value realization.

Moreover, a growing body of relevant research has extended the analysis of the relationship between the property energy component and real estate values in both sales and rental segments to additional markets and contexts. For example, Deng, Li and Quigley (2012) [27] and Chegut, Eichholtz and Holtermans (2016) [28] have confirmed positive price effects of energy efficiency in multiple European countries, while Jiang et al. (2021) [29] and Zhang et al. (2023) [30] have provided evidence from Asia, showing that both sales prices and rental fees benefit from higher energy performance. Other studies, such as Ullah and Sepasgozar (2020) [31], Kahn and Kok (2014) [17] and Allameh, et al. (2012) [32], have emphasized the role of specific building features, including insulation, HVAC systems and smart controls, in shaping contributions for both ownership and rental sectors. Specifically focused on rental markets Reichardt et al. (2012) [33] in the U.S., Fuerst and Warren-Myers (2018) [34] in Australia and Eichholtz, Kok and Quigley (2010) [35] have recognized that energy-efficient properties tend to attract higher rents as well as increase in selling prices.

Overall, the literature on the energy topic associated to the real estate field suggests that property markets increasingly incorporate information related to energy performance and building technologies into property values. However, the magnitude of the weight in the selling and rental values is not uniform, but depends on buyer awareness, energy costs dynamics, regulatory frameworks and the quality of energy information transparency policies. The importance of robust empirical investigations based on effective evaluation methodological approaches is crucial to carry out cross-market comparisons for identifying causal effects and informing both investors and policymakers about the value implications of energy efficiency and technological upgrades.

## 3 Methodological Approach

According to the scope of the present research, a methodological approach aimed at evaluating the impact of building energy performance and related technological systems on residential property values, both for sales and rentals, is proposed and tested. Specifically, the objectives of the methodological approach are i) to identify the key energy-related and technological systems characteristics affecting selling prices and rental rates, and ii) to compare how these determinants operate across the two market segments. In this sense, while sales and rental markets share the same urban context, the role of energy efficiency, HVAC systems, photovoltaic installations and smart automation technologies may differ, reflecting distinct preferences, financial constraints and decision-making patterns of buyers versus tenants.

The approach relies on the definition of two tailored models - the BUY model and the RENT model - calibrated on datasets comprising properties sold or leased in a specific time horizon. By isolating the marginal contribution of each energy-related and structural variable, the methodological approach allows a systematic evaluation of whether the same factors determine comparable, contrasting or negligible effects on market prices and rents. This comparative perspective provides insight into how households incorporate energy considerations into their choices, and supports more informed property appraisals, investment strategies and government policies aimed at promoting energy-efficient housing.

The methodological approach follows six sequential steps:

Phase 1 – Variable definition: key dependent variables (selling price or rental fee depending on the analyzed market segment) and explanatory factors are selected, with a focus on energy efficiency elements (energy labels, heating systems, insulation, renewable energy installations, automation technologies included in the property) alongside ordinary physical/structural and locational attributes (i.e. intrinsic and extrinsic characteristics that are mostly taken into account in the negotiation phases by potential buyers). Stakeholder and local market operators' consultation ensures that the variables to be selected reflect the most relevant drivers in each market.

Phase 2 – Data collection: comprehensive datasets are built from multiple sources to capture both the technical and market characteristics of the housing stock. Special attention is given to obtaining accurate energy performance data. In this sense, for each database (constituted by rented or sold residential unit) the values of the selected variables are recorded.

Phase 3 – Data cleaning and standardization: data are filtered to remove inconsistencies, while variables values are normalized to enable comparison and accurate model estimation.

Phase 4 – Evaluation models definition: econometric techniques are applied separately to the sales and rental datasets to quantify the effect of energy performance and related features on prices and rents, and to identify the functional relationships between dependent and explanatory variables.

Phase 5 – Assessment of marginal contribution: the influence of each energy-related and intrinsic characteristic is analyzed, considering statistical significance and relative importance. This phase highlights which energy features most strongly influence housing market dynamics, including their effect on both selling prices and rental fees. Moreover, it allows for the identification of synergies between different technological systems (e.g., insulation, HVAC, photovoltaic installations and smart automation) and provides insights into how these features are valued by different market participants, helping to explain variations in price formation and tenant or buyer preferences.

Phase 6 – Comparative Analysis: results from the BUY and RENT models are systematically compared to assess whether energy efficiency and technological features have similar, divergent, or limited effects across the two market segments. This analysis provides evidence of how household decision-making and market mechanisms differ and informs targeted strategies for promoting energy-efficient housing, optimizing investment returns and guiding urban policy interventions.

In Fig. 1 the main steps of the proposed methodological approach are summarized.

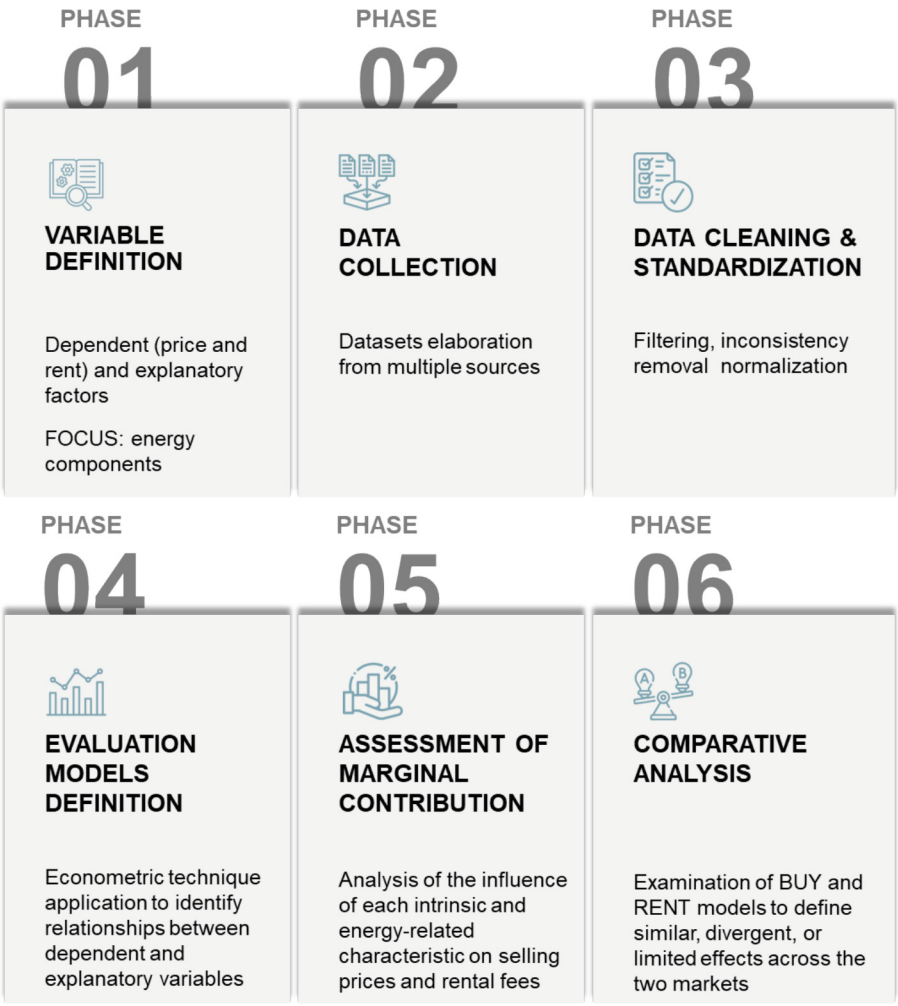


**Fig. 1.** Main steps of the proposed methodological approach

## 4 Case Study

The proposed methodological approach is applied to the city of Rome (Italy) using two datasets of residential properties on rental (1,800 units) and on sale (11,359 units) in the first half of 2025.

The presence of two distinct databases allows for a coherent comparison between the factors influencing asking rents and those affecting asking selling prices, since both samples refer to properties located within the same geographic context. The shared geographical context allows for a consistent comparison of the determinants of rental and selling prices, isolating segment-specific dynamics from locational effects.

The six-step methodology is implemented to estimate the BUY and RENT models, illustrating their ability to capture the key factors driving price formation in both market segments.

Phase 1 involves the definition of the dependent variables, represented by natural logarithm of the asking unitary selling price, expressed in €/m2 for the sales dataset - BUY model - ($Y = \ln(Y_S)$), and by the unitary rental price, denoted as $Y_R$ and expressed in €/m2/month for the rental dataset - RENT model.

For both samples, the selection of intrinsic property characteristics, with particular emphasis on energy performance variables are selected. These include:

- energy label,
- central heating systems,
- photovoltaic installations,
- air conditioning systems,
- building automation technologies,

alongside conventional physical and functional attributes.

It should be pointed out that the set of independent variables considered in this analysis involves exclusively intrinsic variables, while extrinsic factors - such as location and broader market conditions - are not taken into account. This choice is justified by the aim of isolating the specific contribution of building-level factors, particularly energy efficiency features, to price formation, thereby reducing potential confounding effects arising from spatial heterogeneity and local market dynamics.

A summary of the independent variables chosen based on recommendations from key local real estate market operators and reflect the primary attributes considered during negotiation by sellers, buyers, and tenants is reported in Table 1. The acronym, full descriptive name, and corresponding unit of measurement for each variable are specified.

**Table 1.** Summary of the independent variables considered in the analysis

| Variable | Acronym | Unit of measurement |
|---|---|---|
| Property type (apartment) | [A] | dummy variable<br>[0 = absence; 1 = presence] |
| Floor Area | [F] | $m^2$ |
| Number of Bathrooms | [B] | n. |
| Number of Rooms | [R] | n. |
| Number of Bedrooms | [Be] | n. |
| Floor Level | [Mf] | n. |
| Last Floor | [Lf] | dummy variable<br>[0 = absence; 1 = presence] |
| Energy Label | [E] | Score<br>[from 1 = label G to 10 = label A4] |

(*continued*)

**Table 1.** (*continued*)

| Variable | Acronym | Unit of measurement |
|---|---|---|
| Property Maintenance State | [S] | Score<br>[1 = to be refurbished, 2 = poor conditions, 3 = good conditions, 4 = excellent/fully renovated] |
| has_Furniture | [Fu] | Score<br>[0 = unfurnished, 1 = partially furnished (essential furnishings only), 2 = largely furnished (almost fully furnished),<br>3 = fully furnished] |
| Lift (i.e. presence of the lift in the building in which the property is located) | [L] | dummy variable<br>[0 = absence; 1 = presence] |
| Private Garden | [Pg] | dummy variable<br>[0 = absence; 1 = presence] |
| Shared Garden | [Sg] | dummy variable<br>[0 = absence; 1 = presence] |
| Private Garage | [G] | dummy variable<br>[0 = absence; 1 = presence] |
| Parking Space | [Ps] | dummy variable<br>[0 = absence; 1 = presence] |
| Cellar | [C] | dummy variable<br>[0 = absence; 1 = presence] |
| Terrace | [T] | dummy variable<br>[0 = absence; 1 = presence] |
| Building Automation technologies | [Ba] | dummy variable<br>[0 = absence; 1 = presence] |
| Central Heating | [Ch] | dummy variable<br>[0 = absence; 1 = presence] |
| Photovoltaic installations | [Ph] | dummy variable<br>[0 = absence; 1 = presence] |
| Air Conditioning systems | [Ac] | dummy variable<br>[0 = absence; 1 = presence] |
| Optical Fiber | [Of] | dummy variable<br>[0 = absence; 1 = presence] |
| Fireplace | [Fi] | dummy variable<br>[0 = absence; 1 = presence] |
| Alarm | [Al] | dummy variable<br>[0 = absence; 1 = presence] |

(*continued*)

**Table 1.** (*continued*)

| Variable | Acronym | Unit of measurement |
|---|---|---|
| has_Concierge | [Co] | score<br>[0 = never available, 1 = limited availability (only for a few hours), 2 = daytime availability only, 3 = always available (24/7)] |

Phase 2 focuses on the systematic collection and verification of data for all selected variables. In particular, the two datasets are derived from property listings gathered across the leading Italian real estate websites as well as local market operators, providing a uniform and comparable information base for both sales and rental markets.

Phase 3 is dedicated to data filtering and normalization, aimed at removing inconsistencies and outliers and harmonising the scale of the explanatory variables to ensure comparability across observations.

In Phase 4, an econometric technique called Evolutionary Polynomial Regression (EPR) is applied separately to the sales and rental datasets. This method, which integrates hedonic pricing logic with genetic algorithms, allows for the identification of (i) nonlinear relationships between the dependent variable and the explanatory ones and (ii) interaction effects among property characteristics. Adopting this dual approach facilitates a systematic comparison between the determinants shaping rental levels and those influencing selling prices, while maintaining constant the territorial and contextual conditions that characterize both samples. In particular, by estimating two valuation models - one for the purchase market (BUY - Eq. 1) and one for the rental market (RENT - Eq. 2) - within the same geographical context but under different market mechanisms, the distinct contributions of intrinsic property characteristics to the formation of values across the two markets are investigated.

For each of the two examined market segments, the EPR has generated a wide set of candidate polynomial functions, in which the dependent variable corresponds either to the unitary selling price or to the unitary rental fee of the property, whereas the explanatory variables are automatically selected from the group of intrinsic attributes included in Table 1. Each functional specification assumes the form of a sum of additive components, where every term is composed of combinations of independent variables raised to predetermined numerical exponents. Within the modelling phase, the set of admissible exponents is constrained to the values (0; 0.5; 1; 2), and the maximum number of additive components allowed in each equation is fixed at ten. This restriction is introduced to maintain a suitable compromise between the descriptive capacity of the model and the interpretability of the resulting mathematical formulation.

Among the numerous equations determined by the EPR technique for the residential market of Rome, the final models (i.e. the optimal BUY and RENT econometric evaluation models) have been selected by jointly evaluating several criteria, including model statistical goodness, algebraic parsimony and the empirical reliability of the estimated equation terms' coefficients.

$Y_S = \text{Exp}\ (0.74864 \bullet S^{0.5} + 0.082215 \bullet R \bullet G^{0.5} \bullet C * Ph^2 + 0.0013128 \bullet B^2 \bullet Be^2 \bullet A^{0.5} - 0.050351 \bullet F^{0.5} \bullet S^{0.5} + 0.017866 \bullet A^{0.5} \bullet MF \bullet T^2 + 0.00033002 \bullet A^{0.5} \bullet F \bullet R \bullet G^{0.5} - 0.20416 \bullet A + 0.066377 \bullet A \bullet B \bullet E^{0.5} \bullet L^2 + 7.5165)$.

$Y_R = 1.8557 \bullet Ac^{0.5} + 8.4831 \bullet S^2 \bullet Fu^2 \bullet Pg \bullet Ps^{0.5} \bullet T^2 \bullet A \bullet Co^2 + 0.82985 \bullet E^2 \bullet Fu^2 \bullet Of \bullet Co^{0.5} + 2.5035 \bullet Ba \bullet Lf^{0.5} \bullet S \bullet Fu^2 \bullet L^2 \bullet Ac^{0.5} - 116.1861 \bullet F^{0.5} + 94.8019 \bullet F + 120.8465 \bullet F^2 \bullet Fu^2 \bullet Ph^2 \bullet A^2 - 3.4591 \bullet A^{0.5} \bullet Ps + 2.987 \bullet A^{0.5} \bullet Ba^{0.5} \bullet S - 2.0621 \bullet A \bullet F^{0.5} \bullet E^{0.5} \bullet S \bullet T + 43.9611$.

Phase 5 concerns the interpretation of the results. For both models (BUY and RENT) the analysis of the functional relationships between the dependent variable (selling prices and rental fees) is developed. Specifically, the marginal contribution of each selected factor is assessed through a simulation procedure. In particular, the i-th explanatory variable is varied across the range of values observed in the sample, while all other variables are fixed at their respective mean levels.

In line with the objectives of this study, the following results discussion focuses specifically on the functional relationships associated with variables describing building energy performance and technological systems. All the relationships identified by both econometric models are consistent with expectations, reflecting the market mechanisms that are empirically observed and commonly recognised within the residential real estate sector of the city of Rome.

### 4.1 BUY Model

In the BUY model, variables related to building energy performance and technological systems emerge as significant determinants of residential selling prices.

The energy label exhibits a clear positive and progressive relationship with unitary prices, detecting that higher levels of energy efficiency are systematically capitalised into market values. The strongest variation emerges in the transition from the least efficient labels to intermediate classes, signalling that the market strongly penalises properties with poor energy performance. This pattern suggests that buyers explicitly account for expected reductions in energy consumption, operating costs and improvements in indoor comfort when forming their willingness to pay.

Similarly, photovoltaic installations are associated with a distinct price premium, confirming that on-site renewable energy generation is recognised as a value-enhancing feature with long-term economic and environmental benefits. In fact, when the variable shifts from the absence to the presence of the system, the unitary selling price increases significantly, indicating that the market systematically attribute a premium for dwellings equipped with renewable energy technologies. This outcome reflects the growing relevance assigned by buyers to solutions capable of reducing energy expenditure and improving environmental sustainability and contributing directly to property appreciation.

It should also be pointed out that air conditioning systems, building automation technologies and central heating systems have not been included in the final evaluation model, as the EPR selection procedure has not identified them as statistically significant contributors to price formation within the analysed dataset.

Overall, the BUY model reveals a coherent monetisation of energy-related attributes into residential selling prices, underscoring the central role of energy performance in contemporary housing market valuations. The graphical representations of the functional relationships between the selling prices and the factors associated with the building energy performance and technological systems are reported in Fig. 2.

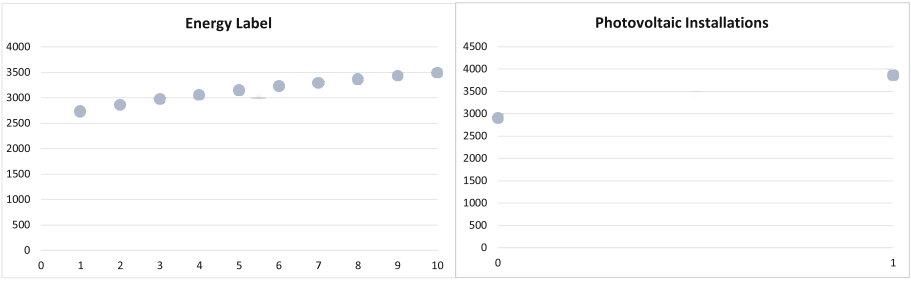


**Fig. 2.** Functional relationships between the energy-related variables selected by the EPR technique and the unitary selling prices in the BUY model

## 4.2 RENT Model

In the RENT model, energy-related variables and technological systems factors exhibit differentiated effects on rental price formation, reflecting tenants' priorities and short-term decision horizons.

The energy label shows a positive but limited influence on unitary rents, indicating that energy efficiency is recognised by tenants but plays a secondary role compared to immediate comfort-oriented attributes. In fact, the model suggests that improvements in the energy rating are associated with marginally higher rental levels, although the effect remains relatively limited in magnitude. This may suggest that the expected savings on operating costs are only partially capitalised into rents within the Roman rental market.

Photovoltaic installations are associated with a rental premium, showing tenants' appreciation for potential energy savings and environmentally sustainable features, albeit with a weaker effect than in the sales market. In this sense, rental units equipped with solar energy systems tend to achieve slightly higher rents, reflecting tenants' appreciation for the potential reduction in electricity costs and the environmental benefits connected to renewable energy production. Moreover, photovoltaic installations may signal the presence of recently renovated or technologically upgraded buildings, indirectly contributing to the overall attractiveness of the dwelling.

The availability of air conditioning systems emerges as one of the most relevant energy-related determinants of rents, reflecting strong demand for indoor comfort under Rome's Mediterranean climate characterised by hot summer periods. The installation of air conditioning therefore increases the perceived quality of the dwelling and reduces potential discomfort related to indoor temperatures, leading to a higher willingness to pay among tenants. The detected relationship confirms that climate-control technologies represent a relevant attribute in shaping rental values.

The presence of building automation technologies shows a positive relationship with rental values. Smart systems capable of managing lighting, climate control or security

features contribute to improving the usability and technological quality of the dwelling. The model therefore attests that tenants attribute additional value to properties integrating modern digital management systems, as these solutions enhance both convenience and perceived housing modernity.

Among the characteristics related to technological and energy components, it should be noted that central heating systems have not been included in the optimized predictive model, as the EPR selection did not identify them as statistically significant contributors to rental price formation. This outcome may be explained by the widespread presence and standardisation of central heating across the properties of the collected sample, which reduces its variability and, consequently, its marginal impact on rental values.

In Fig. 3, the graphs illustrating the detected trends for each selected variable are reported.

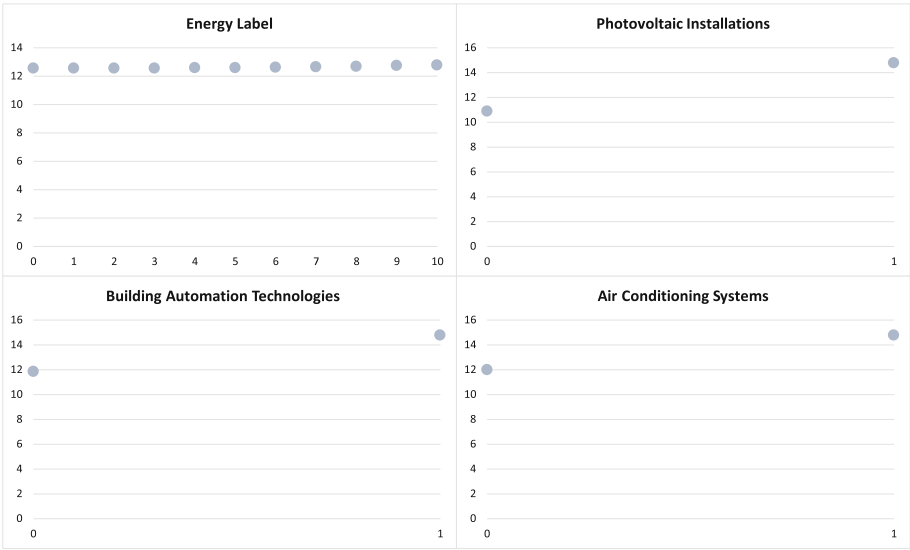


**Fig. 3.** Functional relationships between the energy-related variables and the technological systems factors selected by the EPR technique and the unitary rental prices in the RENT model

### 4.3 Comparing the Two Econometric Models

Phase 6 of the methodological approach applied to the selected case study involves the comparative assessment of the extent to which energy-related variables and technological systems factors are capitalised into selling prices and rental values. The results of the two EPR models highlight fundamental differences in the way energy characteristics of residential buildings influence prices in Rome's housing market. In the sales segment, the BUY model shows that energy performance plays a key role in determining property values. The positive and progressive relationship between the energy label and selling prices indicates that residential buildings with higher energy classes tend to achieve higher market prices. This suggests that buyers consider the economic and qualitative advantages associated with energy-efficient buildings, such as lower energy

consumption, reduced operating costs and improved indoor comfort. In this context, a higher energy label reflects a higher buyers' willingness to pay that is, consequently, reflected in captured in real estate dynamics. On the other hand, the RENT model attests that, while energy-related variables still show a positive influence on rental levels, their overall impact is more limited. The energy label shows a positive but relatively modest effect on rents. This behaviour could demonstrate that tenants recognize the importance of energy efficiency but do not capitalise its long-term benefits when determining their willing to pay for a dwelling on rent, due to the typically shorter time horizon associated with rental rather than buying.

A different result is obtained for the factor "photovoltaic installations", which is associated with a price premium in both the sales and rental market, as the presence of on-site renewable energy production represents an additional value component that can lead to lower electricity expenditures and greater environmental sustainability. The found marginal contribution of photovoltaic installations to property prices is quantitatively analogous in both the sales and rental segments, suggesting that this feature adds comparable value to dwellings whether they are sold or rented,

This similarity may be explained by the increasing importance of energy cost savings and sustainability in household decision-making, which appear to influence both long-term investment choices in the sales market and willingness to pay in the rental market.

By contrast, the availability of air conditioning systems and the presence of building automation technologies emerge among the most influential technological factors only in the RENT model. This result reflects the importance of immediate indoor comfort for occupants, particularly in a city such as Rome where summer temperatures can be high. While energy-efficient features like photovoltaic installations provide value across both sales and rental markets, technologies that enhance short-term comfort, such as air conditioning and smart building systems, are particularly rewarded in the rental segment, where tenants prioritize daily usability and comfort over long-term energy savings. This distinction underscores how different types of building characteristics can influence willingness to pay depending on the time horizon and priorities of buyers versus renters. In particular, the result appears consistent with the underlying dynamics of the two market segments considered. In the rental market, high attention is generally paid to elements such as air conditioning systems and building automation, as these features directly enhance immediate living comfort and represent a relevant factor in tenants' decision-making process: i.e. renters tend to prefer properties that are ready to use and equipped with modern services. Moreover, these technologies can mitigate the perceived discomfort and uncertainty related to short- and medium-term occupancy, thereby further influencing tenants' preferences.

On the other hand, in the sales market, buyers typically adopt a longer-term perspective and assign greater importance to structural characteristics rather than specific technological features. The latter are generally characterized by rapid technological obsolescence and relatively low installation costs, making their presence less decisive at the time of purchase, as they can be easily upgraded or installed at a later stage. In this context, the observed market appreciation of such attributes is different in the sale

sector compared to the rental ones, highlighting that their market appreciation depends on the transaction type and user needs.

Furthermore, the econometric analysis shows that central heating is not identified as a significant factor in any of the two evaluation models, attesting that this feature neither substantially influences property prices nor rental values. This may indicate that central heating is considered a standard provision in the housing stock of the city of Rome and therefore does not serve as a differentiating factor compared to other technological or energy-efficient features.

## 5 Conclusions

From a comparative perspective, the analysis of the obtained BUY and RENT models has highlighted both convergences and divergences in the capitalisation of energy-related variables and technological systems factors within the residential market of the city of Rome. The findings indicate that energy efficiency measures and on-site renewable technologies, such as photovoltaic installations, consistently contribute to price premiums across both market segments. In addition, building technological systems that enhance immediate comfort and control, including air conditioning and building automation, exert a stronger influence on rental price formation, reflecting the shorter planning horizon and day-to-day usability priorities of renters.

These insights point out the differentiated ways in which market participants value sustainability and comfort, and they provide useful indications for policymakers, developers and investors aiming to promote energy-efficient housing strategies that are consistent with the distinct logics of sales and rental segments.

The structured approach implemented in the present work – based on the twofold application of the econometric EPR technique - offers a robust analytical framework for evaluating the role of building energy performance and technological systems in shaping residential market outcomes and for identifying similarities and contrasts between the different market sectors under identical spatial conditions.

Integrating previous works results [36–39], future developments of this research may include the extension of the analysis to different international and national geographical contexts and comparing the results obtained using alternative assessment methodologies. These further insights would allow for a broader evaluation of how energy-related variables and technological systems influence residential property values across diverse markets and would verify the robustness and generalisability of the current findings.

**Note:** The current study has been developed within the current research “Evaluation models for the preservation and the revitalization of the small towns”, Call for Research Projects 2024, Sapienza University of Rome.

## References

1. Tajani, F., Cerullo, G., Stara, F., Sica, F.: Multidimensional models for building decarbonization pathways. Bus. Strategy Environ. 1–21 (2025)

2. Sica, F., Tajani, F., Cerullo, G.: An evaluation model for an optimal decarbonisation process in the built environment. Built Environ. Project Asset Manag. **15**(1), 51–66 (2025)
3. Morano, P., Tajani, F., Di Liddo, F., Guarnaccia, C.: The value of the energy retrofit in the Italian housing market: two case-studies compared. WSEAS Bus. Econ. **15**, 249–258 (2018)
4. Tajani, F., Morano, P., Di Liddo, F., Doko, E.: A model for the assessment of the economic benefits associated with energy retrofit interventions: an application to existing buildings in the Italian territory. Appl. Sci. **12**(7), 3385 (2022)
5. Brounen, D., Kok, N.: On the economics of energy labels in the housing market. J. Environ. Econ. Manag. **62**(2), 166–179 (2011)
6. Hyland, M., Lyons, R.C., Lyons, S.: The value of domestic building energy efficiency—evidence from Ireland. Ener. Econ. **40**, 943–952 (2013)
7. Cajias, M., Piazolo, D.: Green performs better: energy efficiency and financial return on buildings. J. Corp. Real Estate **15**(1), 53–72 (2013)
8. Taruttis, L., Weber, C.: Estimating the impact of energy efficiency on housing prices in Germany: does regional disparity matter? Energy Econ. **105**, 105750 (2022)
9. Högberg, L.: The impact of energy performance on single-family home selling prices in Sweden. J. Euro. Real Estate Res. **6**(3), 242–261 (2013)
10. Cerin, P., Hassel, L.G., Semenova, N.: Energy performance and housing prices. Sustain. Dev. **22**(6), 404–419 (2014)
11. Fuerst, F., McAllister, P., Nanda, A., Wyatt, P.: Energy performance ratings and house prices in Wales: an empirical study. Energy Policy **92**, 20–33 (2016)
12. Jensen, O.M., Hansen, A.R., Kragh, J.: Market response to the public display of energy performance rating at property sales. Energy Policy **93**, 229–235 (2016)
13. Ou, Y., Bailey, N., McArthur, D.P., Zhao, Q.: The price premium of residential energy performance certificates: a scoping review of the European literature. Energy Build. **332**, 115377 (2025)
14. Aydin, E., Brounen, D., Kok, N.: The capitalization of energy efficiency: evidence from the housing market. J. Urban Econ. **117**, 103243 (2020)
15. Rosen, S.: Hedonic prices and implicit markets: product differentiation in pure competition. J. Polit. Econ. **82**(1), 34–55 (1974)
16. Fuerst, F., McAllister, P.M., Nanda, A., Wyatt, P.: Variations in the implicit pricing of energy performance by dwelling type and tenure: a study of Wales (2015). SSRN 2633539
17. Kahn, M.E., Kok, N.: The capitalization of green labels in the California housing market. Reg. Sci. Urban Econ. **47**, 25–34 (2014)
18. Loberto, M., Mistretta, A., Spuri, M.: The capitalization of energy labels into house prices. Evidence from Italy. Evidence from Italy - November 14, 2023. Bank of Italy Occasional Paper 818 (2023)
19. Giarda, E., Panarello, D.: The energy efficiency price premium of residential buildings in three Italian regions. Energy Res. Soc. Sci. **121**, 103932 (2025)
20. Chareyron, S.: The valuation of energy efficiency labels in the French housing market. Urban Studies, 00420980251410866 (2026)
21. de Ayala, A., Galarraga, I., Spadaro, J.V.: The price of energy efficiency in the Spanish housing market. Energy Policy **94**, 16–24 (2016)
22. Hoen, B., Wiser, R., Thayer, M., Cappers, P.: Residential photovoltaic energy systems in California: the effect on home sales prices. Contemp. Econ. Policy **31**(4), 708–718 (2013)
23. Dastrup, S.R., Graff Zivin, J., Costa, D.L., Kahn, M.E.: Understanding the Solar Home Price Premium: Electricity Generation and. NBER Working Paper, w17200 (2011)
24. Wee, S.: The effect of residential solar photovoltaic systems on home value: a case study of Hawai 'i. Renew. Energy **91**, 282–292 (2016)
25. Eichholtz, P., Kok, N., Quigley, J.M.: Doing well by doing good? green office buildings. Am. Econ. Rev. **100**(5), 2492–2509 (2010)

26. Newell, R.G., Siikamäki, J.: Nudging energy efficiency behavior: the role of information labels. J. Assoc. Environ. Resour. Econ. **1**(4), 555–598 (2014)
27. Deng, Y., Li, Z., Quigley, J.M.: Economic returns to energy-efficient investments in the housing market: evidence from Singapore. Reg. Sci. Urban Econ. **42**(3), 506–515 (2012)
28. Chegut, A., Eichholtz, P., Holtermans, R.: Energy efficiency and economic value in affordable housing. Energy Policy **97**, 39–49 (2016)
29. Jiang, Y., Xing, Y., Zhao, D., Jiao, R.: Resale of green housing compensates for its premium pricing: an empirical study of China. J. Green Build. **16**(4), 45–61 (2021)
30. Zhang, B., Zhang, Y., Li, J., Song, Y., Wang, Z.: Does the energy efficiency of buildings bring price premiums? evidence from urban micro-level energy data. Renew. Sustain. Energy Rev. **181**, 113315 (2023)
31. Ullah, F., Sepasgozar, S.M.: Key factors influencing purchase or rent decisions in smart real estate investments: a system dynamics approach using online forum thread data. Sustainability **12**(11), 4382 (2020)
32. Allameh, E., Heidari Jozam, M., de Vries, B., Timmermans, H., Beetz, J., Mozaffar, F.: The role of smart home in smart real estate. J. Euro. Real Estate Res. **5**(2), 156–170 (2012)
33. Reichardt, A., Fuerst, F., Rottke, N., Zietz, J.: Sustainable building certification and the rent premium: a panel data approach. J. Real Estate Res. **34**(1), 99–126
34. Fuerst, F., Warren-Myers, G.: Does voluntary disclosure create a green lemon problem? energy-efficiency ratings and house prices. Energy Econ. **74**, 1–12 (2018)
35. Eichholtz, P., Kok, N., Quigley, J.M.: The economics of green building. Rev. Econ. Stat. **95**(1), 50–63 (2013)
36. Gabrielli, L., Ruggeri, A.G.: Optimal design in energy retrofit interventions on building stocks: a decision support system. Green Ener. Technol. 231–248 (2021)
37. Gabrielli, L., Ruggeri, A.G., Scarpa, M.: Automatic energy demand assessment in low-carbon investments: a neural network approach for building portfolios. J. Euro. Real Estate Res. **13**(3), 357–385 (2020)
38. Ruggeri, A., Di Liddo, F., Gabrielli, L., Tajani, F., Morano, P.: What is the "best" way to measure the relative location variables in the market value assessment? an econometric method applied to an Italian case study. Land Use Policy **148**, 107405 (2025)
39. Morano, P., Locurcio, M., Tajani, F.: Energy production through roof-top wind turbines a GIS-Based decision support model for planning investments in the city of Bari (Italy). In: Gervasi, O., et al. Computational Science and Its Applications -- ICCSA 2015. ICCSA 2015. Lecture Notes in Computer Science(), vol. 9157. Springer, Cham (2015). https://doi.org/10.1007/978-3-319-21470-2_8

# The Impact of Different Polluting Site Typologies on Residential Real Estate Values: a Systematic Literature Review

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**Abstract.** This paper presents a methodical review of the scientific literature examining the relationship between different typologies of polluting sites and residential property values. The analysis distinguishes major categories of contamination sources, including landfills, incinerators, petrochemical plants and brownfields. This allows to explore how different environmental conditions affect housing market dynamics. Such a dynamic produces a synthesis of the empirical data the report identifies as recurring patterns and differences across studies as well as the main methodological approaches adopted in the selected academic papers, highlighting the varied effects of environmental risks on property prices. In recent years increasing attention to environmental quality and public health has strengthened the relevance of this topic in policy discussion.

For this reason, the review seeks to serve as a comprehensive reference for researchers, policymakers and practitioners, offering useful insights for urban planning and policy evaluation, particularly in contexts affected by environmental risk.

**Keyword:** Polluting Sites · Property Values · Environmental Risk

## 1 Introduction

Pollution caused by environmental issues has become a very complex challenge of our time, particularly due to its impact on urban systems, human health, economics and land use. Public awareness of these topics has been increasing since the 1970s, when a number of important events and publications helped to define the first shared international environmental agenda. The publication of The Limits to Growth by the Club of Rome in 1972, alongside the United Nations Conference on the Human Environment held in Stockholm, is generally regarded as an important turning point in the international debate [1, 2]. These events contributed to raising awareness of the risks associated with unsustainable urban economic growth and underscored the urgent need to reconsider prevailing development models.

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The publication of "The Limits to Growth" by the Club of Rome in 1972, alongside with the United Nations Conference on the Human Environment held in Stockholm, is generally regarded as an important turning point in the international debate. These events contributed to raising awareness of the risks associated with unsustainable urban economic growth and underscored the urgent need to reconsider prevailing development models.

In the following decades, issues related to sustainability and intergenerational responsibility have increasingly become relevant within international environmental policies, starting from the Brundtland Report (1987) [3] up to the Rio Conference of 1992. At European level, this process has been accompanied by more and more integrated strategies, such as the Environment 2010 programme [4], which favoured the adoption of directives on air quality, waste management and soil protection. At the same time, the advancement of scientific disciplines has contributed to a more detailed and multidimensional understanding of pollution, thanks to environmental epidemiology, urban planning, health geography and environmental economics.

Pollution is now widely acknowledged as a key determinant of public health, as highlighted by the World Health Organization (WHO) guidelines [5] and the reports of the European Environment Agency [6]. Among the most studied forms, air pollution occupies a central position due to its direct correlation with morbidity and premature mortality. Pollutants such as fine particles (PM2.5 and PM10), nitrogen dioxide ($NO_2$) and tropospheric ozone ($O_3$) have been associated with an increased risk of cardiovascular, respiratory and neurological diseases [7]. In response to this evidence, the WHO has updated its standards in 2021 [5], proposing more restrictive thresholds, that have been implemented by the European Union with the 2024 Directive [8], foreseeing a realignment to the standards by 2030.

At a territorial level, the impact of pollution is highly uneven. Polluting industrial sites – such as steel plants, petrochemical facilities, coal-fired power plants, landfills and incinerators – constitute localised sources of environmental pressure, whose effects spread persistently over time and space. In Italy, studies such as the SENTIERI Project [9] and HEAPSS [10] have highlighted an excess of mortality and morbidity in the territories adjacent to Sites of National Interest (SIN) for environmental remediation [11], with significant correlations between exposure to contaminants and serious pathologies. Within the socio-economic and territorial context of Southern Italy, the city of Taranto can be considered as a paradigmatic case: over time, the long-standing presence of the former ILVA steel plant has contributed to a combination of environmental degradation, public health issues and social tensions, making it a relevant context for examining the interactions between environment, health and urban systems [6].

From a larger perspective, European experiences show different models for the management and regeneration of contaminated sites. In Germany the *Brachflächen* - that is, abandoned or underutilized brownfield sites - have been the focus of systematic reconversion strategies thanks to the cooperation between public institutions and private actors. Similarly, in the Netherlands, the *Nota Bodembeheer* program, introduced in the 1990s, anticipated the integration of environmental land registries with urban planning instruments, laying the groundwork for more coordinated land-use policies and sustainable redevelopment processes. The case of the city of Bilbao, in Spain, is often cited

as a relevant example of urban and environmental regeneration, with the transformation of the Nervión river, that crosses the Basque Country, from a degraded industrial area to an attractive hub [12], highlighting the role of long-term, multi-level governance approaches. By contrast, within the Italian context— particularly in Southern Italy— persistent structural issues remain, mainly related to regulatory fragmentation, the lack of unified governance frameworks and long procedural timelines. Significant examples include the so-called Land of Fires in Campania, the Sulcis area in Sardinia, several industrial zones in Sicily, and numerous SINs across the "Mezzogiorno" (Southern Italy).

Within this context, the concept of environmental justice plays a key role in understanding the unequal distribution of pollution. Originating in the United States in the 1980s [13], environmental justice concept highlights how the most vulnerable communities are often those more heavily exposed to environmental risks. This unequal exposure does not only affect health and social conditions but also has significant economic repercussions, particularly influencing the real estate market. In most cases, the presence of a polluting source is associated with a reduction of the residential attractiveness of an area, generating a decrease in property values that reflects the perception of danger, the loss of urban quality and landscape degradation [14].

This effect is not only related to physical contamination, but also to social risk perception, influenced by media coverage, direct experiences, community-based knowledge flows, and, more recently, the increasing availability of online data [15].

In line with these dynamics, younger generations - who tend to display greater sensitivity to environmental issues - are increasingly inclined to favour contexts perceived as healthier, even when this entails trade-offs with other housing attributes, such as price or dwelling size. At the same time, technological developments have increased environmental transparency: geoportals, air quality maps, environmental registries and open data platforms have made information widely accessible, thereby profoundly modifying housing demand patterns and influencing real estate price dynamics [16]. In this energetic context, information transparency emerges as an economic variable, affecting price formation to the same extent as the intrinsic characteristics of properties. To assess the impact of environmental factors on real estate values, urban economics has developed specific analytic tools. Among these, hedonic regression models [17] allow the breakdown of market prices into the contributions of individual property attributes, including environmental ones. Furthermore, the integration of these models with geospatial data via Geographic Information Systems (GIS) allow the accurate representation of the effects of proximity to polluting sources, highlighting market depreciation gradients and tolerance thresholds [18].

From a regulatory and urban planning perspective, the presence of a contaminated site has a significant impact on urban dynamics. Directive 2004/35/EC [19], transposed into Italian law by Legislative Decree 152/2006, introduced the so- called '*polluter pays*' principle, which governs the characterisation and remediation of contaminated sites. This regulatory framework imposes constraints on construction activity and urban regeneration strategies, requiring an economic assessment of environmental impacts to guide public policy decisions.

## 2 Aim

Within the above outlined context, this paper examines the existing literature on the impact of polluting sites on residential real estate values, with particular attention to spatial proximity, the type of pollution source and the perception of environmental risk in shaping market prices. The analysis is organised to differentiate findings according to the typology of polluting sites, making it possible to better understand how different sources of contamination - such as landfills, incinerators, thermoelectric power plants, petrochemical plants, brownfields, river and marine pollution, other polluting sources - affect property values and local housing markets.

The study draws on a set of international scientific contributions to outline the current state of knowledge regarding the consequences of major environmental hazards on real estate prices, encompassing both empirical findings and methodological approaches.

The analysis also aims to identify similarities and differences across studies, to highlight recurring interpretative frameworks and to uncover gaps and limitations in the literature for further investigations.

More specifically, this paper provides a consolidated reference for researchers, policymakers and practitioners by providing an overview of the relationship between environmental risk, market dynamics and urban planning. By integrating evidence from diverse geographic and regulatory contexts, the analysis not only maps existing knowledge but also identifies directions for future research, with potential implications for more informed and sustainable decision-making.

The following part of the paper is organised as specified below. Section 3 describes the methodology developed for the systematic analysis of the relevant literature, with the aim of selecting the contributions that discuss the main aspects of the topic in the various geographical contexts with reference to the different polluting site typologies.

Section 4 is dedicated to the presentation of the main outcomes and to a summary of the main issues outlined by the different Authors. Finally, in Sect. 5 the conclusions and future development are discussed.

## 3 The Methodology Adopted for the Literature Review Development

This research work is based on a systematic review of the national and international scientific literature aimed at analyzing the impact of polluting sites on residential property values. The methodology adopted - following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines - allows for a comparative analysis of the empirical evidence, correlating the type of polluting site with the nature of the impact on property value, its intensity and its persistence over time. Specifically, the analysis aims to assess whether the presence of the polluting site is associated with a reduction, increase or absence of significant changes in housing prices. The intensity of the impact refers to the magnitude of the price change, expressed in different studies in percentage terms, monetary terms or through spatial gradients related to the distance from the polluting site. Finally, the persistence of the impact concerns the temporal duration of the effect and evaluates whether and to what extent the site's influence on

the real estate market is evident only during certain phases (announcement, construction, operation, etc.) or persists over time, for example, after the plant's closure, or, conversely, diminishes following remediation and regeneration interventions. For the purpose of conducting a systematic review of the scientific literature on the impact of contaminated sites on residential property values, a corpus of 60 studies [20–80] was compiled by consulting the most important academic databases, in particular Scopus, Web of Science and Google Scholar. These databases were selected according to their ability to identify studies from various disciplinary fields connected to the wider topic (urban economics, real estate appraisal and valuation, land-use planning, environmental sciences, etc.), ensuring pluridisciplinary coverage of the topic. To ensure a broad investigation consistent with the research objective, specific keywords were identified and used in the literature search: "landfill", "incinerator", "power plant", "petrochemical plant", "refinery", "brownfield", "river pollution", "property values", "housing prices", "real estate", "hedonic pricing model", "spatial analysis" and "spatial econometrics". The keywords were combined through Boolean operators such as AND and OR in order to retrieve the most relevant contributions from the selected databases.

Starting from the initial set of identified documents, a progressive screening phase was carried out based on explicit inclusion and exclusion criteria. Specifically, here are the contributions that were included in the final set of retrieved research: (i) explicitly analyzing the relationship between the presence of/proximity to a polluting site and changes in residential property values; (ii) using observed data relating to prices/market values, rents or real estate transactions; (iii) adopting an empirical-quantitative approach, with estimates attributable to hedonic models, econometric approaches (including spatial ones) or comparable statistical analyses; (iv) providing information useful for comparative interpretation of the impact (e.g., magnitude of the effect, spatial extent of influence, contextual conditions).

Contributions were excluded if: (i) exclusively theoretical or descriptive, lacking empirical results on the real estate market; (ii) focused on non-residential properties without disaggregated evidence on the housing sector; (iii) addressing to pollution or environmental risk in general terms, without quantifying the effect on real estate prices/values; (iv) not available in full text or lacking sufficient methodological information for comparison.

The described selection process led to the definition of the final set of 60 contributions. The different macro-phases of the selection process—identification, screening and inclusion—are represented in the PRISMA diagram (Fig. 1).

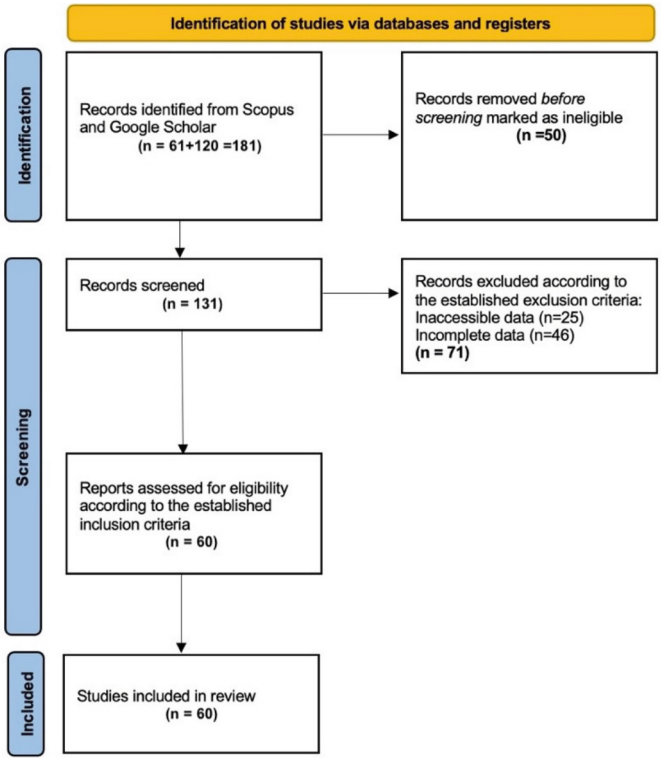


**Fig. 1.** PRISMA workflow

The selected articles were then examined to carry out a comparative analysis of the results of each collected paper. In line with the research objective, three main criteria were identified for the organization and interpretation of the literature: (i) the type of polluting site analysed; (ii) the nature of the impact on the property value, understood as a reduction, increase or absence of significant price variations; (iii) the intensity and persistence of the impact, referring respectively to the extent of the change in property values and the duration of the effect.

This methodological framework allows overcoming a mere descriptive review of case studies, providing a systematic and comparative overview of the available evidence and supporting the identification of recurring patterns, differences between site types and influencing factors (e.g., risk perception, socioeconomic context, operational life cycle, and quality of available information) that influence the capitalization of environmental impacts on the residential real estate market.

## 4 Results

On the basis of the objectives outlined above, a structured synthesis of the evidence emerging from the comparative review of the international literature is presented below.

Findings are organised according to the typology of polluting site (landfills, incinerators, thermoelectric power plants, petrochemical plants, brownfields, river and marine pollution, other polluting sources), and are examined in relation to spatial proximity, characteristics of the contamination source and the role of environmental risk perception in shaping residential property values.

### 4.1 Landfills

Landfills are one of the most studied types of polluting sites due to their impact on the real estate market. In many contexts, proximity to a landfill results in a significant reduction in property prices, due not only to direct effects – such as unpleasant odours, heavy vehicle traffic or landscape degradation – but also by the perception of environmental and health risks. The peripheries of Rome (Italy) are emblematic examples of the following observations: the Malagrotta landfill highlights the interaction between environmental mismanagement and socio-economic vulnerability. It shows that, without coordinated remediation and community engagement, property values may continue to decline over time, increasing spatial inequalities and constraining local development opportunities [20].

Looking at Franklin County (Ohio), the negative effects of landfills on nearby residential real estate prices endure over time, even after the site's closure, suggesting that environmental externalities can persist in collective memory and continue to influence property market valuation mechanisms [21].

South African academic studies have shown that the negative impact of landfills leads to progressive reductions in residential property values, with estimated loss ranging from 0.11% to 0.44% for every 100 m away from the facility, with stronger evident effects observed in more vulnerable market segments [22, 23].

Similar dynamics are also found in Romania: in fact, in a neighborhood in Bucharest suburbs, property values near the landfill declined by 31.2% [24].

In developing contexts, such as in the case of Lagos (Nigeria), different studies have shown that the impact is selective, disproportionately affecting certain market segments - often those with lower levels of protection and access to information - thereby creating spatial inequalities in property value depreciation [25]. Moreover, North American literature offers numerous confirmations: in Minnesota a reduction in prices of up to 12% has been highlighted [26], whereas in the Cleveland metropolitan area losses between 5.5% and 7.3% have been estimated, depending on the distance and the type of landfill [27]. A synthesis of these findings has been provided by a meta-analysis of 125 cases in the United States: an average loss of 13.7% has been assessed in the district of high-volume landfills, demonstrating that the intensity of the facility plays a crucial role in determining the effect on the market [28]. The composition and typology of waste also have a crucial function: in Toledo (Spain) Smolen et al. have observed that for every mile closer to a landfill containing hazardous waste, a property can lose up to USD 14,200 in value [29]. Finally, the case of Tseung Kwan in Hong Kong attests that the effect of the presence of a landfill on residential market is not uniform. By using big data techniques, the study of Li et al. [30] has detected that while apartments exposed to winds coming from the landfill suffer a depreciation, the selling price of units not affected by the odours, within the same complex, increases, likely due to a media effect driven by widespread complaints. This advertising effect highlights that the perception

of pollution is also shaped by indirect factors and suggests that, in addition to distance, other variables should be considered, such as wind direction, building characteristics, morphology and local market. Taken together, the available evidence shows that while landfills systematically affect property values, the magnitude and distribution of these effects are influenced by socio-economic, technological and cultural contexts.

### 4.2 Incinerators

Another type of polluting industrial issue discussed in the literature refers to incinerators. Municipal solid waste incinerators are among the most debated types of plants in environmental dissertations, due to concerns related to emissions and potential health risks, as well as their impact on the perceived quality of the urban setting. For this reason the real estate market is often considered a sensitive and reactive indicator of their presence. A relevant case can be observed in China, where the Nengda municipal incineration plant has led to a reduction of up to 25.9% on the housing asking price located within a three-kilometer radius, with the effect gradually decreasing with distance [31]. In the Czech city of Liberec, a statistically significant reduction in properties values in the area surrounding the city of Termizo a.s. plant has been evidenced as follows: the effect decreases with distance but remains detectable over several kilometres [32]. In North American contexts, the literature has explored the dynamics related to both the construction and operational phases of incinerators. Studies on the North Andover plant in Massachusetts have highlighted how the impact is more marked in the initial phases (pre- announcement, construction and commissioning), with an estimated loss of USD 2,283 per mile during construction, which increases to USD 8,100 at the time of opening and stabilizes around USD 6,607 in the operational phase [33, 34]. These outcomes are confirmed by Zeiss [35], which has investigated the effect of the Salem incinerator (Oregon) on real estate market, finding a moderate but stable reduction in property selling values, especially in the period between the announcement and the start of operation. More broadly, a meta-analysis of over 75 peer-reviewed studies on pollution sources and environmental degradation has indicated that incinerators are among the facilities with a significant negative effect on property values, although the strength of the effect depends on the visibility of the plant, the quality of available information and the urban context [36].

Particularly interesting is also the case study conducted in Phuket, Thailand, where the municipal incinerator has been perceived negatively by the resident population, due to emissions and fear of health effects, negatively influencing the perceived value of neighboring properties, as documented in the analysis carried out with a risk perception assessment approach [37]. Finally, the French case study comparing three different plants located in urban areas, suggests that the loss of real estate value can vary between 0.4% and 1.3%, depending on the distance, the presence of visual barriers and the technological efficiency of the site [38]. Incinerators produce effects that, while not always macroscopic, are systematically negative for the housing value, especially where the information environment is uncertain or risk communication is lacking. Unlike other polluting plants, however, their impact also appears to be modulated by factors such as the phase of the plant's life cycle, the presence of mitigation infrastructure and the

perceived fairness in the distribution of energy benefits compared to the environmental costs borne by local communities.

### 4.3 Thermoelectric Power Plants

With reference to thermoelectric power plants, public interest is currently focused on the contrast between energy needs and social acceptance of environmentally intensive infrastructures. One of the most analyzed cases concerns the United States: it has been estimated that the opening of 92 large fossil fuel power plants in the 1990s has led to a reduction in property values of between 3% and 7% within a two-mile radius of the plant. The effect has been particularly relevant near the largest capacity plants and has been accompanied by a lowering of average income, education and home ownership levels in adjacent areas [39]. A similar case has been documented in China where Deng et al. [40] have studied the positive effect on the real estate market resulting from the closure of two coal-fired power plants in a large city: the removal of the plants has caused an immediate increase in housing prices ranging from 12% to 14% within a 5 km radius, along with an increase in transactions of up to 31%, confirming the negative impact that these plants have determined on the market. In South Korea, Kim et al. have shown that proximity to a gas-fired power plant has led to an average price reduction of about 8 million won per kilometer (about USD 7,100 per kilometer), equal to 0.7% of the average value of the apartments analyzed, in a highly densified urban context with increasing housing demand [41].

Significant effects also emerge in the European context: analyzing over 1.5 million real estate transactions in the Netherlands, Eichholtz et al. have found that gas-fired power plants generate a systematic negative effect on residential prices in surrounding areas, with a particularly visible dynamic in urban contexts. The study compares the effect of coal, gas, biomass and wind turbine plants, showing that gas-fired plants lead to reductions similar to those observed for wind farms, while biomass plants show positive effects only when located in areas with low initial values [42].

A research in Manama (Bahrain) estimates that air pollution, largely attributed to thermoelectric production, accounts for about 16.7% of the variation in real estate prices in the metropolitan area, highlighting the link between energy production, air quality and market dynamics [43].

On the contrary the Indian case of Kalisindh Thermal Power Project [44] shows a complex evolution: while the opening of the power plant has brought benefits in terms of employment and infrastructure, it has also fuelled real estate speculation and local variations in land prices, making it difficult to define a clear overall impact on housing values.

In Finland there is an emerging topic: the integration of local heat production within district heating networks, as a more decentralized alternative to large thermoelectric power plants. Although the study does not directly measure real estate value, it suggests that increased thermal efficiency and reduced operating temperatures may also lead to improve in residential quality.

From a political and territorial perspective, the analysis carried out by Cowell [46] has investigated the location of gas-fired power plants in the UK from 1988 to 2019, showing how they have often occupied areas previously dedicated to coal or oil plants,

thus avoiding the most bitter conflicts but still contributing to the reproduction of a high-carbon energy system. Finally, a regional experimental study conducted in China [47] has confirmed that the negative perception associated with gas-fired power plants has a persistent effect on housing prices, regardless of the size of the plant and its efficiency, proving that perceived unattractiveness plays a decisive role in real estate dynamics.

### 4.4 Petrochemical Plants

An increasingly discussed aspect in the relevant literature, especially in urban or semi-urban contexts where such infrastructures coexist with residential settlements, concerns the impact of petrochemical plants and the oil & gas sector on the real estate market. Studies conducted in densely industrialized areas have shown how proximity to refineries, gas pipelines, liquefaction plants and petrochemical hubs significantly influences housing values, although this effect can take different directions, depending on the socioeconomic context, environmental conditions and the population's perception of risk.

A strongly noted case is in the United States, where two petrochemical refineries have been associated with a significant reduction of nearby real estate, particularly as a function of the distance from the plant and the presence of significant events (such as accidents or environmental disputes). In this context, several studies report a more pronounced negative capitalization effect in lots adjacent to refineries, which is only partly reduced by the presence of buffer zones [48]. Proximity to refineries is associated with a statistically significant increase in a dangerous cancer risk, particularly for lymphoma and bladder cancer, with the most severe and critical effects observed within 10 miles of the plants: this criticity emerges from the analysis of data from 6.3 million Texas residents [49]. The implications for the study of the real estate market are indirect but relevant, since perceived health risks can significantly influence housing demand.

An emblematic paradoxical effect is being observed on Bonny Island in Nigeria. In fact, the presence of oil and liquefied natural gas facilities (such as those operated by Shell and Exxon Mobil) has led to rising property values, due to increased employment, improved infrastructure and strong housing demand from incoming workers. However, concerns have been highlighted about a speculative dynamic, aggravated by a lack of regulation and potential long-term environmental damage, including oil spills and air pollution [50]. Similarly, in East Malaysia, the project to establish a petrochemical hub has generated initial uncertainty on the local real estate market, with depressive effects in the pre-announcement phase, which were later partially recovered thanks to the construction of new infrastructures. Also in this case, the perceptual factor and institutional communication played a decisive role [51].

An additional element that affects real estate values trends is the history of industrial accidents which can shape the reputation of a territory and affect market perceptions.

For instance, a study by the University of Texas [52] on Teesside in the UK has highlighted how neighbourhoods closer to large industrial complexes show higher mortality rates from lung cancer and respiratory diseases, especially among women, thus fuelling a negative territorial image that is reflected in property values.

In a more strictly economic context, the operational flexibility of refineries - that is, their ability to adapt production according to crude oil and derivatives prices – not only affects the resilience of the industrial asset, but also shapes the expectations of real estate

investors in surrounding areas [53]. In a doctoral thesis at Birkbeck College [54], this issue is examined from a financial point of view, with valuation models developed for the Vadinar refinery in India, demonstrating that environmental risks and the volatility of refined product prices significantly affect the site's assessment as a "neighborhood" for potential real estate investors. Using a multivariate analysis, Martin and Reed [55] show that the negative externalities associated with refineries are perceived more strongly in low-income areas, where residents have limited resources to mitigate or avoid exposure, which reinforces spatial and social disparities in property values.

Taken together, the available evidence suggests that petrochemical and oil & gas plants have a differentiated impact on the real estate market. In some contexts, the effect is negative, especially where environmental risk is strongly perceived and not compensated by visible economic benefits, while in other cases the impact can be neutral or even positive, particularly when these infrastructures support local development and employment, provided that environmental management is effective and communication between companies, institutions and local communities is transparent [56, 57].

### 4.5 Brownfields

Brownfield sites, as they are commonly known, are regarded as a major challenge in urban regeneration. At the same time, they can also present an opportunity to restore and revitalize severely degraded areas without contributing to uncontrolled urban sprawl.

If managed appropriately, the regeneration of brownfield sites can support local economic growth, improve environmental conditions and contribute to social cohesion, transforming underused areas into productive urban spaces.

Several studies show that the remediation and redevelopment of these areas can have positive effects on the real estate market, particularly when supported by targeted planning interventions. For example, in Cuyahoga County, Ohio, a relevant research has found that housing prices increase significantly after brownfield rehabilitation, with particularly marked effects in low- and moderate-income neighborhoods. In these contexts, the conversion of contaminated sites into residential, commercial or recreational areas has led to an increase in the perceived value of the district, also thanks to the improvement of environmental quality and the reduction of the negative connotation associated with pollution [58]. Similarly, a nationwide analysis in the United States have estimated that property values near sites redeveloped under the federal Environmental Protection Agency program increased on average between 5% and 11.5%, reaching up to 15% in the most successful cases [59].

In England, a significant effect on the most deprived neighborhoods, both by increasing housing values and by reducing urban marginalization, has been associated to the residential redevelopment of brownfield sites. Specifically, between 2001 and 2008, the most disadvantaged districts experienced a 25% increase in regenerated surface area, accompanied by parallel improvements in socio-economic indicators [60]. Building on these findings, analysis of English cities have also showed that the probability of redeveloping a brownfield site responds elastically to housing prices: a 21% increase in prices can incentivise the regeneration of most brownfields, suggesting that residential policies can play a propulsive role in fostering sustainable urban densification [61]. Similarly, from a United States perspective, the Northeast-Midwest Institute summarizes the environmental, economic and fiscal benefits of brownfield regeneration, including higher

property values, new local tax revenues and infrastructure cost savings compared to greenfield development [62].

Similarly, in New Jersey, studies indicate that amended brownfields can meet part of the demand for affordable housing, particularly for more vulnerable and weak social groups. About 14% of respondents are willing to live on a previously contaminated site, provided that the site has been properly reclaimed, with stronger preferences observed among younger individuals and lower-income households [63].

Another relevant aspect concerns the relationship between risk perception and property value variations: although the negative effects of environmental stigma tend to decrease after restoration, property values are also influenced by factors such as trust in the decontamination process, information transparency and the future use planned for the site [64].

In this regard, evidence from Canadian and U.S. cases suggests that effective brownfield regeneration, particularly when supported by effective planning strategies and community involvement, can result in property value increases of up to 30% [65].

### 4.6 River and Marine Pollution

In the literature considered in this study, river and marine pollution is examined as an environmental issue that significantly influences property values, particularly in coastal areas and along urban waterways. Degradation of water quality, in fact, affects both the direct use of aquatic ecosystems and the perceived aesthetic and health quality of the surrounding residential environment, and directly influences housing prices. A study conducted in Narragansett Bay (Rhode Island, United States) shows that high chlorophyll concentrations - an indicator of eutrophication - negatively influence housing prices up to one kilometer from the coast. Real estate values appear more sensitive to acute pollution events, such as algal blooms or fish kills, than to annual average levels. The spatial and temporal impact is significant, with estimated losses ranging from USD 18 million to USD 136 million for the entire coastal strip in scenarios of declining environmental quality [66].

Similar results are reported in the study by Bin and Czajkowski [67] in which technical and perceptual indicators of water quality in Florida (United States) have been compared.

The study finds that objective measures, such as nutrient concentration or dissolved oxygen levels, provide more robust and reliable predictions of real estate marketeffects than subjective indices based on site appeal. Similarly, in Chesapeake Bay within the same national context, Leggett and Bockstael show the important role of watershed environmental quality in determining waterfront property values, with reductions in water clarity causing depreciation of up to 7% [68].

Also in river area, the link between water quality and real estate market is clear: the study carried out by Poor et al. [69] on rivers and lakes in Wisconsin (United States) has quantified an increase in value of up to 16% for each improvement in ecological status (from “polluted” to “acceptable”), showing the responsiveness of the remediation interventions.

Another important pollution effect is caused by agricultural wastewater, which produces a localised decline in property prices near river confluences, for example the

Danube and Rhine basins (European rivers), particularly where environmental degradation is greatly evident: turbid water or damaged riparian vegetation. For this reason homes lose visual or recreational access to watercourses [70].

Conversely, the rediscovery and renaturalisation of riverbeds referring to buried watercourses in Los Angeles led to property value increases of over 10% for nearby homes; this is an example of how environmental restoration can mitigate and avoid long-term declines associated with pollution [71]. More recently, a study of coastal areas in China, based on a spatial approach and machine learning techniques, found that the presence of marine litter and microbiological contaminants reduces property values, with effects varying according to tourist seasons and visual exposure [72].

Overall, these findings highlight a broader issue addressed in the theoretical literature: the economic quantification of damage caused by marine contamination is still underestimated, due to difficulties in distinguishing between direct uses of the ecosystem (such as bathing and fishing) and its intrinsic or existence value. Nevertheless, initial attempts at monetary valuation indicate substantial and persistent effects on private property values, particularly in densely populated areas and regions subject to heavy tourist pressure [73].

### 4.7 Other Polluting Sources

Recent studies have considered additional types of sites together with the primary sources of environmental pollution. Although these belong to categories that have been considered less systematically, they may still have a significant impact on property values in nearby areas. This applies, for example, to disused military areas, which are often affected by contamination from heavy metals, fuels or munitions, making their reuse particularly challenging [74]. Consistent with these findings, a study conducted in Germany shows that regeneration initiatives involving former North Atlantic Treaty Organization (NATO) installations—although often complex—can contribute to a gradual recovery in real estate prices in medium-sized cities such as Augsburg and Mannheim, particularly when remediation processes are carried out effectively and communicated transparently to the public [75].

Another category concerns disused mining areas and quarries, where landscape degradation is frequently accompanied by environmental risks related to soil and groundwater contamination, further influencing the dynamics of surrounding property markets [76]. In this context, Weber and Christophersen show that the presence of abandoned mines can reduce the value of nearby assets by up to 20%, with negative effects that persist even after mining activities have ended [77]. Similar findings emerge from studies conducted in Peru, which show that mining operations can generate long- lasting adverse impacts on residential selling prices. These effects tend to decrease only when environmental remediation measures and social compensation programs are effectively implemented [78].

Finally, intensive agricultural sites—particularly those associated with industrial livestock farming, such as Concentrated Animal Feeding Operations (CAFOs)—can also generate negative externalities, including odours, liquid waste and nitrate pollution. Empirical studies conducted in a North American context [79, 80] have documented a significant decrease in property values in rural areas of Iowa located near CAFO facilities. This suggests that even forms of pollution not directly linked to industrial production,

but rather to land use practices and natural resource management, can substantially affect local residential real estate markets, especially in contexts where regulatory frameworks and information transparency are limited.

## 5 Conclusions

This paper not only analyses the basic aspects linked to the relationships between different typologies of polluting sites and residential property values, but also identifies the main mechanisms through which environmental contamination influences housing market dynamics. The review is organised according to the main categories of contamination sources with the aim of understanding how different environmental hazards affect local residential systems.

The analysis of the selected studies highlights that the impact on property values is consistently negative in most cases, although its magnitude and persistence vary significantly across site typologies. In particular, landfills emerge as one of the most penalizing factors, with property value reductions often ranging between 5% and over 30%, and with effects that may persist even after site closure. Incinerators show generally moderate but systematic negative impacts, often concentrated in the pre-operational and construction phases. Thermoelectric power plants are associated with price decreases typically between 3% and 7% in surrounding areas, although these effects may be partially reversible following plant decommissioning.

By contrast, petrochemical plants and oil-related infrastructures present more heterogeneous outcomes: while negative impacts prevail in contexts characterized by high environmental risk perception, neutral or even positive effects may occur where economic benefits and employment opportunities offset environmental externalities.

A different pattern is observed for brownfield sites, where remediation and redevelopment processes are generally associated with increases in property values, commonly ranging between 5% and 15%, and reaching higher levels in the most successful regeneration cases. Similarly, environmental quality improvements in river and coastal areas produce measurable positive effects on housing prices, while pollution events generate significant economic losses.

Overall, the findings confirm that the effect of polluting sites on residential real estate values is not determined solely by physical contamination, but rather by a combination of factors including risk perception, information availability, socio-economic conditions and the lifecycle stage of the site.

Relevant international academic contributions have been examined focusing on the current body of knowledge on the effects of environmental risks on property prices, highlighting heterogeneous impacts: both common patterns and differences across contexts have been considered. This topic is part of a broader and increasingly relevant public debate. The future research may benefit from more systematic comparative analyses of different types relating to contaminated sites, in order to better understand the conditions under which their impacts on property values become more or less pronounced [81].

Another area for future research concerns the integration of real estate valuation techniques with advanced spatial and temporal analytical tools, which can help capture both the localized distribution of impacts and their evolution over time. More attention

could also be given to the role of remediation policies, urban regeneration processes, and institutional and official communication strategies, as these factors influence market expectations and the perception of environmental risk. From this point of view, the intersection of economic evaluation, spatial planning and environmental governance represents a promising direction for supporting more informed and sustainable decisions in urban transformations [82].

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## References

1. Meadows, D.H., Meadows, D.L., Randers, J., Behrens, W.W.: The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind. Universe Books (1972)
2. United Nations: Report of the United Nations Conference on the Human Environment. UN Publications (1972)
3. World Commission on Environment and Development: Our Common Future. Oxford University Press (1987)
4. European Commission: Environment 2010: Our Future, Our Choice – The Sixth Environmental Action Programme. Publications Office of the European Union (2001)
5. World Health Organization: Global Air Quality Guidelines. WHO (2021)
6. European Environment Agency: Air Quality in Europe – 2022 Report. Publications Office of the European Union (2022)
7. The lancet public health: air pollution and health. Lancet Publ. Health **2**(1), e4–e5 (2017)
8. European Union: Direttiva UE sulla qualità dell'aria. https://www.epicentro.iss.it/ambiente/direttiva-ue-qualita-aria-2024. Accessed 29 Mar 2026
9. Ministero della Salute – Istituto Superiore di Sanità: Progetto SENTIERI. Epidemiologia & Prevenzione, Suppl. 3 (2010)
10. ISPRA: Annuario dei dati ambientali. Istituto Superiore per la Protezione e la Ricerca Ambientale, Roma (latest edn.)
11. Consulcesi: Inquinamento atmosferico e salute: dati aggiornati per l'Italia. https://www.consulcesi.it. Accessed 29 Mar 2026
12. Bartke, S., Schwarze, R.: Urban land and soil in European environmental policy. Land Use Policy **48**, 176–183 (2015)
13. Zuin, V., Bedogni, T., Cecchetti, G.: Environmental justice and risk perception: a European overview. Sustainability **3**(2), 234–249 (2011)
14. Boyle, M.A., Kiel, K.A.: A survey of house price hedonic studies of the impact of environmental externalities. J. Real Estate Lit. **9**(2), 117–144 (2001)
15. Gayer, T., Viscusi, W.K.: Housing price responses to newspaper publicity of hazard risks and the EPA's Toxic Release Inventory. J. Environ. Econ. Manag. **43**(3), 272–292 (2002)
16. Ready, R.C., Abdalla, C.W.: The amenity and disamenity impacts of agriculture. Am. J. Agr. Econ. **87**(2), 314–326 (2005)
17. Rosen, S.: Hedonic prices and implicit markets: product differentiation in pure competition. J. Polit. Econ. **82**(1), 34–55 (1974)
18. Bastian, C.T., Keske, C.M., Hoag, D.L.: Spatial effects in hedonic property valuation models incorporating environmental disamenities. Ecol. Econ. **132**, 268–276 (2017)

19. European Union: Directive 2004/35/EC on environmental liability. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32004L0035. Accessed 29 Mar 2026
20. Barbieri, M., Sappa, G., Vitale, S., Parisse, B., Battistel, M.: Soil control of trace metals concentrations in landfills. J. Geochem. Explor. **143**, 146–154 (2014)
21. Hite, D., Chern, W., Hitzhusen, F., Randall, A.: Property-value impacts of an environmental disamenity: the case of landfills. J. Real Estate Financ. Econ. **22**(2), 185–202 (2001)
22. du Preez, M., Lottering, T.: Determining the negative effect on house values of proximity to a landfill site by means of an application of the hedonic pricing method. South Afr. J. Econ. Manag. Sci. **12**(2), 256–262 (2009)
23. du Preez, M., Balcilar, M., Razak, A., Koch, S.F., Gupta, R.: House values and proximity to a landfill in South Africa. J. Real Estate Lit. **24**(1), 133–149 (2016)
24. Gradinaru, G.I., Ioan, I.: Estimating the impact of landfill proximity on the value of real estate goods. Amfiteatru Economic **14**(31), 38–45 (2012)
25. Arimah, B.C., Adinnu, F.I.: Market segmentation and the impact of landfills on residential property values: empirical evidence from an African city. Netherlands J. Housing Built Environ. **10**(2), 157–171 (1995)
26. Nelson, A.C., et al.: Price effects of landfills on house values (1992)
27. Reichert, A.K., Small, M., Mohanty, S.: The impact of landfills on residential property values (1992)
28. Ready, R.: Do landfills always depress nearby property values? (2010)
29. Smolen, G.E., Moore, T., Conway, D.: Economic effects of hazardous waste landfills (1992)
30. Li, R.Y.M., Li, H.C.Y.: Have housing prices gone with the smelly wind? Sustainability **10**, 341 (2018)
31. Zhao, Q., Simons, R.A., Li-jun, F., Fen, Z.: The effect of the Nengda incineration plant on residential property values. J. Real Estate Lit. **24**(1), 85–102 (2016)
32. Humpolová, Š.: Evaluation of the Impact of Incinerator Proximity on Property Values. Masaryk University (2018)
33. Kiel, K.A., McClain, K.T.: House prices during siting decision stages. J. Environ. Econ. Manag. **28**(2), 241–255 (1995)
34. Kiel, K.A., McClain, K.T.: The effect of an incinerator siting on housing appreciation rates. J. Urban Econ. **37**(3), 311–323 (1995)
35. Zeiss, C.: Property value impacts of an incinerator facility. J. Urban Plan. Dev. **116**(2), 52–67 (1990)
36. Simons, R.A., Saginor, J.D.: A meta-analysis of environmental contamination impacts. J. Real Estate Res. **28**(1), 71–104 (2006)
37. Adisak, et al.: Valuing risk perception and disamenity of incinerator: a case study (n.d.)
38. Rivas-Casado, M., Serafini, J.: Assessing the impact of incineration plants on housing markets in the UK (2016)
39. Davis, L.W.: The effect of power plants on housing values. Rev. Econ. Stat. **93**(4), 1391–1402 (2011)
40. Deng, G., Hernandez, M.A., Xu, S.: Environmental quality and housing markets in China. Environ. Resour. Econ. **77**, 751–780 (2020)
41. Kim, J.-H., Kim, Y.-K., Yoo, S.-H.: Power plant proximity and housing values. Energies **16**, 1983 (2023)
42. Eichholtz, P., Kok, N., Langen, M., van Vulpen, D.: Clean electricity and house prices. J. Real Estate Financ. Econ. **66**, 743–777 (2023)
43. Buhammoud, S.R., El-Kholei, A.O., Al Ubaydli, O.: Air pollution and real estate prices. Arab Gulf J. Sci. Res. **38**(3), 172–188 (2021)
44. Karra, R., Mishra, P.N., Jain, P.: Economic impact of a thermal power project. Ind. J. Soc. Polit. Sci. **4**(3), 75–86 (2017)

45. Penttinen, P., et al.: District heat production and real estate investments. J. Sustain. Dev. Energy **9**(2), 1080343 (2021)
46. Cowell, R.: The role of place in energy transitions. Geoforum **112**, 73–84 (2020)
47. Garriga, C., et al.: Migration and housing markets in China. Am. Econ. J. Macroecon. **15**(2), 413–440 (2023)
48. Flower, P.C., Ragas, W.R.: The effects of refineries on property values. J. Real Estate Res. **9**(3), 319–338 (1994)
49. Williams, S.B., et al.: Proximity to oil refineries and cancer risk. J. Natl. Cancer Inst. **112**(10), 978–986 (2020)
50. Jumbo, A., Ihuah, P.W.: Oil and gas industry and residential property values. Int. J. Innov. Environ. Stud. Res. **12**(1), 19–28 (2024)
51. Cheng, E.K., Chin, Y.S.: Petrochemical hubs and housing prices. INSPEN (2010)
52. Bhopal, R.S., et al.: Living near petrochemical industries and health. Occup. Environ. Med. **55**(12), 812–822 (1998)
53. Dong, H., Liao, W., Gu, Q.: Flexibility of oil refineries under price uncertainty. Energy Econ. **42**, 271–280 (2014)
54. O'Driscoll, P.J.: Financial valuation of an oil refinery. PhD Thesis, University of London (2016)
55. Martin, D., Reed, R.: Environmental risks and real estate value. Working Paper (2005)
56. INSPEN: Petrochemical hub and property value. Research Monograph (2010)
57. Institute for Corporate Real Estate: Corporate real estate and sustainability reporting (2011)
58. Woo, A., Lee, S.: Brownfield redevelopment and housing prices. Environ Plan A **48**(6), 1107–1132 (2016)
59. Haninger, K., Ma, L., Timmins, C.: The value of brownfield remediation. J. Assoc. Environ. Resour. Econ. **4**(1), 197–241 (2017)
60. Schulze Bäing, A., Wong, C.: Brownfield residential development. Urban Stud. **49**(14), 2989–3008 (2012)
61. Carozzi, F.: Estimating the house price elasticity of brownfield redevelopment (n.d.)
62. Paull, E.: Impacts of brownfields redevelopment. Northeast Midwest 9 (2008)
63. Greenberg, M., et al.: Brownfield redevelopment as a smart growth option. Environmentalist **21**(2), 129–143 (2001)
64. Gallagher, D.R., Jackson, S.E.: Community involvement at brownfields sites. J. Environ. Plan. Manage. **51**(5), 615–630 (2008)
65. De Sousa, C.: Brownfield vs greenfield development. J. Environ. Planning Manage. **43**(6), 831–853 (2000)
66. Liu, T., Opaluch, J.J., Uchida, E.: Water quality and housing prices. Water Resour. Res. **53**(8), 6454–6471 (2017)
67. Bin, O., Czajkowski, J.: Water quality and coastal housing values. Ecol. Econ. **85**, 213–221 (2013)
68. Leggett, C.G., Bockstael, N.E.: Water quality and residential land prices. J. Environ. Econ. Manag. **39**(2), 121–144 (2000)
69. Poor, P.J., Pessagno, K.L., Paul, R.W.: Hedonic value of water quality. Ecol. Econ. **60**(4), 797–806 (2001)
70. Klemick, H., et al.: Water quality and real estate in Europe. Sci. Rep. **13**, 39022 (2023)
71. Saphores, J.D.M., Li, W.: Value of urban stream restoration. Urban Stud. **49**(14), 3277–3295 (2012)
72. Liu, Y., et al.: Marine pollution and housing prices. Sustainability **15**(1), 500 (2023)
73. Boyle, K.J., Parmeter, C.F., Pope, J.C.: Assessing damages to contaminated property. Risk Anal. **26**(3), 635–650 (2006)
74. McGrath, D.T.: Industrial land redevelopment and contamination risk. J. Urban Econ. **47**(3), 414–442 (2000)

75. Wenger, A., Möckli, D.: NATO and European identity. In: Routledge Handbook of Transatlantic Security, pp. 103–122. Routledge (2010)
76. Stolz, R., Rink, D., Külke, M.: Re-use of former military areas. Urban Res. Pract. **12**(2), 153–171 (2019)
77. Weber, B., Christophersen, A.: Mining brownfields and policy approaches. Environ. Pract. **4**(4), 209–218 (2002)
78. Aragon, F.M., Rud, J.P.: Pollution and economic growth. Econ. J. **126**(597), 939–963 (2016)
79. Herriges, J.A., Secchi, S., Babcock, B.A.: Livestock facilities and property values. Land Econ. **81**(4), 530–545 (2005)
80. Kim, J., Goldsmith, P.D.: Swine CAFOs and property values. Environ. Resource Econ. **42**(4), 509–534 (2009)
81. Gerelli, E.: Mobilità urbana, congestione e inquinamento. Economia Italiana 1 (2002)
82. Bettoni, M.: Prevenzione degli effetti sanitari dell'inquinamento atmosferico. Annali Istituto Superiore di Sanità **36**(3), 263–266 (2000)

# A Methodological Approach to Assessing the Territorial Impacts of Industrial Decarbonisation on Real Estate Values

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**Abstract.** This research proposes an innovative methodological approach to assess the territorial impacts of industrial decarbonisation, using the real estate market as a proxy indicator. The present study focuses on the investigation of how property values reflect both the negative externalities of industrial activities and the potential benefits associated with low-carbon transformation processes. The developed methodological proposal is structured into two phases: in the first one, there is an analysis of the current state carried out to evaluate the influence of an industrial site on residential property values; in the second, there is the definition of a transformation scenario performed to simulate the prospective effects of decarbonisation on the real estate market. An econometric technique is implemented to analyze the relationships between property characteristics, environmental factors and market dynamics, both in the current situation and in the post intervention scenario assuming the stability of the functional relationship derived from the current context. The results demonstrate that changes in property values can provide a valuable lens for understanding the broader socio-economic and environmental consequences of industrial transformations. The methodology is adaptable and replicable in other contexts, offering a tool to support public and private decision-making and to guide regeneration policies consistent with the objectives of the ecological transition.

**Keywords:** Industrial Decarbonisation · Real Estate Market · Property Values

## 1 Introduction

The decarbonization of production systems represents one of the main objectives of contemporary climate policies and constitutes a fundamental pillar for the pursuit of climate neutrality targets in the medium and long term.

The industrial sector accounts for a significant share of global greenhouse gas emissions, arising both from fossil fuel combustion for energy production and from inherently emission-intensive production processes, such as those involved in steel, cement

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and basic chemicals manufacturing. In this context, the transition towards low- carbon production models constitutes a structural transformation affecting technologies, value chains, plant location decisions and territorial infrastructures.

Since the Paris Agreement, the European Union has progressively consolidated its commitment to reducing greenhouse gas emissions, proposing a regulatory and strategic framework aimed at the rational transformation of both the economic and the industrial development model [1, 2].

In this context, the European Green Deal outlines a transition strategy aimed at achieving a climate-neutral economy in the European Union by 2050; it encourages the shift of growth models towards lowering reliance on heavy use of natural resources and cutting carbon emissions [3, 4]. Therefore, decarbonisation is not imposed as an external constraint on the economy, but rather it is an intrinsic and integral element of the new European development paradigm, in which environmental sustainability, industrial competitiveness and social cohesion are strictly interconnected.

The *Fit for 55* regulatory package, introduced in 1990, reinforces this goal. It sets binding targets for emissions reduction by 2030, strengthening both regulatory and market tools, including the *European Union Emissions Trading System* (EU ETS) and the *Carbon Border Adjustment Mechanism* (CBAM) [5, 6]. These measures directly affect energy- and carbon-intensive industrial sectors and foster accelerated technological innovation and production transition processes [7].

In Italy, European objectives have been included through planning and programming tools such as the National Integrated Plan for Energy and Climate (NIPEC) and the National Recovery and Resilience Plan (NRRP), both of which assign a central role to the ecological transition and the decarbonisation of industry. These frameworks not only set ambitious targets for reducing greenhouse gas emissions but also provide a roadmap for investments in clean energy, technological innovation and sustainable industrial practices. In particular, the so-called "*hard-to-abate*" sectors – including steel, chemical metallurgy, cement, glass, and other energy-intensive industries – represent one of the most significant challenges for the transition. This is due to the inherent process emissions that cannot be easily eliminated, to the high energy consumption associated with production, and to the long operational lifespan of existing industrial plants, which limits the speed at which emissions reductions can be achieved. Addressing these challenges requires a combination of technological innovation, policy incentives and investment in low-carbon infrastructure, as well as the promotion of circular economy principles to maximize resource efficiency and minimize environmental impact [8].

Consequently, the decarbonisation of heavy industry opens up new scenarios not only from a technological standpoint, for example regarding plant design and operation, but also in economic and institutional terms, creating opportunities for innovation, regulatory adaptation, and sustainable growth.

Numerous production processes, however, require high temperatures or are based on chemical reactions that generate emissions that are not easily reduced and/or eliminated, making the electrification of consumption alone insufficient. At the same time, the reconversion of plants implies the need for significant investments and prolonged implementation times, which require close coordination between industrial policies, incentive mechanisms and public regulation [9, 10].

Fundamentally, the European Green Deal marks a shift from the traditional paradigm of the State as a mere regulator, emphasizing a more proactive and strategic role for public institutions and governments in directing industrial transformation through green industrial policies, targeted support measures and comprehensive planning tools.

This framework highlights that the ecological transition entails costs and benefits that are unevenly distributed across sectors, regions and social groups, thereby necessitating policies capable of managing its economic, technological, and social implications [11].

By positioning public authorities as active facilitators of sustainable development, the Green Deal reinforces the need for coordinated action across innovation, legislative frameworks and industrial strategy, ensuring that decarbonization pathways are both feasible and equitable, while fostering long-term sustainable growth.

Within decarbonisation processes, a particularly critical aspect concerns how transformations are planned, monitored and managed over time. Climate and industrial policies are typically designed with long-term horizons (e.g., 10–30 years), setting emission reduction targets and industrial transition strategies.

However, the areas where these policies produce concrete effects—such as local communities, industrial sectors, or energy markets—respond according to different timescales, often shorter and highly sensitive to cyclical factors such as economic fluctuations, demand shifts, or energy price changes.

This temporal misalignment between long-term planning and the immediate response of economic and social systems complicates the assessment of the actual impacts of the ecological transition, particularly in intermediate phases. In other words, while policies are designed for the future, their tangible effects show themselves at different times, making it difficult to determine promptly whether the strategies are achieving the intended outcomes or require adjustments [12].

In addition to temporal challenges, territorial governance introduces further complexities in decarbonisation processes that extend beyond the simple measurement of avoided emissions or the technological efficiency of industrial plants.

Industrial transformations progressively reshape the economic and social landscape of territories, influencing the location of economic activities, public and private investments and the expectations and behaviours of local communities. These impacts, however, are often difficult to capture using conventional monitoring tools typically employed in environmental policy. Current evaluation frameworks are frequently constrained by their focus on discrete phenomena, whereas industrial decarbonisation generates cumulative and dispersed effects that unfold over time. Without tools capable of interpreting these dynamics, a significant risk that transition policies will be assessed solely on the basis of technical targets is strong, thereby overlooking the territorial and social dimensions that ultimately determine their medium- and long-term economic and social sustainability [13].

In this context, the assessment of industrial transformations requires a relevant shift in perspective, aimed at observing local responses to transition processes. Attention is therefore moved from the interventions to their effects on local dynamics; the need to identify indicators that integrate environmental, economic and spatial domains is highlighted. This requirement is particularly critical in complex industrial contexts,

where the ecological transition is intertwined with consolidated production legacies and fragile regional balances.

In this scenario, an analysis of the territorial impacts of decarbonization is increasingly fundamental. This research line is currently partially unexplored but crucial to support decision-making processes. Indeed, understanding the reaction of territories to industrial transformations allows for a more informed orientation of regeneration policies, evaluating the effectiveness of the ecological transition not only in environmental terms, but also in relation to its capacity to produce lasting territorial benefits [14].

By taking into account the multilevel nature of decarbonization processes, in which both regulatory and strategic choices profoundly change production and territorial systems, assessing these transformations is essential for effectively guiding public policies to promote investments consistent and adequate with climate objectives and to ensure a fair and sustainable transition.

Despite the extensive national and international literature on decarbonization technologies, attention to tools capable of interpreting their territorial and socioeconomic impacts remains limited, particularly in complex European industrial contexts.

## 2 Aim

The present research aims to develop a structured, step-by-step methodological approach to assess whether, and to what extent, the real estate market can serve as a proxy indicator for interpreting the territorial impacts associated with the presence of the steel plants and the ongoing industrial decarbonisation processes. The assumption is that property values and market dynamics may incorporate, over time, both the negative externalities linked to industrial activities and the expected benefits arising from environmental upgrading and low-carbon transition.

In a specific way the study tries to evaluate the true capacity of the real estate market to absorb and reflect industrial plants transformation processes, considering both short-term modifications and longer-term structural changes.

In this perspective, real estate prices are interpreted not merely as economic variables, but as composite indicators capable of capturing broader socio-economic expectations, perceiving environmental quality and shifts in territorial attractiveness.

Methodologically, the study aims to contribute to the debate on evaluation tools capable of integrating environmental, industrial and territorial dimensions, by proposing an assessment tool for the analysis of the relationship between decarbonization strategies and real estate values. Through an econometric analysis of the current context, property values are linked to intrinsic housing characteristics, environmental conditions, and proximity to the industrial site, capturing the externalities associated with its presence.

A prospective industrial decarbonisation scenario is then constructed to simulate how technological and environmental improvements may affect contextual variables and, consequently, future property values. By comparing estimated prices before and after the intervention, changes in real estate values are interpreted as an indirect measure of the territorial benefits of decarbonisation. In this perspective, the real estate market serves as a synthetic indicator of economic, environmental, and perceptual dynamics, supporting public and private decision- making in areas undergoing industrial transformation.

In this sense, the expected outcomes of the research are intended to provide knowledge support to public decision-makers - particularly in the context of cost– benefit analyses, industrial transition strategies, and territorial regeneration policies - as well as to private investors assessing the attractiveness and risk profile of real estate investments in areas undergoing profound industrial and environmental transformations. Finally, the research aspires to suggest an interpretative framework that enhances the understanding of how ecological transition processes are inserted within local socio-economic systems and reflected in property market dynamics.

The structure of the present paper is outlined as follows. Section 3 provides the background framework, discussing the main dynamics linking industrial regeneration and decarbonisation strategies with local environmental conditions and their potential effects on residential property markets. Section 4 describes the proposed methodological approach, detailing the different phases to be carried out. In Sect. 5 the conclusions are explained, discussing the main methodological implications and outlining possible future developments.

## 3 Background

Industrial regeneration and energy transition processes are gradually assuming an increasingly central role in territorial transformation policies, particularly in contexts characterised by the presence of large production plants and energy-intensive industrial sectors. Decarbonisation and technological conversion strategies for productive systems are progressively redefining the relationship between industrial activities and the surrounding territory, affecting not only economic and production dynamics, but also environmental quality and the residential attractiveness of nearby areas [15].

Several international studies have shown that local environmental conditions represent a determining factor in the functioning of property markets. According to hedonic pricing approach, the value of properties does not depend exclusively on their intrinsic characteristics – such as dwelling size, construction quality or maintenance state – but also reflects the characteristics of the territorial context in which they are located, including variables such as air quality, noise levels, the presence of environmental amenities and the perception of environmental risk [16–18].

A fundamental key factor, that is represented by the air quality, influences the value of residential properties: several empirical researches attest that improvements in air quality can translate into significant increases in housing prices [19].

A particularly relevant study analyses the effects of air pollution regulation policies in the United States by exploiting changes in air quality determined by the Clean Air Act, one of the main federal environmental strategies introduced to reduce industrial emissions and improve air condition [20].

The outcomes indicate that emissions reduction contributed to measurable improvements in air quality, which were subsequently capitalised on in property values: a decrease in atmospheric particulate matter concentrations is associated with increases in housing prices of approximately 0.7% to 1.5% per unit reduction in the pollutant [21].

In addition, more recent evidence confirms this relationship, demonstrating that the decline in fine particulate matter (PM2.5) concentrations associated with more stringent environmental policies can lead to average increases in property values of up to

approximately 6% in the areas concerned [22]. Similar analyses carried out on residential property markets detect that higher levels of air pollution are connected to significant reductions in residential prices of up to 8% [23, 24]. Further empirical findings emerge from the analysis of Toxic Release Inventory data in the United States, which shows that the decrease in industrial emissions has been progressively reflected in property values in the areas close to production facilities [25].

Complementary to air quality, noise pollution is also a significant environmental disamenity in urban contexts, arising from industrial activities and heavy traffic. High levels of environmental noise negatively affect residents' quality of life and, consequently, residential property values.

The relevant literature points out that higher levels of noise exposure are generally associated with reductions in housing prices. Analyses based on hedonic price models indicate that a 1 dB increase in environmental noise levels can determine a decrease in property values of between approximately 0.5% and 2% [26].

Similarly, empirical investigations developed on the Stockholm property market validate these results, highlighting that exposure to road traffic noise has significant negative impacts on residential market mechanisms. In particular, dwellings located in areas characterised by higher levels of traffic-related noise may experience price reductions of up to approximately 5–10%, depending on the intensity and persistence of noise exposure [27].

Additional evidence concerns the role of landscape quality and the presence of urban environmental amenities on real estate dynamics.

A substantial number of studies reveal that proximity to green spaces or contexts characterised by high landscape quality can generate significant increases in housing prices. For example, proximity to urban parks is capable of affecting property values, leading to increases of approximately 7% to 15% [28]. With the same aim, other studies show that the presence of green spaces can generate rises in residential prices of up to around 20% in immediately adjacent neighborhood [29]. More recent analysis also highlights how the quality of natural landscape views can result in marked property premiums in urban residential markets [30].

Furthermore, residents' perception of environmental risks related to industrial activities or contaminated sites constitutes another factor influencing property values.

The scientific literature emphasizes how the presence of polluting industrial sites can give rise to a reduction in property values in the surrounding areas [31]. Conversely, environmental remediation and targeted redevelopment measures may produce the opposite effect. In this sense, contaminated site remediation programmes in the United States have been shown to positively impact the real estate prices of nearby residential units [32]. Moreover, empirical analyses suggest that brownfield redevelopment may contribute to higher property values in adjacent urban zones, especially when remediation efforts enhance environmental quality and visual appeal or provide new public amenities [33, 34].

Overall, these findings point out that the property market is strongly sensitive to changes in local environmental conditions. Improvements in air quality, noise levels, landscape quality and in the perception of environmental safety tend to be progressively reflected and, therefore, capitalised in housing prices, as they contribute to increased

livability, attractiveness and residential desirability. From this perspective, industrial regeneration processes aimed at decarbonisation - and, more generally, at ecological transition strategies that do not involve the dismantling of existing production activities - may play a crucial role in shaping local environmental conditions.

These processes are based on the technological transformation and conversation of industrial facilities, favouring the adoption of innovative solutions capable of reducing the environmental impact of production systems. In recent years, the growing emphasis on ecological transition objectives has fostered the development of technological policies designed to lower emissions and improve the environmental performance of industrial processes [35].

In this context, among the main technological solutions currently being developed in energy-intensive industrial sectors, Carbon Capture, Utilisation and Storage (CCUS) systems, industrial hydrogenation processes (Green Hydrogen) and the electrification of production processes are included, as well as the specific measures aimed at upgrading the plants energy efficiency. These technologies are assuming an increasingly important role in the so-called hard-to-abate sectors, such as steelmaking, cement production and basic chemicals [36–39].

Within the mentioned framework, residential property markets provide particularly sensitive indicators of territorial transformations, as housing prices tend to incorporate changes in environmental quality, risk perception and expectations of economic and urban development over time. From this perspective, trends in property values can act as an indirect yet meaningful proxy for assessing the impacts of industrial regeneration processes on the local context, encompassing both ecological changes and evolving expectations for economic and urban development.

It should be pointed out that, however, despite the growing attention and relevance of production regeneration or decarbonization strategies in contemporary industrial and climate policies, scientific literature has so far paid limited attention to the effects of these targeted processes on residential property markets. Indeed, most existing studies focus on the impacts of the presence of polluting industrial sites on real estate mechanisms or on the territorial implications of environmental remediation plans, whereas the dynamics through which technological transformations aimed at reducing $CO_2$ emissions can affect property values in areas surrounding production facilities remain largely underexplored.

From this standpoint, the analysis of the relationship between industrial regeneration processes oriented towards decarbonisation and the residential property prices is a field of research that is still partially unexamined but potentially interesting for understanding the territorial effects of the ecological transition and for effectively supporting decision-making processes in industrial development and urban regeneration governance initiatives.

## 4 Methodology

According to the aim of the present research, the proposed methodological approach for the assessment of the decarbonization of industrial plants on real estate values is divided into twelve phases. This is designed to ensure internal consistency, transparency of the analytical process and replicability in other contexts characterized by the presence of large, polluting industrial sites and ecological transition processes.

The methodological approach adopts a sequential framework to evaluate whether, and to what extent, property prices can be interpreted as a proxy indicator of the territorial impacts associated with the presence of steel plants and ongoing decarbonisation processes. In this sense, the first part (phases 1–7) of the methodology is dedicated to the analysis of the current state, whereas the second part (phases 8–12) is oriented towards the prospective exam of the potential impacts associated with the planned transformation, through the construction of a future industrial decarbonization scenario. This distinction allows to separate the empirical observation of existing dynamics from the simulation of expected impacts, avoiding overlap between descriptive analysis and potential assessment. Therefore, the analysis is structured as a twofold investigation. The first stage examines the influence of the industrial and potentially polluting site on property values, assessing the extent to which its presence affects local real estate dynamics. The second one develops an ex ante predictive assessment aimed at estimating the potential impacts of the decarbonisation process on the property values, thereby exploring how environmental and technological transformation may reshape territorial attractiveness over time.

The steps into which the proposed methodology is structured are described below.

Phase 1 consists of the case study definition, which allows to delimit the analysis area and to frame the territorial industrial, and urban context in which the industrial site to be explored is located. This phase is essential for understanding local specificities and ensuring consistency between the research objectives, the scale of analysis and the available data.

Phase 2 focuses on the selection of intrinsic and extrinsic variables, identified in line with the factors most commonly considered during property bargaining processes. Particular attention is given to variables capturing urban quality and the perception of environmental risk, which are regarded as key determinants in the formation of residential property values, especially in the context of proximity to the industrial site.

Phase 3 concerns the identification of the real estate sample and is aimed at building a dataset representative of the local residential market. The sample is selected to ensure adequate spatial and temporal coverage, thus allowing for the analysis of price dynamics in relation to proximity to the industrial site and other variables considered.

Phase 4 involves the georeferencing of the collected data and the assessment of their statistical robustness through descriptive analysis. This step aims to identify potential anomalies, outliers and preliminary relationships among the variables, ensuring the reliability and consistency of the dataset prior to econometric analysis.

Phase 5 includes the application of the econometric technique, targeted at analyzing the relationships between real estate characteristics, environmental factors and property values. In this sense, this phase provides an empirical basis for isolating and interpreting the impacts of the presence of the industrial site and the territorial characteristics on real estate market dynamics.

Phase 6 addresses the critical analysis of the empirical findings. Particular attention is given to the magnitude, direction and statistical significance of the estimated effects, as well as to their coherence with the territorial and environmental local context specificities.

Phase 7 focuses on the validation of the econometric results, assessing their robustness and consistency with theoretical expectations and the evidence emerging from

scientific literature. This step strengthens the baseline analysis and provides a solid foundation for the subsequent development of the prospective assessment.

Phase 8 begins with the description of a (planned, to be implemented, in progress, etc.) transformation scenario related to the decarbonisation of the selected industrial site, focusing on its key technological, energy and territorial features.

Phase 9 concerns the identification of variables that are potentially subject to change in the transformation scenario, with particular reference to the environmental and perceptive components that can influence real estate values in the medium-long term. This step highlights the main contextual elements likely to be affected by the industrial transformation, providing a basis for simulating its potential impacts on the local property market. In this phase, the post-intervention values of the selected variables are assessed according to the nature of each factor:

(i) for variables directly related to measurable environmental or technological changes (e.g., air quality, noise levels, emissions), values are estimated by making assumptions;
(ii) for variables related to the perception of environmental quality and risk, values are estimated by implementing stated preference techniques, such as surveys aimed at capturing the perceptions of the community.

Starting from these hypothesized variations, in phase 10 the determination of expected real estate values in the future transformation scenario is carried out, using the relationships derived from the current state analysis, to simulate the potential effects of industrial decarbonisation. It is assumed that the function linking real estate values to intrinsic and extrinsic factors remains unchanged and that, therefore, the variables influencing the price formation process remain the same.

The estimated prices are obtained by keeping constant the values of intrinsic variables and the values of those extrinsic characteristics that are not affected by the proposed transformation, while introducing the values of the extrinsic variables for which a variation is expected in the post-intervention scenario.

Phase 11 consists of comparisons between the estimated property values before the decarbonization process and those assessed after the intervention, i.e. in the transformation scenario. The interpretation of the differences between the two temporal periods is performed in order to point out the potential territorial benefits associated with the industrial transformation as reflected in the real estate market.

Phase 12 provides a final overview of the results obtained, which integrates the evidence from both phases analyses (that are current state and transformation scenario), offering a comprehensive assessment of the territorial impacts of decarbonization.

Figure 1. Provides a summary of the phases of the proposed methodological approach, highlighting the sequential structure of the process and the distinction between current state analysis and prospective assessment.

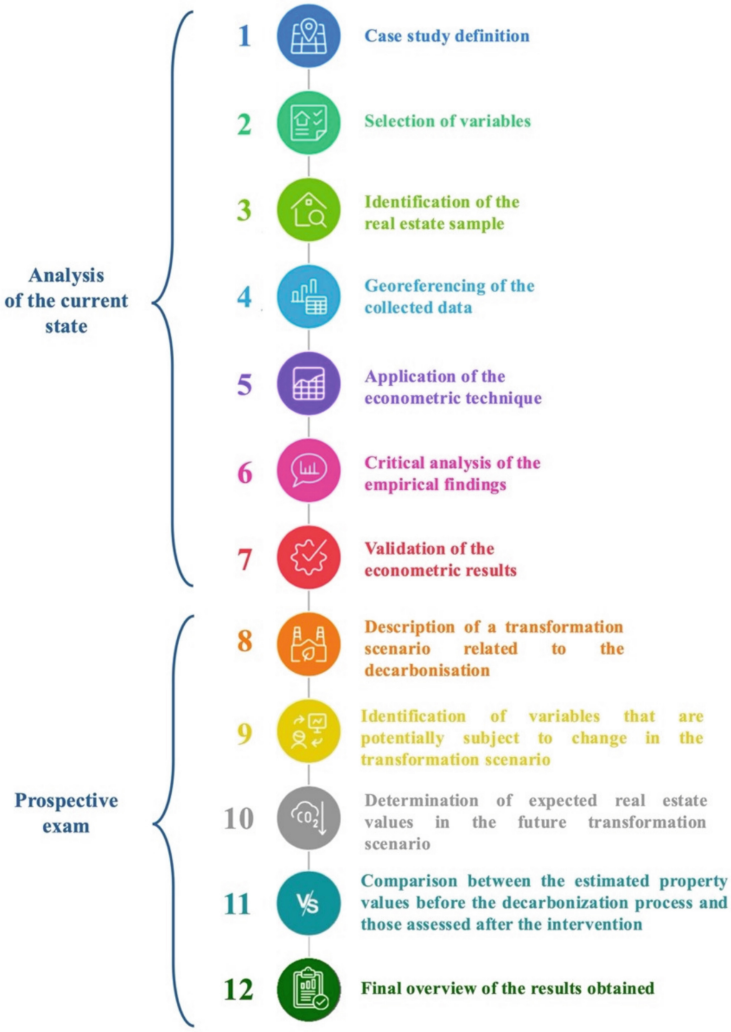


**Fig. 1.** Phases of the proposed methodological approach.

## 5 Conclusions

With reference to the current and relevant topic of industrial sites decarbonization, the present research has proposed a methodological approach aimed at assessing the impacts of transformation processes on real estate values. In this sense, the methodology aims to provide a practical evaluation tool capable of supporting environmental transition policies by offering insights into the broader socio-economic implications of decarbonisation.

The methodology relies on the real estate market as a proxy indicator for interpreting the territorial impacts associated with the presence of the steel plants and the ongoing low-carbon transformation processes. The main underlying assumption is that property

values and market dynamics reflect, over time, both the negative externalities of industrial activities and the expected benefits arising from environmental improvement [40, 41].

A key strength of the approach lies in its two-phase structure, which separates the analysis of the current state from the construction of a prospective transformation scenario. This design enhances the methodology's adaptability and potential replicability in other contexts characterized by environmental transition processes. In fact, the proposed approach is characterized by its flexibility and reproducibility, allowing for continuous monitoring of each step and adaptation to different inputs arising from evolving contextual conditions.

The possibility of adjusting the phases sequence to the characteristics of diverse territorial contexts enables its application to the exam of decarbonisation processes effects on real estate market, including their environmental, social, and economic impacts. Such adaptations can be proposed by public authorities, real estate market operators and local communities, according to the specific features of industrial areas undergoing transformation and the decarbonisation projects being implemented.

Nevertheless, several limitations must be pointed out. Firstly, the assumption that the fundamental structural dynamics of the real estate market remain constant represents a crucial aspect to be investigated.

The analysis, in fact, modifies only those variables deemed susceptible to change as a result of the industrial decarbonization intervention, while underlying the other market mechanisms that are considered unchanged, thus by assuming that supply-demand interactions, liquidity conditions and broader economic trends are unvaried.

This simplification allows for a controlled assessment of the intervention's potential effects but may underestimate or overlook indirect or systemic impacts that emerge when structural market conditions evolve over time [42].

In addition, the interpretation of changes in real estate values assumes that the residential market is able to timely and consistently incorporate information relating to environmental and industrial changes, a condition that may be affected by external factors such as macroeconomic trends or sector-specific policies.

Furthermore, the use of variables connected to the perception of environmental risk requires the definition of proxies that, while allowing for quantitative analysis, fail to fully capture the complexity of the socio-economic factors that influence the choices of real estate operators. In this sense, to address this critical issue, targeted qualitative analyses should be conducted to evaluate stakeholders' perceptions of the industrial site and its ongoing or planned transformation.

However, also in situations where the transformation scenario is only proposed, the prospective component of the methodology is crucial to provide indications to decision-makers for implementing effective regeneration policies on territories.

In fact, although the scenario-based estimations of the effects of industrial decarbonisation do not represent deterministic forecasts, they serve as interpretative tools for exploring plausible directions of change.

Accordingly, the results should be regarded as indicative of general trends of predictions of future property values [43], by supporting the choices processes of urban decarbonization initiatives. In light of these considerations, this work leads to several future developments.

Firstly, the proposed methodology could be applied to real-world industrial contexts undergoing transition processes, such as steel districts, petrochemical clusters or energy-intensive production areas. In these settings, the framework may support ex-ante evaluation of decarbonisation strategies, enabling public authorities to compare alternative technological pathways and to guide the allocation of public resources in territorial regeneration processes [44].

Secondly, the methodological approach could be further strengthened through the integration of complementary analytical techniques. In particular, spatial econometric models could be adopted to account for spatial dependence in property values, while panel data approaches may allow for the analysis of temporal dynamics associated with industrial transformation processes. In addition, machine learning techniques could be explored to capture non-linear relationships among variables, and stated preference methods could enhance the representation of residents' perception of environmental quality and risk.

Thirdly, further developments could focus on improving the construction of prospective scenarios by incorporating alternative pathways and sensitivity analyses. This would allow for testing the robustness of the estimated impacts under different assumptions and for better capturing the complexity and uncertainty associated with decarbonisation processes.

Finally, the application of the proposed framework to specific case studies represents a crucial step for future research, in order to validate its empirical effectiveness and refine the estimation procedures in real-world contexts [45].

From a broader perspective, the decarbonisation of industrial systems remains a critical challenge for territorial planning, environmental governance and sustainable urban development.

In this context, the proposed methodology aims to contribute to the development of integrated evaluation tools capable of supporting public and private decision-making processes, by linking environmental transformation dynamics with real estate market responses and territorial attractiveness.

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## References

1. Guarna Assanti, E.: Il contenzioso climatico europeo: profili evolutivi dell'accesso alla giustizia in materia ambientale (2024)
2. Aristei, L.: L'Accordo di Parigi: obiettivi e disciplina. Rivista quadrimestrale di diritto dell'ambiente 73–96 (2017)
3. Fetting, C.: The European green deal. ESDN Report **2**(9), 53 (2020)
4. Szpilko, D., Ejdys, J.: European Green Deal—research directions: a systematic literature review. Ekonomia i Środowisko **2**, 8–38 (2022)
5. Ovaere, M., Proost, S.: Cost-effective reduction of fossil energy use in the European transport sector: an assessment of the Fit for 55 Package. Energy Policy **168**, 113085 (2022)

6. Zhong, J., Pei, J.: Carbon border adjustment mechanism: a systematic literature review of the latest developments. Climate Policy **24**(2), 228–242 (2024)
7. Gandiglio, M., Ferrero, D.: La decarbonizzazione del settore energetico attraverso l'uso dell'idrogeno. Equilibri **23**(2), 419–427 (2019)
8. Ministero dello Sviluppo Economico et al.: Piano nazionale integrato per l'energia e il clima. Ministero dello Sviluppo Economico, Rome (2019)
9. Morettini, I.: Verso la neutralità climatica: integrazione delle strategie di riduzione delle emissioni e di rimozione della $CO_2$. Università Politecnica delle Marche, Ancona, Tesi di laurea magistrale (2024)
10. Bramanti, O., Capobianchi, M.: Transizione energetica e decarbonizzazione. Gruppo 24 Ore, Milano (2024)
11. Ronchi, E.: Le sfide della transizione ecologica. Edizioni Piemme, Milano (2021)
12. Pani, M.M.: Spazi intermedi e neutralità climatica. Protocolli di valutazione ambientale applicati agli spazi intermedi per la decarbonizzazione dei distretti urbani. In: Climate Equity and Climate Gentrification, pp. 92–98. Planum Publisher (2024)
13. Premoli Vilà, L.: Modellazione bottom-up del settore residenziale italiano: sviluppo, validazione e applicazione per la valutazione di percorsi di decarbonizzazione. Tesi di laurea magistrale, Politecnico di Milano, Milano (2018)
14. Arbizzani, E., Clemente, C., Mangiatordi, A., Sica, F., Tajani, F.: Percorsi di transizione energetica e ambientale per la rigenerazione del patrimonio immobiliare. Techne **30**, 229–240 (2025)
15. Mallach, A.: The Divided City: Poverty and Prosperity in Urban America, vol. 115. Island Press, Washington, DC (2018)
16. Rosen, S.: Hedonic prices and implicit markets: product differentiation in pure competition. J. Polit. Econ. **82**(1), 34–55 (1974)
17. Ansink, E., Hein, L., Hasund, K.P.: To value functions or services? an analysis of ecosystem valuation approaches. Environ. Values **17**(4), 489–503 (2008)
18. Palmquist, R.B.: Property value models. In: Mäler, K.G., Vincent, J.R. (eds.) Handbook of Environmental Economics, vol. 2, pp. 763–819. Elsevier (2005)
19. Anderson, R.J., Crocker, T.D.: Air pollution and residential property values. Urban Stud. **8**(3), 171–180 (1971)
20. Bayer, P., Keohane, N., Timmins, C.: Migration and hedonic valuation: the case of air quality. J. Environ. Econ. Manag. **58**(1), 1–14 (2009)
21. Chay, K.Y., Greenstone, M.: Does air quality matter? evidence from the housing market. J. Polit. Econ. **113**(2), 376–424 (2005)
22. Sager, L., Singer, G.: Clean identification? the effects of the clean air act on air pollution, exposure disparities, and house prices. Am. Econ. J. Econ. Pol. **17**(1), 1–36 (2025)
23. Miłuch, O., Kopczewska, K.: Fresh air in the city: the impact of air pollution on the pricing of real estate. Environ. Sci. Pollut. Res. **31**(5), 7604–7627 (2024)
24. Chasco, C., Gallo, J.L.: The impact of objective and subjective measures of air quality and noise on house prices: a multilevel approach for downtown Madrid. Econ. Geogr. **89**(2), 127–148 (2013)
25. Bui, L.T., Mayer, C.J.: Regulation and capitalization of environmental amenities: evidence from the toxic release inventory in Massachusetts. Rev. Econ. Stat. **85**(3), 693–708 (2003)
26. Ottoz, E.: Costi del rumore ed economia della qualità acustica. In: Rumore e qualità della vita, pp. 1–17. AIA, Firenze (2013)
27. Andersson, H., Jonsson, L., Ögren, M.: Property prices and exposure to multiple noise sources: hedonic regression with road and railway noise. Environ. Resource Econ. **45**(1), 73–89 (2010)
28. Jim, C.Y., Chen, W.Y.: External effects of neighbourhood parks and landscape elements on high-rise residential value. Land Use Policy **27**(2), 662–670 (2010)

29. Gibbons, S., Mourato, S., Resende, G.M.: The amenity value of English nature: a hedonic price approach. Environ. Resour. Econ. **57**(2), 175–196 (2014)
30. Lee, H., Lee, B., Lee, S.: The unequal impact of natural landscape views on housing prices. Sustainability **12**(19), 8275 (2020)
31. de Vor, F., de Groot, H.L.: The impact of industrial sites on residential property values. Tinbergen Institute Discussion Paper 09-035/3 (2009)
32. Greenstone, M., Gallagher, J.: Does hazardous waste matter? evidence from the housing market and the Superfund program. Quart. J. Econ. **123**(3), 951–1003 (2008)
33. Gamper-Rabindran, S., Timmins, C.: Does cleanup of hazardous waste sites raise housing values? J. Environ. Econ. Manag. **65**(3), 345–360 (2013)
34. Haninger, K., Ma, L., Timmins, C.: The value of brownfield remediation. J. Assoc. Environ. Resour. Econ. **4**(1), 197–241 (2017)
35. Hospers, G.J.: Industrial heritage tourism and regional restructuring in the European Union. Eur. Plan. Stud. **10**(3), 397–404 (2002)
36. Davis, S.J. et al.: Net-zero emissions energy systems. Science **360**(6396), eaas9793 (2018)
37. Rissman, J., et al.: Technologies and policies to decarbonize global industry. Appl. Energy **266**, 114848 (2020)
38. Bataille, C.G.: Physical and policy pathways to net-zero emissions industry. Wiley Interdisciplinary Rev. Climate Change **11**(2), e633 (2020)
39. Bashmakov, I.A., et al.: Climate change 2022: mitigation of climate change. In: Shukla, P.R., Skea, J., Slade, R., et al. (eds.) IPCC Sixth Assessment Report, Working Group III, chap. 11. Cambridge University Press (2022)
40. Bianco, E., Blanco, H.: Green hydrogen: a guide to policy making. Int. Renew. Energy Agency (IRENA), Abu Dhabi (2020)
41. González, S.: Bilbao and Barcelona 'in motion.' Urban Stud. **48**(7), 1397–1418 (2011)
42. Greco, L.: La decarbonizzazione dell'industria siderurgica italiana. Working Paper, Fondazione Di Vittorio, n. 4/2022, Roma (2022)
43. Novati, G.: Decarbonizzazione dell'industria italiana: analisi del potenziale tecnico e costruzione di possibili scenari. Tesi di laurea magistrale, Politecnico di Milano, Milano (2019)
44. Tajani, F., Cerullo, G., Stara, F., Sica, F.: Multidimensional models for building decarbonization pathways. Bus. Strategy Environ. 1–21 (2025)
45. Morano, P., Tajani, F., Di Liddo, F., Amoruso, P.: A feasibility analysis of energy retrofit initiatives aimed at existing property assets decarbonisation. Sustainability **16**(8), 3204 (2024)

# Sustainability Performance Assessment: Models, Approaches, and Applications Toward Interdisciplinary and Integrated Solutions (SPA 2026)

# The Corporate Social Responsibility in Agrifood System: An Integrated Methodological Approach to Assessing Corporate Integration and Communication

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**Abstract.** In recent decades, companies have developed innovative sustainable business management models capable of integrating green, resilient and inclusive approaches. Recently, partly as a result of EU and international regulatory guidelines, Corporate Social Sustainability (CSR) is becoming more diffuse in business models through which companies have attempted to integrate the three dimensions of sustainability (economic, social and environmental). The CSR approach has directed companies to revise their "mission" and business functions, shifting the focus from operating income to environmental and social impact. Several studies have analyzed the relationship between CSR and firm performance, between CSR and value chain, but few studies in the literature investigate the mode to communicate CSR to stakeholders, particularly through websites and in livestock enterprises. The objective of the paper is to present the methodological approach of the research, which is currently in progress, focusing on the analysis of the processes of CSR integration into business management and the related online communication of implemented sustainable actions. The integrated methodological approach is based on the analysis of the websites of Italian agribusinesses, in particular in livestock companies, using the "7S" model of analysis, supplemented by specific Focus Groups, to acquire qualitative information about the motivations toward sustainable actions, directly from a sample of companies. In the paper, the methodological approach will be proposed, as the research is in progress and includes among the objectives, the identification of key drivers and the implementation of strategies for a CSR in line with the SDGs related to the corporate ecosystem. The paper will propose the methodological approach and initial results obtained by the analysis of the websites of a sample of livestock enterprises. The research, still in progress, will identify key drivers for the development of strategies for CSR in line with the SDGs related to the business ecosystem and could have operative developments for the application of recent European Union legislation (CSRD 2022).

**Keywords:** Corporate Social Responsibility · sustainability report · website analysis · "7S" model · SDGs · agri-food system · livestock companies

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## 1 Introduction

The notion of 'sustainable development' [1] combines the requirements of economic growth with those of human and social development, quality of life and protection of the planet from a long-term welfare perspective.

The United Nations 2030 Agenda [2] and its 17 Sustainable Development Goals (SDGs) also pose new challenges to businesses, which are called upon to adapt their business functions and strategies to the requirements of the SDGs.

The European strategy (Green Deal, 2019 [3]) has as its aim to make the EU economy sustainable through a set of initiatives geared toward making the economy achieve climate neutrality Union by 2050.

The Green Deal is the EU's new growth strategy that aims to transform the EU into a modern, efficient and competitive economy, with the goal of zero net greenhouse gas emissions by 2050. It also intends to protect, conserve and enhance the EU's natural capital and protect the health and well-being of citizens from environmental hazards and their consequences. The Green Deal intends, therefore, to guide the EU toward a socially just transition and a sustainable economic system so that no person and no place is excluded. It will contribute to the goal of creating an economy that serves citizens by strengthening the EU's social market economy, generating stability, jobs, growth, and sustainable in-vestment [3]. The principal actions are: the efficient use of resources through the transition to a clean, circular economy, the curbing of biodiversity loss, the reduction of pollution and, in particular, actions against climate change.

As part of the Green Deal, an orientation for businesses toward relevant, comparable, and reliable reporting of sustainability information can be identified in order to achieve the goals set forth in the "Action Plan for Financing Sustainable Growth" [4]. Specifically, they are: redirecting capital flows toward sustainable investments in order to achieve sustainable and inclusive growth; managing financial risks derived from climate change, re-source depletion, environmental degradation, and social issues; and promoting transparency and long-term vision in economic-financial activities.

The Directive 2022/2464/EU (Corporate Sustainability Reporting Directive, CSRD) [5] is part of the European Green Deal and aims to promote transparency and disclosure by companies regarding the Environmental, Social and Governance (ESG) impacts of their activities, through enhanced reporting requirements by companies. The aim is to enable access by investors and stakeholders to more detailed, clear and as standardized and comprehensive as possible sustainability disclosures, with obvious positive consequences for the financial market in terms of completeness of information, transparency and comparability of data. Thus, the rules on corporate sustainability reporting have been reformulated, extending them to a wider range of companies.

For decades, there has been a gradual shift in business management from a conventional approach (based on the linear economy) to a sustainable approach (based on the circular economy). Businesses, as well as the various actors involved in the so-cio-economic growth processes of economic systems, are called upon to take responsibility for the negative externalities produced as a result of their production processes, and it is to them that policies oriented towards a sustainable development model are addressed [6]. Among the various approaches that have been adopted in business over the past decades, we have focused on the Corporate Sustainability Responsibility (CSR), the innovative

model through which companies have attempted to integrate the three dimensions of sustainability (economic, social and environmental).

This is a new corporate "vision" and "mission" to which companies are gradually approaching, albeit in a differentiated manner among countries and among different production sectors [7, 8]. The aspect related to the communication of CSR adoption to stakeholders is also very diverse and not always effectively executed [9].

The increased awareness of shareholders, consumers and the general public about the negative externalities produced by business and their social responsibility represents a turning point, including in the debate about performance measurement systems [10, 11]. Ethical and sustainable investments have seen a strong increase over the past few years, influencing corporate strategies, in order to gather consensus from stakeholders sensible to social and environmental issues.

The Legislative Decree 125/2024 (effective September 15, 2024), transposed the CSRD Directive into Italian law, representing a significant step toward greater accountability and transparency in sustainability reporting, with impacts extending to various aspects of corporate management.

The objective of the paper is to present the methodological approach of the research, which is currently in progress, focusing on the analysis of the processes of CSR integration into business management and the related online communication of implemented sustainable actions. The integrated methodological approach is based on the analysis of the websites of Italian agribusinesses, in particular in livestock companies, using the "7S" model of analysis, supplemented by specific Focus Groups, to acquire qualitative information about the motivations toward sustainable actions, directly from a sample of companies. The research, in progress, includes among the objectives, the identification of key drivers and the implementation of strategies for a CSR in line with the SDGs related to the corporate ecosystem. The paper aims to provide an initial contribution of the ongoing and just described research. In particular, the CSR approach in agribusinesses, the methodological framework adopted and, then, the results inherent only in the survey carried out on the websites of some Italian livestock enterprises, using the "7S" model, will be explained. The information obtained from the Focus Groups provided in the methodological framework (in progress) will be the object of a next submission, which will provide an additional opportunity to develop a more complete contribution to the literature by developing a framework that could assess the factors that influence agribusinesses to implement actions related to sustainability in agriculture.

## 2 The Corporate Social Responsibility Approach in the Agrifood Enterprises

Corporate contribution to the preservation of the environment and the well-being of society, including through the adoption of appropriate governance systems, is an increasingly mainstream approach [12, 13]. Businesses have realized that corporate durability rests not only on long-term economic-financial balances, but also on the sustainability of choices with respect to the physical-natural and social environments with which the company interacts.

Also farmers faced with the new development model in which competitiveness also derives from a commitment to ensure adequate levels of economic, social and environmental sustainability in the territorial context in which they operate [8, 14–16]. It follows that the success of agriculture with respect to the new requirements of society resides in the ability of the agri-firm to produce healthy and genuine food and at the same time contribute to the protection of natural resources and the the balanced development of the territory, creating employment and paying more attention to the quality of work [17–20]. The agricultural enterprise has a unique characteristic: it organises the factors of production in an open context where environmental and climatic factors are determinant for the achievement of objectives.

The integration of the circular and green economy approach in the agrifood sector is considered strategic and necessary to transform society and address future challenges [21]. The key to making production systems, communities, and cities more circular is the conversion to a sustainable, inclusive, circular economic system based on reducing pressure on natural resources and recovery [17, 22–24].

The shift of businesses from a traditional management approach to a green economy approach has changed the way of "doing business." New business functions have enriched corporate management, and strategic planning is being developed using innovative approaches based on smart, green, inclusive and resilient models [25–28].

It is not easy to give a definition of social responsibility, as there are many definitions in the literature. We can cite that of the European Community in the Green Paper [29], which describes it as '*the voluntary integration of the social and ecological concerns of companies in their business operations and in their relations with stakeholders….Being socially responsible means not only fully complying with applicable applicable legal obligations, but also going beyond by investing 'more' in human capital, in environment and in relations with other stakeholders"* ([29], p. 7).

The acronyms associated with a "socially responsible" enterprise are ESG (Environmental, Social and Governance) [30, 31] and CSR (Corporate Social Responsibility) [32]. ESG considers the environmental, social and governance consequences of the enterprise. The term ESG was introduced in 2004 in the report '*Who Cares Wins*' of the United Nations Global Compact Initiative [30]. According to the report: *"…Companies are asked to take a leadership role by implementing environmental, social and corporate governance principles and polices and to provide information and reports on related performance in a more consistent and standardised format. They should identify and communicate key challenges and value drivers and prioritise environmental, social and governance issues accordingly.."* [30, pag. Iii]. But in 2005, the meaning of ESG was deepened and the importance of the three dimensions for investment was emphasised in the study of the United Nations Environment Programme Finance Initiative (UNEP FI), in particular in the Report "*A legal framework for the integration of environmental, social and governance issues into institutional investment"* [31].

On the corporate side, regulatory intervention has mostly focused on the guidance to be provided to companies in order to communicate their ESG strategies transparently to stakeholders, and thus also to potential investors. In order to develop up-to-date reference standards, the EU finally approved the CSRD (Corporate Sustainability Reporting Standard Directive) in 2022 [5], entered into force in 2024. The directive updates the

pre-existing legislation on sustainability reporting, with particular references to physical and transitional risks with respect to the environmental sphere, the focus on human rights and Diversity & Inclusion in the social sphere, and business ethics together with corporate risk management in relation to sustainability in the area of governance.

The acronym CSR takes a broader view, as it considers: economic responsibility to shareholders; stakeholder welfare; environmental protection; and improving social conditions (from a legal, ethical, and human perspective). The underlying approach is that corporate performance can no longer be measured by considering only corporate economic performance, but also actions in the social, environmental, and governance areas.

CSR is defined as the process of innovation in management models based on optimizing relationships with stakeholders and strategically integrating social and environmental objectives into the company's guidelines, processes and operations [32]. This new approach involves moving beyond investment in tangible resources alone since in modern economies it is intangible resources that represent a source of sustainable competitive advantage for the firm.

Carroll's [33, 34] basic definition of CSR argues that an organization can be considered socially responsible when it meets the economic, legal, ethical and philanthropic expectations that society has of an organization at a given time. In relation to the food industry, CSR is defined in terms of food safety and quality, as well as environmental and social sustainability [8]. Several definitions of CSR can be found in the literature [13, 35], but we feel that the one from the European Commission (EC) is most suitable for the proposed research. The EC concisely defines CSR as "*a concept whereby companies integrate social and environmental concerns in their business operations and in their interaction with their stakeholders on a voluntary basis*" ([12], p.6).

For companies, internalizing sustainability, in its three dimensions, into business functions means responding to the increasingly attentive community demand for the externalities produced, the associated costs as well as compensatory measures (especially in the case of negative externalities). Consumers are becoming more attentive and oriented towards conscious purchases and include in the concept of quality of agri-food products [14, 36] also values such as environmental and social sustainability of production. Agriculture therefore pays attention to transversal issues such as food safety, traceability of production, product quality, respect for the environment and human resources.

In addition to serving the social welfare of the network and the surrounding environment, sustainable practices can ensure a company's long-term benefits. For example, the adoption of employee-friendly regulations will bring human resource involvement to the pursuit of corporate sustainability goals. In the long run, a company's sustainability-focused vision, publicized on products, may gain additional market share, especially by tapping into more environmentally and socially sensitive customer targets [37–39].

Agricultural enterprises, in addition to their economic and productive function, provide by their very nature, a function of environmental protection and the enhancement of rural areas, traditions and local knowledge [11, 18, 19]. Therefore, they have introduced aspects of social responsibility into their strategies. In recent years, moreover, social and

environmental issues have become an integral part of the Community's agricultural policy, enhancing their consideration as important competitive levers in business strategies [36, 39, 40].

The researches in the literature currently focus attention on different aspects of CSR in agrifood firms. In particular, some authors have developed a multi-stage procedure to help analytically evaluate supply chains' sustainability performance [8, 14, 38]. Other authors have analyzed metrics of indicators related to keywords found in sustainability reports [15, 37, 40]; several researches have explored only a few aspects related to CSR, particularly have focused on the evaluation of the circular economy in CSR in agri-food companies [24, 41–43]. There are few researches on the analysis of the integration of the different aspects of sustainability in the functions of agri-food companies and, in particular, agricultural companies in Italy [7, 19, 43]. There is an ongoing development of the research area that analyses CSR communication to the stakeholders involved [44–48], but, at the moment, there are few (if not absent) studies on CSR communication through company websites in the Italian agri-food system and, in particular, in livestock companies.

## 3 Methodology

The methodology adopted for the study of the CSR analysis in Italian livestock companies is based on an integrated approach between a quantitative and a qualitative analysis. The objective is to analyze the CSR of agribusiness enterprises and related communication to stakeholders (customers, suppliers, institutions, etc.). In particular, the objective is to analyze how CSR is communicated online, through websites, and the strengths and weaknesses of this business transition, through Focus Groups with a sample of livestock companies in order to explore the motivations that guide toward a sustainable business model.

The information collected will provide a framework for describing:

- Current performance: through website analysis, using the "7S" model;
- Key drivers: identifying motivations to implement and improve CSR;
- Implementation: propose possible short and long-term actions and strategies to develop CSR (Fig. 1).

In particular, the quantitative analysis will be carried out through the evaluation of the websites of Italian livestock companies, according to the "7S" model [49–51] (Fig. 2). Site analysis started in January 2025 and is in progress. The analysis was performed on the websites of a sample of Italian livestock farms, located in different regions of the country with the aim of constituting a sufficiently representative sample of the Italian livestock reality. The "7S" model is articulated in the analysis of 7 evaluation criteria, each of which analyses a particular aspect of the CSR. The criteria and the subcriteria were defined based on the analysis of other researches performed [16, 41–43, 48, 52–55], and on the indicators selected internationally for specific studies on CSR [5, 29].

Specifically, each criterion, provides for the articulation into sub-criteria (rating from 1 to 5), as listed below:

*Economic Sustainability* (innovation, risk management, growth enhancement, competitive behaviour)

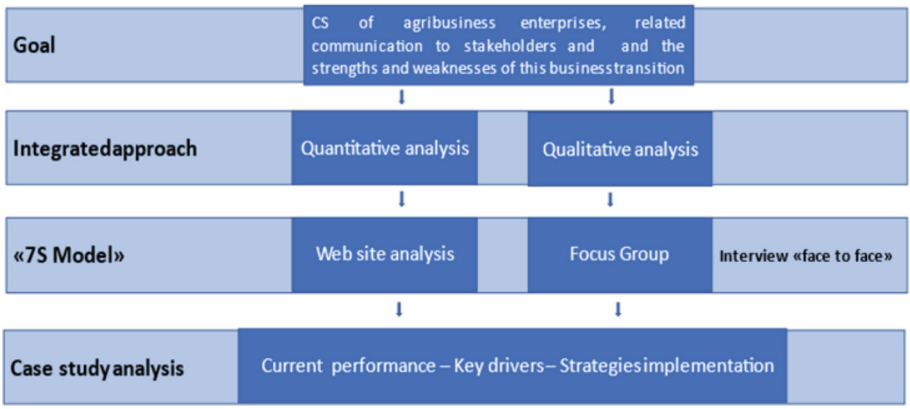


**Fig. 1.** Framework research

*Environmental Sustainability* (water and land emissions reductions, clean air; biodiversity; ecological impact)

*Social Sustainability* (customer welfare; human rights; labour relations; gender free)

*Ethical Sustainability* (jobs creation; skills enhancement; employee health and safety; diversity and inclusion)

*Circular Sustainability* (resource efficiency; life cycle management; no waste)

*Climate Sustainability* (environmental regulations; global climate change actions; energy management)

*Territorial Sustainability* (local economic impacts; social investment; business ethics)

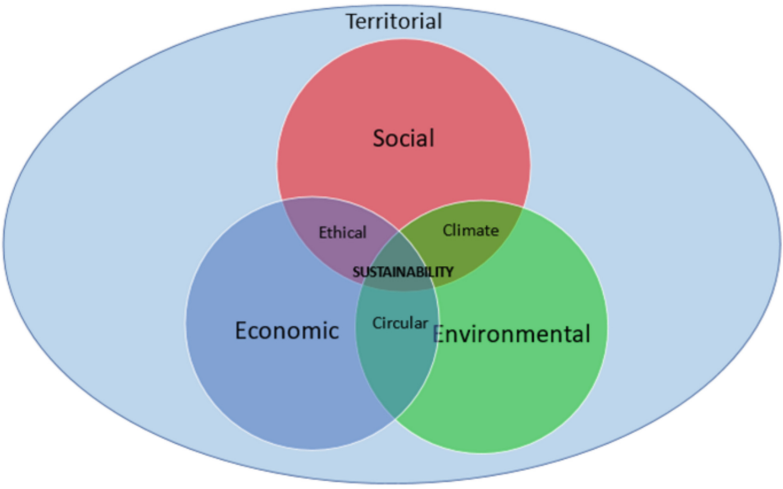


**Fig. 2.** "7 S" Model (author's elaboration)

The information was gathered by analyzing the institutional websites of various livestock companies (n. 10) identified through web research, using adherence to sustainability reporting principles and the actual preparation of a non-financial report as selection criteria.

The analysis consists of an objective component related to the presence or absence of the requested information on the website and a subjective component based on the evaluator's opinion and assessment criteria.

A score from 1 to 5 was assigned to the subcategories composing the seven parameters, and the final score was obtained through the arithmetic mean.

For completeness, the specific parameters are:

1: Not mentioned.
2: Mentioned marginally or unclearly.
3: Equal to the category average.
4: Communicated clearly and effectively, but with room for improvement.
5: Communicated with extreme efficiency.

In this scale, the value 2 indicates communication that is present but insufficient or underdeveloped, while 4 represents well-structured communication that is not yet excellent.

The qualitative phase will be articulated in the development of specific Focus Groups with company managers of agrifood companies, with the use of a special questionnaire, which will make it possible to acquire specific information on motivations and problems connected to the adoption of CSR and the innovations, strengths and weaknesses.

**Table 1.** Companies' characteristics.

| Companies | Site | Production | ESG balance |
|---|---|---|---|
| **Company 1** | Cingoli (MC) | Poultry | Yes |
| **Company 2** | San Vittore di Cesena (FC) | Poultry | Yes |
| **Company 3** | Capo d'Orlando (ME) | Bovine/Swine | Yes |
| **Company 4** | Tavernerio (CO) | Swine | Yes |
| **Company 5** | Bonemerse (CR) | Bovine/Swine | Yes |
| **Company 6** | Delebio (SO) | Bovine | Yes |
| **Company 7** | Verona (VR) | Bovine/Swine | Yes |
| **Company 8** | Cafasse (TO) | Poultry | Yes |
| **Company 9** | Arborea (OR) | Bovine | Yes |
| **Company 10** | Imola (BO) | Poultry | Yes |

Source: our web surfing.

Source: our elaboration on data web surfing.

This paper will report only the initial results of the survey performed on the websites of the livestock enterprises analyzed in this first phase. This is, therefore, an initial

contribution of the research that is currently being conducted, both for the website survey phase, with the "7S" model, and for the survey through Focus Groups, that is currently being conducted.

## 4 Results

The selected companies are medium-to-large farms or holdings that have vertically integrated the supply chain by incorporating agricultural businesses engaged in animal husbandry, such as meat-producing livestock (sheep and cattle), dairy farming and poultry farming.

The sample tried to represent the national reality by analyzing companies located in different parts of the country (Table 1). In particular, it is composed of seven companies located in northern Italy, one in central Italy, and the remaining two in southern and insular Italy. Four of them are exclusively dedicated to poultry production, three focus on mixed pig and cattle farming, one specializes solely in pig farming, and the last two are specialized in cattle farming.

All companies analyzed have an ESG report, tracked on the website, that reports the social, environmental and economic performance to provide transparency to their stakeholders.

Using the "7S" analysis framework as a reference, data was collected on sustainability communication exclusively through institutional websites.

The Fig. 3 shows the average values obtained by each of the "7S" in the considered sample, providing a synthetic overview of the application of ESG policies on corporate websites. Table 2 shows, instead, the average values achieved by each sub-dimension within each of the "7S" considered in the analysis model (considered on a scale of 1 to 5).

*Economic Sustainability* achieved a mean score of 3.18, reflecting a moderate level of performance. Within this category, the sub-dimension of "Competitive Behaviour" stands out with the highest score of 3.80, indicating that organizations are prioritizing strategies to maintain a competitive edge. Very interesting is the value obtained by the sub-dimension "Innovation", equal to 3.10. In fact, the companies considered, have activated a number of innovative projects, especially with reference to the digitization of different business processes (from production to administration to marketing). However, "Risk Management" scored the lowest at 2.50, suggesting that efforts to mitigate potential economic risks need enhancement.

In the comparative analysis among companies, Company 3 emerges as the leader with a score of 4.25, demonstrating strong "Innovation" and "Competitive behavior". Conversely, Company 5 scored the lowest at 1.50, highlighting significant challenges in this area.

The mean score for *Environmental Sustainability* is 2.45, the lowest among all the "7S". This reflects the significant challenges in addressing environmental issues for such as "Biodiversity" (1.90) and "Clean Air" (2.40) highlight areas where improvement is urgently needed. On the positive side, "Ecological Impact" received a relatively higher score of 2.90, indicating some progress in minimizing environmental degradation. The

**Table 2.** "7 S" evaluation (scale from 1 to 5).

| Categories | Mean value |
|---|---|
| *Economic Sustainability* | *3,18* |
| Innovation | 3,30 |
| Risk management | 2,50 |
| Growth Enhancement | 3,10 |
| Competitive behaviour | 3,80 |
| *Enviromental Sustainability* | *2,45* |
| Water and land emissions reductions | 2,60 |
| Clean air | 2,40 |
| Biodiversity | 1,90 |
| Ecological impact | 2,90 |
| *Social Sustainability* | *2,63* |
| Customer welfare | 3,60 |
| Human rights | 2,10 |
| Labour relations | 2,70 |
| Gender Free | 2,10 |
| *Ethical Sustainability* | *2,81* |
| Jobs creation | 3,70 |
| Skills enhancement | 2,70 |
| Employee health and safety | 2,60 |
| Diversity and inclusion | 2,00 |
| *Circular Sustainability* | *2,67* |
| Resource efficiency | 2,60 |
| Life cycle management | 2,60 |
| No waste | 2,80 |
| *Climate Sustainability* | *2,73* |
| Enviromental regulations | 2,80 |
| Global climate change actions | 2,80 |
| Energy management | 2,60 |
| *Territorial Sustainability* | *3,73* |
| Local economic impacts | 3,20 |
| Social investment | 3,60 |
| Business ethics | 4,40 |

Source: our elaboration on data web surfing.

sub-dimension "Water and land emissions reductions" reports an average of 2.60, representing a moderate focus on actions taken by companies to reduce emissions both on land and in water.

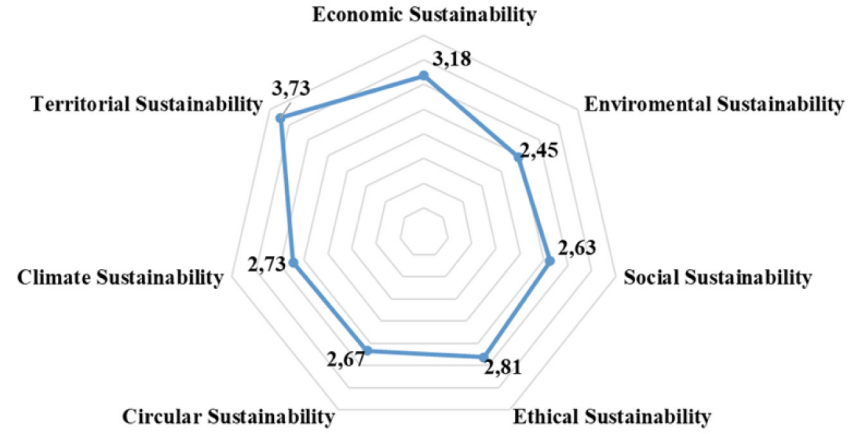


**Fig. 3.** The average rating of the "7S" in the sample (Source: Our elaborations)

Within the sample analyzed, Company 3 again leads this category with a score of 4.50, showcasing strong efforts in "Water and land emissions reductions" and "Clean air" initiatives. Company 5 scored only 1.75, indicating substantial room for improvement.

*Social Sustainability* scored an average of 2.63, showcasing a modest performance.

"Customer Welfare" emerged as a strength with a score of 3.60, suggesting that organizations are attentive to customer well-being. Conversely, "Human Rights" and "Gender Free" both scored 2.10, pointing to critical gaps in equity and inclusion that must be addressed. Bisogna evidenziare che le problematiche di carattere sociale sono ancora poco attenzionate nelle strategie aziendali, soprattutto per quanto riguarda la parità di genere e le relazioni con i lavoratori, mentre l'attenzione è ancora rivolta maggiormente sul consumatore. Le politiche connesse alla CSR dovrebbero consentire questa apertura nella vision aziendale, transitando le imprese da un approccio tradizionale ad uno innovativo, sostenibile e inclusivo.

Among the companies, Company 3 leads with a score of 4.25, reflecting strong "Customer welfare" and "Labor relations". At the lower end, Company 5 scored 1.00, indicating pressing challenges in this dimension.

*Ethical Sustainability* Achieved an average score of 2.81, indicating a fair level of commitment to ethical practices. "Jobs Creation" is a standout with a score of 3.70, demonstrating a strong focus on employment opportunities. L'aspetto collegato a "Skill enhancement" ha registrato un valore medio di 2,70, con notevoli margini di crrescita nel fututo, attraverso azioni mirate ad arricchire le competenze delle risorse umane presenti in azienda. However, "Diversity and Inclusion" scored only 2.00, reflecting a need for greater efforts in fostering an inclusive workplace.

Company 2 and Company 3 lead this category with scores of 4.50, demonstrating strong job creation and skills enhancement. Company 5, however, scored 1.00, highlighting areas requiring immediate action.

*Circular Sustainability* recorded a mean score of 2.67, representing moderate performance. The sub-dimension "No Waste" scored the highest within this category at 2.80, showing a promising focus on waste reduction. Nevertheless, "Life Cycle Management" and "Resource Efficiency" scored 2.60, highlighting areas where efficiency improvements are necessary.

Company 1 achieved the highest score of 5.00, reflecting exceptional performance in "Resource efficiency" and "waste management". At the other end of the spectrum, Company 5 scored 1.00, underscoring a critical need for improvements.

*Climate Sustainability* had an average score of 2.73, reflecting an intermediate level of achievement. "Environmental Regulations" and "Global Climate Change Actions" both scored 2.80, suggesting compliance with regulatory standards and engagement in climate-related initiatives. However, "Energy Management" scored lower at 2.60, emphasizing the need for more robust energy strategies.

Company 3 leads with a score of 4.67, demonstrating a strong focus on "Environmental regulations" and "climate actions". Company 5 scored 1.00, indicating substantial deficiencies in this area.

*Territorial Sustainability* stands out as the highest-scoring category with an average of 3.73, indicating substantial progress in this area. "Business Ethics" scored an impressive 4.40, showcasing exceptional ethical practices in local economic contexts. "Social Investment" also scored highly at 3.60, emphasizing the importance placed on community welfare.

Company 3 and Company 10 are the leaders with scores of 5.00, reflecting outstanding contributions to local economic impacts and business ethics. On the other hand, Company 5 scored 2.33, signaling a need for greater emphasis on territorial development.

The radar chart illustrates the relative strengths and weaknesses across the seven categories. *Territorial Sustainability* emerges as the strongest dimension, driven by high scores in "Business Ethics" and "Social Investment." On the other hand, *Environmental Sustainability* requires the most attention, with low scores in critical areas such as "Biodiversity" and "Clean Air."

Further details on the performance of the individual companies surveyed can be seen in Fig. 4, which shows the '7S' scores for each company considered. Among the companies analyzed, Company 3 results to be a south/insular company excellency consistently demonstrating excellence across multiple dimensions, while Company 5 struggles significantly, particularly *in Environmental*, *Social*, and *Ethical Sustainability.*

This analysis underscores the need for targeted interventions to address deficiencies, particularly in Environmental and Social Sustainability. Simultaneously, it highlights the importance of leveraging strengths in areas like *Territorial* and *Economic Sustainability* to drive overall improvement.

By surfing the websites, it was possible to identify other useful information to understand the CSR level of the analysed companies. These aspects are not included in the sub-dimensions of the '7S' foreseen in the model, but could be included to complete the framework of the phenomenon that can certainly be improved. All the companies in the

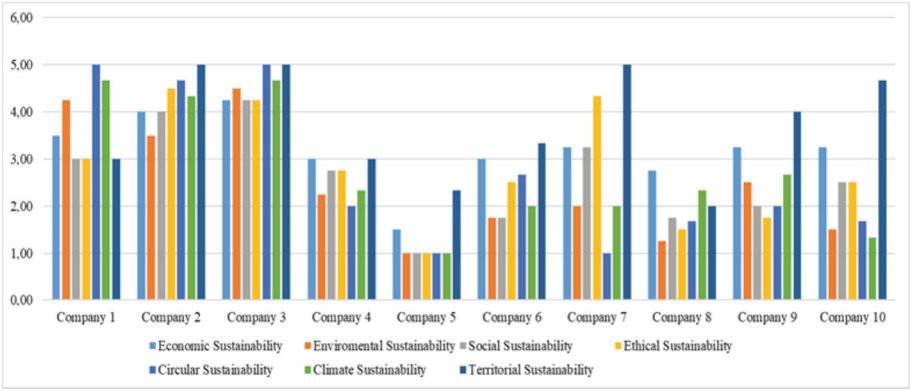


**Fig. 4.** The rating of the "7S" for each company in the sample (Source: our elaborations)

sample report on the sustainable development objectives pursued in their sustainability reports; some of them are Benefit companies. The companies in the sample have drawn up their sustainability reports by voluntarily adhering to the GRI Sustainability Reporting Standard, committing themselves to integrating their corporate information network with the data and information necessary to be able to comply with the EU Directive 2022/ 2464 in the near future.

## 5 Discussion and Conclusion

Businesses, as well as the various actors involved in the social-economic growth processes of economic systems, are called upon personally to take responsibility for the negative externalities produced of their production processes, and it is to them that policies oriented toward a model of sustainable development are addressed. Among the various approaches that businesses have adopted over the past decades, there has been a growing focus on innovative models through which businesses have sought to integrate the three dimensions of sustainability (economic, social and environmental).

The CSR approach has oriented companies to review their 'mission' and business functions, shifting the focus from operating income to environmental and social impacts. In fact, during strategic planning, companies pay particular attention to the definition of their 'mission' and 'vision', no longer taking into account only the profit margin, profitability, but considering the effects of the company's activities both at an environmental level (such as CO2 emissions, ecological footprint, etc.) and at a social level (through actions that aim at the wellbeing of its human resources and the territorial reference communities).

CSR, sustainability and stakeholders are three pillars that lead companies, or a part of them, to confront new objectives and, as a result, more complex strategic and organizational orientations than traditional models.

The transition towards an integration of sustainability in business management can be promoted at this particular time, especially in the E.U, by specific actions. The first major opportunity identified by the European Commission is represented by the National

Recovery and Resilience Plans (NRRPs) approved by each Member State. Among their objectives are to better support companies in decarbonising their production processes, adopting greener, circular technologies and promoting social inclusion actions. The proposed research, although limited to the presentation of the online CS evaluation approach, as the first step of a research in progress, could have operational developments in light of the recent 2022 E.U. Corporate Sustainability Reporting Directive (CSRD) [5] will generate important changes in the regulatory frameworks of EU member countries. One of the most significant innovations is that companies would be required to disclose sustainability information according to the EU Sustainability Reporting Standards including climate, pollution, water, biodiversity, workers and business conduct [56] (European Financial Reporting Advisory Group).

From the analysis of the sample, although currently limited to just a few companies that are representative of the Italian livestock reality, a growing awareness of the complex interaction of variables that lead to balanced economic-financial results is evident in company management. Enterprises are perceiving the importance of integrating in their strategic choices the many stakeholders who are directly interested in the company's results. Economic-financial equilibrium (with its related goals) is a necessary but not sufficient condition of overall corporate 'sustainability'. This implies that all 'stakeholders' in the company are aware of this and contribute to the final result for their part. The so-called 'multi-stakeholder' view presupposes a collaborative, win-win approach to benefit all stakeholders. This attitude would reduce the risk of so-called 'greenwashing', meaning a false environmentalism that is not matched by a real commitment to corporate sustainability, that might have an obvious negative impact on the corporate image and, therefore, on the economic-financial results.

This paper presents the initial findings of an ongoing study (as mentioned) and it has limitations derived from the small sample size, that affect the interpretation of the results. The "7S" model will be further validated in order to ensure reproducibility and reduce the element of subjective assessment.

This study could help develop future research based on the combination of psychological and socio-economic factors to understand the dynamics of sustainability adoption in Agribusiness System enterprises as well as weaknesses and strengths related to CSR implementation in new business models.

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## References

1. UN. Our Common Future. The World Commission on Environment and Development, Oxford University Press (1987)
2. UN. Transforming Our World: The 2030 Agenda for Sustainable Development. United Nations. Department of Economic and Social Affairs, New York, NY, USA (2015)
3. EC. The European Green Deal. 2019. Available online: EUR-Lex - 52019DC0640 - EN - EUR-Lex. Accessed 16 December 2025

4. EC. COM: 97 final. Action Plan: Financing Sustainable Growth**.** Bruxelles, 2018. Available online: EUR-Lex - 52018DC0097 - EN - EUR-Lex (2018). Accessed 16 December 2025
5. EC. Directive (EU) 2022/2464. Corporate sustainability reporting**.** Available online: Directive - 2022/2464 - EN - CSRD Directive - EUR-Lex. Accessed 16 December 2025
6. Scuderi, A., Bellia, C., Foti, V.T., Sturiale, L., Timpanaro, G.: Evaluation of consumers' purchasing process for organic food products. AIMS Agricult. Food **4**(2), 251–265 (2019)
7. Opferkuch, K., Caeiro, S., Salomone, R., Ramos, T.: Circular economy in corporate sustainability reporting: a review of organisational approaches. Bus. Strateg. Environ. **30**(8), 4015–4036 (2021)
8. Devin, B., Richards, C.: Food waste, power, and corporate social responsibility in the Australian food supply chain. J. Bus. Ethics **150**, 199–210 (2018)
9. OECD. Global Corporate Sustainability Report 2024. Global Corporate Sustainability Report 2024 | en | OECD. Accessed 20 January 2024
10. Timpanaro, G., Branca, F., Cammarata, M., Falcone, G., Scuderi, A.: Life cycle assessment to highlight the environmental burdens of early potato production. Agronomy **11**(5), 879 (2021)
11. Sturiale, L., Scuderi, A., Timpanaro, G., Foti, V.T., Stella, G.: Social and inclusive "value" generation in metropolitan area with the "urban gardens" planning. Green Energy Technol. 285–302 (2020)
12. European Commission: Directorate-General for Employment, Social Affairs and Inclusion, Promoting a European framework for corporate social responsibility - Green Paper, Publications Office, 2001. Available online: Microsoft Word - en 366-5.doc. Accessed 13 November 2025
13. Matten, D., Moon, J.: 'Implicit' and 'Explicit' CSR: a conceptual framework for a comparative understanding of corporate social responsibility. Acad. Manag. Rev. **33**(2), 404–424 (2008)
14. Risitano, M., Romano, R., Rusciano, V., Civero, G., Scarpato, D. The impact of Sustainability on marketing strategy and business performance. Bus. Strategy Environ. **31** (1) (2021)
15. Porter, M.E., Kramer, M.R.: The link between competitive advantage and corporate social responsibility. Harv. Bus. Rev. **84**, 78–92 (2006)
16. Martos-Pedrero, A., Cortés-García, F.J., Jiménez-Castillo, D.: The relationship between social responsibility and business performance: an analysis of the Agri-Food sector of Southeast Spain. Sustainability **11**, 6390 (2019)
17. Scuderi, A., Sturiale, L.: Multi-criteria evaluation model to face phytosanitary emergencies: the case of citrus fruits farming in Italy. Agricult. Econ. (Czech Republic) **62**, 205–214 (2016)
18. Scuderi, A., Sturiale, L., Bellia, C., Foti, V.T., Timpanaro, G.: The redefinition of the role of agricultural areas in the city of Catania. Rivista di Studi sulla Sostenibilità **2**, 237–247 (2016)
19. Heyder, M., Theuvsen, L. Corporate social responsibility in agribusiness: empirical findings from Germany. In a resilient European food industry and food chain in a challenging world. In: Proceedings of the European Association of Agricultural Economists (EAAE), 113th EAAE Seminar, Chania, Greece, 3–6 September 2009
20. Luhmann, H., Theuvsen, L.: Corporate social responsibility in agribusiness: literature review and future research directions. J. Agric. Environ. Ethics **29**, 673–696 (2016)
21. European Commission. COM (2020) 98 final. A new Circular Economy Action Plan For a cleaner and more competitive Europe. Available online: EUR-Lex - 52020DC0098 - EN - EUR-Lex (europa.eu). Accessed 23 November 2025
22. Scuderi, A., Sturiale, L. Evaluations of social media strategy for green urban planning in metropolitan cities. Smart Innovation, Systems and Technologies**,** vol. 100, pp. 76–42019 (2018) 3rd International New Metropolitan Perspectives. Local Knowledge and Innovation Dynamics Towards Territory Attractiveness Through the Implementation of Horizon/Europe2020/Agenda2030, 2018 Reggio Calabria 22 May 2018 through 25 May 2018, Code 213639

23. Scuderi, A., Sturiale, L., Timpanaro, G., La Via, G., Pecorino, B.A.: Possible circular approach for social perception of climate adaptation action planning in metropolitan cities. Green Energy Technol. 155–169 (2021)
24. Fortunati, S., Morea, D., Mosconi, E.M. Circular economy and corporate social responsibility in the agricultural system: cases study of the Italian Agri-food industry. Agric. Econ. – Czech **66**, 489–498 (2020)
25. Poponi, S., Arcese, G., Pacchera, F., Martucci, O.: Evaluating the transition to the circular economy in the agri-food sector: selection of indicators. Resour. Conserv. Recycl. **176**, 105916 (2022)
26. El Bilali, H., Callenius, C., Strassner, C., Probst, L.: Food and nutrition security and sustainability transitions in food systems. Food Energy Secur. **8**(2) (2019)
27. Scuderi, A., Timpanaro, G., Sturiale, L.: Economic evaluation of innovative investiments in agri-food chain. Qual. - Access Success **19**(S1), 482–488 (2018)
28. Sturiale, L., Scuderi, A.: The marketplaces and the integration between physic and virtual in the business models of fruit and vegetables e-commerce. CEUR Workshop Proc. **2030**, 79–90 (2017)
29. EC. 2001. GREENPAPER Promoting a European framework for Corporate Social Responsibility. Available online: Microsoft Word - en 366-5.doc. Accessed 20 December 2025
30. UN. Who Cares Wins. Connecting Financial Markets to a Changing World. The UN Global Compact. 2004. Available online: World Bank Document. Accessed 13 November 2025
31. UNEP FI. A legal framework for the integration of environmental, social and governance issue into institutional investment (2005). A legal framework for the integration of environmental, social and governance issues into institutional investment, October 2005. Accessed 13 November 2025
32. European Commission. COM 681 final. A renewed EU strategy 2011-14 for Corporate Social Responsibility. Url:EUR-Lex - 52011DC0681 - EN - EUR-Lex (europa.eu) (2011)
33. Carroll, A.B.: A three-dimensional conceptual model of corporate performance. Acad. Manag. Rev. **4**(4), 497–505 (1979)
34. Carroll, A.B.: The pyramid of corporate social responsibility: towards the moral management of organization stakeholders. Bus. Horizon **34**(4), 39–48 (1999)
35. Dahlsrud, A.: How corporate social responsibility is defined: an analysis of 37 definitions. Corp. Soc. Responsib. Environ. Manag. **15**(1), 1–13 (2008)
36. de Olde, E.M., Valentinov, V.: The moral complexity of agriculture: a challenge for corporate social responsibility. J. Agric. Environ. Ethics **32**(3), 413–430 (2019). https://doi.org/10.1007/s10806-019-09782-3
37. Jindřichovská, I., Kubíčková, D., Mocanu, M.: Case study analysis of sustainability reporting of an agri-food giant. Sustainability **12**, 4491 (2020)
38. Yakovleva, N., Sarkis, J., Sloan, T.: Sustainable benchmarking of supply chains: the case of the food industry. Int. J. Prod. Res. **50**(5), 1297–1317 (2011)
39. Coppola, A., Ianuario, S., Romano, S., Viccaro, M.: Corporate social responsibility in agri-food firms: the relationship between CSR actions and firm's performance. AIMS Environ. Sci. **7**(6), 542–558 (2020)
40. Topp-Becker, J., Ellis, J.D.: The role of sustainability reporting in the agro-food supply chain. J. Agricult. Environ. Sci. **6**, 17–29 (2017)
41. Cayzer, S., Griffiths, P., Beghetto, V.: Design of indicators for measuring product performance in the circular economy. Int. J. Sustain. Eng. **10**(4–5), 289–298 (2017)
42. Elia, V., Gnoni, M.G., Tornese, F.: Measuring circular economy strategies through index methods: a critical analysis. J. Cleaner Prod. **142**, Part 4, 2741–2751 (2017)
43. Corona, B., Shen, L., Reike, D., Carreón, J.R., Worrell, E.: Towards sustainable development through the circular economy—a review and critical assessment on current circularity metrics. Resour. Conserv. Recycl. **151**, 104498 (2019)

44. Bianchi, E., Bruno, J.M., Sarabia-Sanchez, F.J.: The impact of perceived CSR on corporate reputation and purchase intention. Eur. J. Manag. Bus. Econ. **28**, 206–221 (2019)
45. Chung, K.-H., Yu, J.-E., Choi, M.-G., Shin, J.-I.: The effects of CSR on customer satisfaction and loyalty in China: the moderating role of corporate image. J. Econ. Bus. Manag. **3**, 542–547 (2015)
46. Irshad, A., Rahim, A.: The impact of corporate social responsibility on customer satisfaction and customer loyalty, moderating effect of corporate image (evidence from Pakistan). City Univ. Res. J. **1**, 63–73 (2017)
47. Zhang, Q., Cao, M., Zhang, F., Liu, J., Li, X.: Effects of corporate social responsibility on customer satisfaction and organizational attractiveness: a signaling perspective. Bus. Ethics A Eur. Rev. (2019)
48. Öberseder, M., Schlegelmilch, B.B., Murphy, P.E., Gruber, V.: Consumers' perceptions of corporate social responsibility: scale development and validation. J. Bus Ethics. **124**, 101–115 (2014)
49. Sturiale, L., Scuderi, A.: Interaction between the emotional and rational aspects in consumer buying process for typical food products of Italy. Apply. Neurosci. Bus. Pract. 142–162 (2016)
50. Sturiale, L., Timpanaro, G., La Via, G.: The online sales models of fresh fruit and vegetables: opportunities and limits for typical Italian products. Qual. - Access Success **18**, 444–451 (2017)
51. Sturiale, L., Scuderi, A.: Information and communication technology (ICT) and adjustment of the marketing strategy in the agrifood system in Italy. CEUR Workshop Proc. **1152**, 77–87 (2011)
52. Kloppers, E., Fourie, L.: CSR communication in a South African agricultural company. Communication **40**, 305–322 (2014)
53. Scuderi, A., Sturiale, L.: Social commerce and marketing strategy for "made in Italy" food products. CEUR Workshop Proc. **1498**, 509–519 (2015)
54. Sturiale, L., Scuderi, A.: The digital economy: new e-business strategies for food Italian system. Int. J. Elec. Market. Retail. **7**, 287–310 (2016)
55. Foti, V.T., Sturiale, L., Timpanaro, G.: An overview of food waste phenomenon: by problem to resource. Qual. - Access Success **19**, 232–240 (2018)
56. European Commission: Implementing and delegated acts – CSRD (2023). https://finance.ec.europa.eu/regulation-and-supervision/financial-services-legislation/implementing-and-delegated-acts/corporate-sustainability-reporting-directive_en. Accessed 20 January 2026

# Tourism as a Spatially Structured Territorial System: A STESY-Based Interpretation of the Bay of Cádiz Tourism Ecosystem

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**Abstract.** The Bay of Cádiz represents a complex coastal tourism system in which tourism appears deeply embedded in the territorial structure and local economy. Rather than being concentrated in a single urban destination, tourism-related functions are distributed across a polycentric metropolitan area characterized by differentiated roles, short-stay dynamics, and high levels of spatial interdependence. This study applies the STESY framework to interpret the Bay of Cádiz as a structured tourism ecosystem, focusing on the spatial relationship between attractors, services, and accessibility. The methodology combines territorial analysis, mapping of tourism-related points of interest, cluster-based classification, and the use of composite indicators, including the Balanced Tourism Supply Index (BTSI), Attraction Potential Index (API), and Diversity Reachability Index (DRI). The results suggest that the tourism system is not simply organized around isolated destinations, but rather around a set of complementary territorial functions distributed across municipalities. The study contributes to a spatial reading of tourism as a territorially organized system and supports the definition of planning strategies aimed at improving integration, mobility, and long-term sustainability in coastal metropolitan areas.

**Keyword:** Sustainable tourism planning; · spatial analysis; · cluster analysis

## 1 Introduction

Sustainable tourism becomes more and more a core argument in territorial development debate defining local multi-stakeholders' perspectives and global framework for innovation and better management of such complex phenomena [1, 2]. Today tourism is recognized as a dominant driver of economic growth in coastal and heritage destinations, yet its rapid expansion has also generated critical spatial and temporal imbalances [3]. In the perspective of the authors, tourism opens to relevant debate in urban and regional planning research as the decision making process connected with tourism management represent a comprehensive framework in which sustainable urban regeneration

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and transformation, landscape protection actions, economic development issues interacts generating an effective environment to apply sustainable urban development principles, methods and agendas for short term and strategic territorial design [4–8]. Those applications are also oriented to improve the competences of students in academic curricula dealing with territorial design professionals, and this paper comes as a result of a studio in architectural classes following the research tradition [9–14] of sustainable urban planning and design at UNIBAS [15–18].

Tourism as a spatial phenomenon is a multidisciplinary domain where spatial dimension represents a robust analytical dimension for managing information and designs, applying collaborative approach for strategic planning [19–25].

Within this perspective, tourism may be interpreted not only through the volume of visitors or the intensity of seasonal flows, but also through the territorial structures that support, enable, and organize tourism-related activities.[26].

The Bay of Cádiz offers a relevant case for investigating these dynamics. The area is characterized by a polycentric territorial structure in which tourism-related functions are distributed across multiple municipalities, each contributing differently to the overall organization of the system. Rather than corresponding to a single dominant destination, the tourism ecosystem appears to be articulated through a set of complementary roles involving accommodation, gastronomy, heritage, leisure, mobility, and accessibility [24].

In this context, the study does not aim to frame tourism solely as a pressure or imbalance to be corrected. Instead, it proposes an interpretation of tourism as a territorial system whose internal structure can be analyzed in order to better understand its functioning, spatial logic, and planning implications [27].

This paper aims to develop a spatially informed planning framework capable of supporting the transition from a short-duration, high-pressure tourism model toward a more balanced system based on extended stays and territorial redistribution. The study proposes an integrated methodological approach combining spatial analysis, cluster-based interpretation, and policy-oriented design strategies in compliance with NUA principles. The contribution lies in bridging analytical diagnosis and operational planning within a coherent framework transferable to similar tourism destinations.

## 2 Study Area

To understand the study area, it is essential to recognize that the Bay of Cadiz is not a traditional urban center, but rather a polycentric metropolitan area heavily conditioned by its geography: a collection of cities interwoven by the Atlantic Ocean and separated by salt marshes. In this context, tourism in the Bay of Cadiz is a strategic destination that relies on the balance between natural resources and a historical urban structure. The influx of visitors drives the improvement of public spaces, infrastructure, and services, reinforcing a tourism model linked to leisure, the landscape, and culture. At the same time, it acts as an engine for economic and urban transformation, generating both opportunities and challenges related to sustainability and coastal preservation. To understand the true impact of this model on the territory, it is key to compare the local population with the arrival of visitors. The following graphs show the stark contrast between the number of residents and tourists, as well as their length of stay (Fig. 1).

The demographic analysis shows that Jerez de la Frontera is, by far, the municipality with the highest number of residents in the study area, exceeding 200,000 inhabitants. It acts as the main logistics hub and the major "commuter town" of the region. Meanwhile, the capital, the city of Cadiz, stands at around 110,000 to 120,000 inhabitants, a figure very similar to that of the municipality of San Fernando. On a second tier, Chiclana de la Frontera, El Puerto de Santa Maria, and San Fernando form a ring of demographic importance ranging between 80,000 and 100,000 inhabitants. This distribution highlights a clear territorial dynamic: the population resides mostly inland (Jerez), but the flow of work and leisure shifts daily toward the coast. This spatial dissociation forces a constant and massive use of private vehicles.

A drastic drop is observed in 2020 due to COVID, falling to 2.1 million visitors. However, the recovery has been highly positive, approaching the 4 million mark in 2024 and surpassing the record levels of 2018–2019.

Cross-referencing this data exposes the reality of a highly stressed territory. The sum of the entire resident population in the analyzed area does not even reach one million inhabitants; however, the territory bears the burden of more than 3.5 million tourists. This represents a ratio of more than 4 to 5 visitors for every resident. Consequently, basic infrastructures, which are scaled for the local population, must support a floating multitude that multiplies the actual pressure. This transforms the cities into giant weekend "hotels," overwhelming public services and hindering habitability for regular residents.

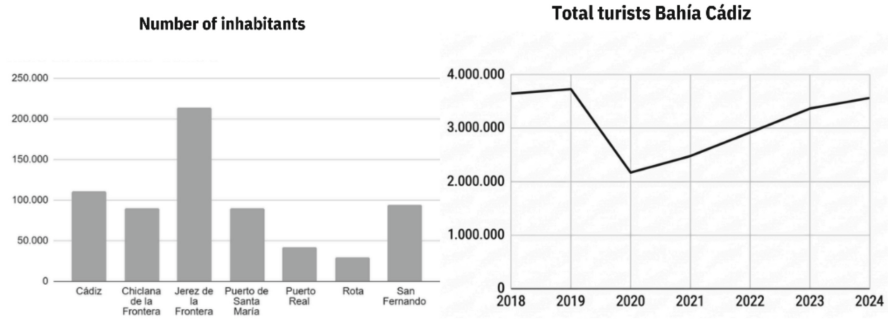


**Fig. 1.** Comparative overview of tourism dynamics in Bay of Cadiz. Source: personal elaboration of INE (https://www.ine.es/dyngs/INEbase/es/operacion.htm?c=Estadistica_C&cid=1254736177095&menu=ultiDatos&idp=1254735572981)

## 3 Territorial Analysis

The approach adopted in this study is based on the STESY framework [28] conceived as an integrated analytical and interpretative tool for the identification of territorial imbalances and the support of evidence-based planning strategies.

The first phase consists of a contextual analysis of the study area, focusing on the identification and classification of key georeferenced components (PoIs) of the tourism system, including attractors, services, and reachability (Fig. 2). The most striking data is the "Restaurants" category, with 317 recorded points. This indicates that the Bay's

tourism supply is based around the food sector. “Attractors Monuments” make up the second largest group with 130 points.

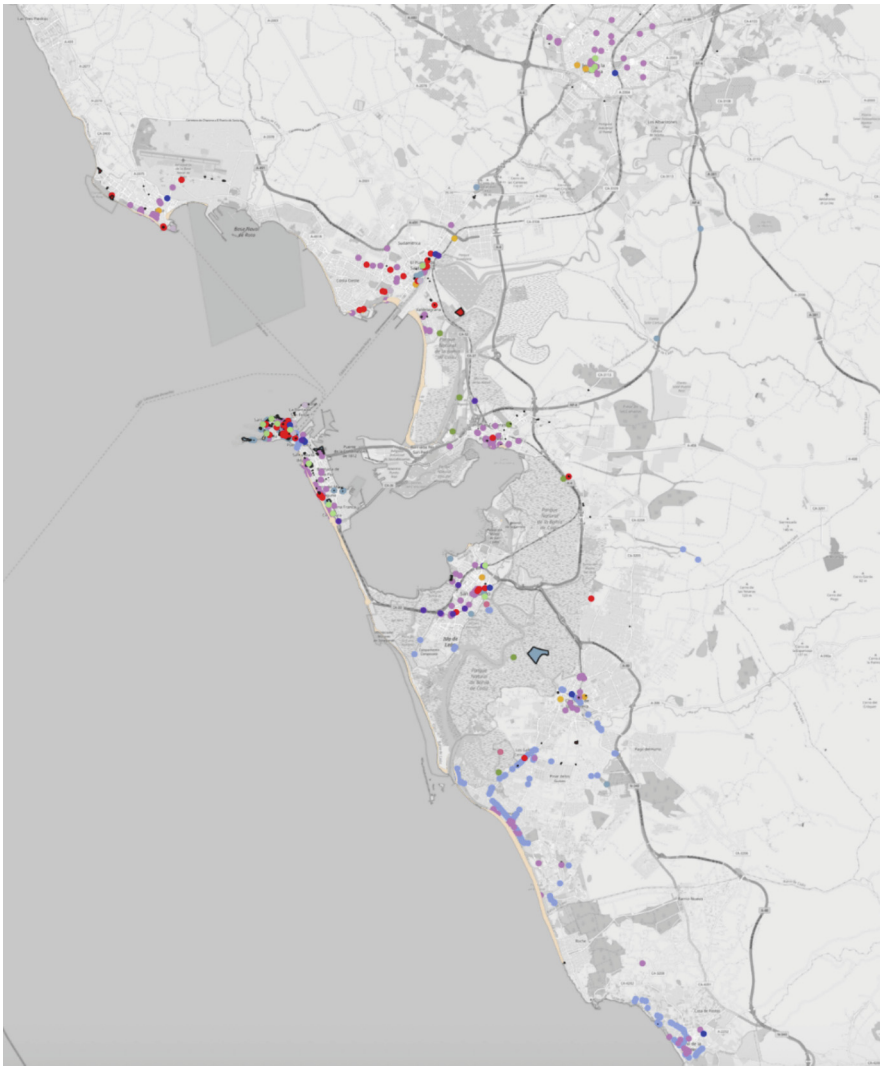

**Fig. 2.** Distribution of Attractors, services and reachability.

The second phase involves the spatial interpretation of these components through a cluster-based approach in order to identifying the Destination Areas of the tourism system in the case study. The territorial system is divided into homogeneous clusters using GeoDA software[29] aimed at identifying distinct spatial patterns. The optimal number of clusters is determined through the application of the Elbow Method[30], ensuring a balance between analytical detail and interpretative clarity (Fig. 3).

To quantify the characteristics of each cluster, three composite indicators are employed (Fig. 3). The Balanced Tourism Supply Index (BTSI) measures the relationship between accommodation capacity and consumption services, distinguishing between overnight-oriented and day-trip-oriented areas. The Attraction Potential Index (API) evaluates the strength of attractors based on their relevance and scale, while the Diversity Reachability Index (DRI) assesses accessibility and intramodality within the transport system.

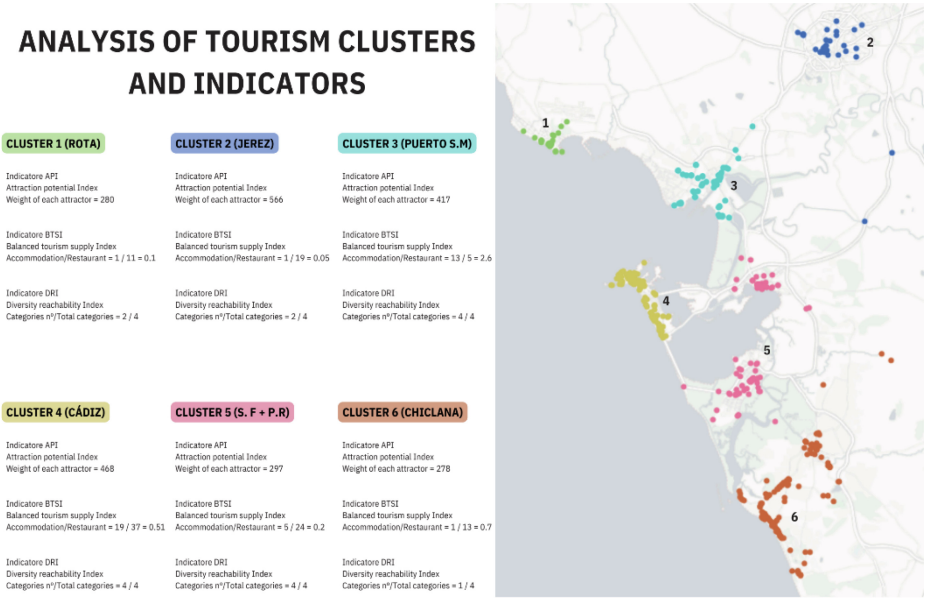


**Fig. 3.** Clusters and indicators of Attractors, services and reachability.

The tourism structure of the Bay of Cádiz reveals a markedly differentiated territorial organization, in which the municipalities do not perform the same role within the regional tourism system. Some areas appear to be primarily oriented toward attraction and daily consumption, while others are more clearly specialized in accommodation and longer stays. In this sense, Jerez de la Frontera emerges as the municipality with the strongest attraction capacity, followed by Cádiz, both characterized by a high concentration of cultural, gastronomic, and urban functions. However, in both cases the accommodation offer appears comparatively limited in relation to their attraction potential, suggesting a tourism model strongly based on short visits and daily inflows, rather than on prolonged stays. A similar, though less intense, condition can be observed in Rota, which also appears to operate mainly as a short-stay or excursion-oriented destination. By contrast, El Puerto de Santa María stands out as the most balanced and structurally mature tourism cluster, combining a strong accommodation base with a diversified offer of activities and services, thus supporting a more autonomous and stable stay experience.

A different role is instead played by San Fernando and Puerto Real, which seem to function as intermediate or service-support areas within the wider bay system, providing complementary urban functions but showing a more limited tourism centrality in terms of both attraction and overnight capacity. Chiclana de la Frontera, on the other hand, appears to be characterized by a more specialized and seasonal tourism profile, largely dependent on coastal and beach-related demand, with a comparatively weaker diversification of tourism functions. Overall, these patterns suggest that the Bay of Cádiz should not be interpreted as a homogeneous tourism destination, but rather as a spatially fragmented and functionally specialized system, where tourists are encouraged to move continuously between municipalities in order to combine accommodation, leisure, cultural consumption, and coastal experiences. In this framework, one of the main critical issues concerns mobility and accessibility, as the current territorial articulation seems to generate a high dependence on road-based travel, with significant implications in terms of congestion, seasonal pressure, and the overall efficiency of the tourism system.

## 4 Discussion and Planning Strategy

The findings of the analysis support the development of a multi-scalar planning strategy aimed at transforming the existing tourism system. The downscaling of NUA [31, 32]compliance assessment supports the definition of spatial strategies aimed at rebalancing tourism flows and enhancing the sustainability of the territorial system. The proposed approach is based on the combination of hard interventions, designed to influence both visitor behavior and spatial organization.

The results suggest that tourism should not be read exclusively in terms of localized concentration or isolated destinations, but rather as a broader territorial organization in which multiple municipalities contribute to the overall performance of the system.

Within this perspective, one of the main planning issues concerns not only the quantity of tourism-related activities, but the degree of integration between the different components of the system. The analysis highlights the importance of improving the relationships between attraction poles, accommodation areas, consumption spaces, and mobility infrastructures in order to support a more coherent territorial functioning.

Mobility therefore emerges as a key planning dimension. Given the fragmented geography of the Bay and the differentiated specialization of municipalities, accessibility and intermodality play a central role in shaping the usability and efficiency of the tourism ecosystem. The territorial structure appears to rely significantly on movement between municipalities, suggesting that the quality of connections may influence not only visitor experience but also the capacity of the system to function as an integrated tourism area.

In this regard, the proposal developed in the original report introduces a mobility-oriented strategy aimed at strengthening intermodal connectivity through the integration of existing railway systems, tram extensions, tram-bus solutions, cycling infrastructure, and enhanced maritime transport. Rather than simply increasing transport supply, this strategy may be interpreted as an attempt to improve the territorial cohesion of the tourism system and to better connect its differentiated components (Fig. 4).

The strategy include two main intervention:

- The Intermodal Ring: It will be organized through the introduction of a Tram-bus in a dedicated lane and the development of bike lanes. The already existing heavy rail infrastructure will be leveraged, complementing it with branch lines from the current Bay Tram. By integrating the tram into this 'Intermodal Ring', we are not only solving traffic jams and the natural barrier of the marshes; we are guaranteeing that the Bay grows without destroying its fragile environment*, and ensuring that the residents who have left can recover their neighborhoods thanks to genuine urban improvement. We want transportation to be the tool that restores our unique identity and protects our natural surroundings, turning the Bay of Cádiz into a benchmark for sustainable mobility for the future.
- New Maritime Infrastructure: Upon analyzing the maritime transport situation in the area, we realized that the current network is quite limited, as we only have the ferry service connecting Cádiz with Rota and El Puerto de Santa María, which leaves out key points of our geography. For this reason, our strategy focuses on expanding these connections through the creation of two new seaports in Puerto Real and San Fernando. This measure will allow us to develop many more routes and increase frequencies so that boats become a real and efficient alternative for moving directly throughout the entire Bay of Cádiz.

In conclusion, the creation of an integrated transport system that provides a circular connection is proposed. This initiative aims to optimize travel, reduce traffic congestion, establish a strong connection between the various natural parks, and encourage the use of public transport, ultimately improving citizens' quality of life and promoting environmental sustainability. The transport system would feature intermodal stations strategically located at key points in each municipality, allowing for quick and efficient transfers between different modes of transport. It is proposed to leverage the existing railway infrastructure, complementing it with the extension of the Bay Tram. Additionally, dedicated paths for bicycles and pedestrians could be developed, promoting healthier and more accessible mobility.

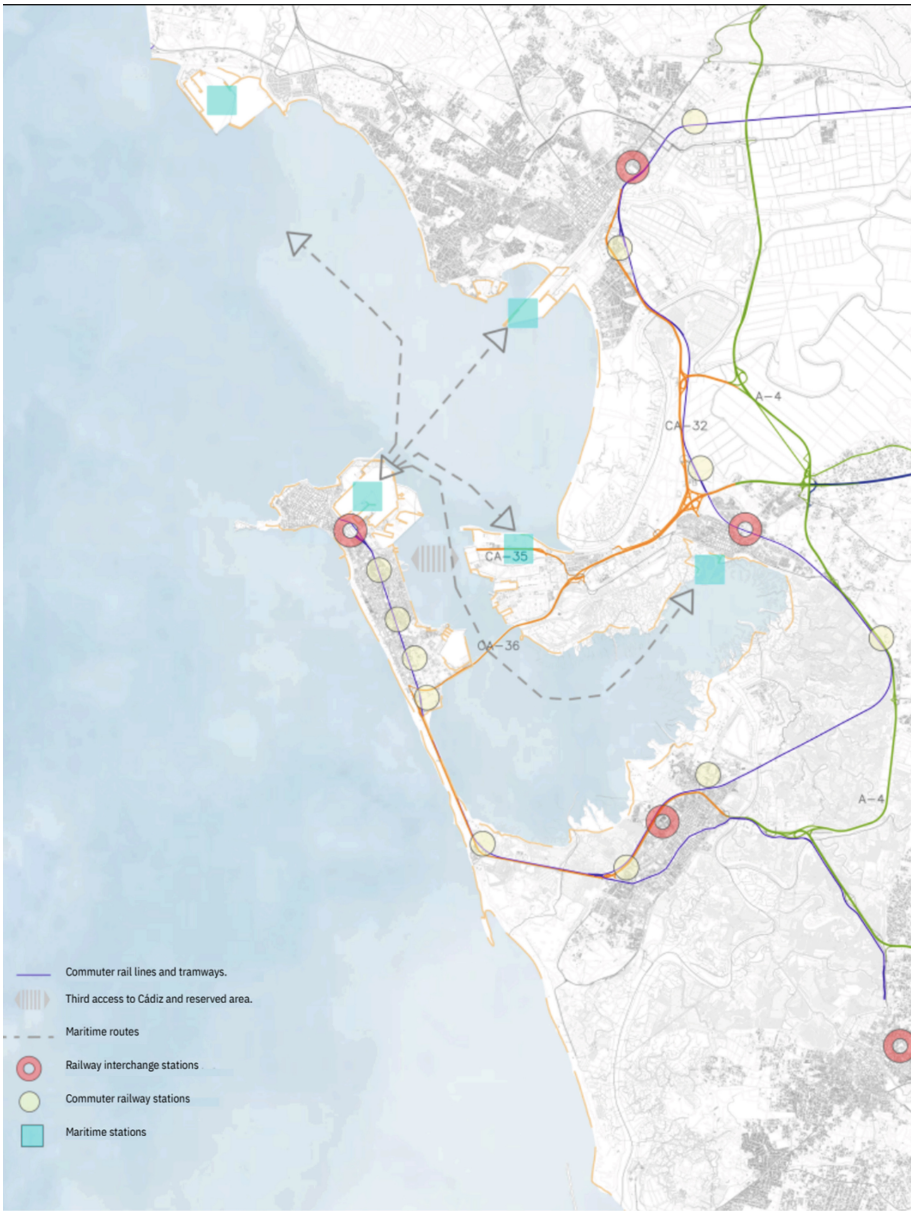


**Fig. 4.** Map of the interventions.

## 5 Conclusions

This study has proposed a spatial interpretation of the Bay of Cádiz tourism ecosystem through the application of the STESY framework. The analysis has shown that tourism in the area may be more effectively understood as a territorially structured system rather than as a set of isolated destinations or localized concentrations of visitors.

The results suggest that the Bay of Cádiz is characterized by a differentiated and functionally articulated tourism organization, in which municipalities contribute through distinct but complementary roles. Cultural, gastronomic, coastal, logistical, and accommodation-related functions are distributed across the territory, contributing to a tourism system that appears both spatially extensive and internally specialized.

This allows tourism to be interpreted as a relevant component of territorial structure and not only as a temporary or external dynamic.

The whole application is structured on the STESY framework [28, 33, 34]: a robust spatial analytical framework driving from the early stages the strategic design in sustainable tourism for a specific destination area. The framework had been applied in a number of local studies selected among major destinations (i.e. EU Capitals, UNESCO Sites, Environmental global attractors etc.) [35, 36], minor inland tourism areas (i.e. Vulture, Pollino national Park) [37, 38] and niche tourism sites (i.e. Islands) [39–41].

In this paper the main limitation comes from the lack of discussion with local stakeholders. In facts the research was fully development on desk and remotely. It is also relevant to point out how the STESY method effectively supported the process providing a guide to students to start with effective local analysis, to perform meaningful spatial interpretation of a complex phenomenon, to identify design options/solution for a strategic proposal compliant with NUA international principles [42–49].

The indicator dashboard included in the STESY platform allows to compare this application with other case study in a significant and effective way, supporting the decision making process in identifying intervention priority to better plan tourism sector locally benefitting of multi scale assessment options and accountability management of global objective for sustainable and climate responsive design [50–52].

## References

1. Williams, A.M., Shaw, G.: Internationalization and innovation in tourism. Ann. Tour. Res. **38**, 27–51 (2011). https://doi.org/10.1016/j.annals.2010.09.006
2. Lenzen, M., Sun, Y.-Y., Faturay, F., Ting, Y.-P., Geschke, A., Malik, A.: The carbon footprint of global tourism. Nat. Clim. Chang. **8**, 522–528 (2018). https://doi.org/10.1038/s41558-018-0141-x
3. Stojčić, N., Mikulić, J., Vizek, M.: High season, low growth: the impact of tourism seasonality and vulnerability to tourism on the emergence of high-growth firms. Tour. Manag. **89**, 104455 (2022). https://doi.org/10.1016/j.tourman.2021.104455
4. UN HABITAT: New Urban Agenda. United Nations (2016)
5. Las Casas, G., Scorza, F., Murgante, B.: New urban agenda and open challenges for urban and regional planning. In: Calabrò, F., Della Spina, L., and Bevilacqua, C. (eds.) New Metropolitan Perspectives. ISHT 2018, pp. 282–288. Springer, Cham (2019). https://doi.org/10.1007/978-3-319-92099-3_33
6. Morphet, J., Morphet, R.: New Urban Agenda: New Urban Analytics: A Report Prepared for the MacArthur Foundation (2019)
7. Tajani, F., Manganelli, B., Cerullo, G., Morano, P., Morente, M.A.: The student housing as a catalyst for virtuous processes of "win-win" revitalization of property assets in disuse. In: Gervasi, O., Murgante, B., Rocha, A.M.A.C., Garau, C., Scorza, F., Karaca, Y., Torre, C.M. (eds.) Computational Science and Its Applications – ICCSA 2023 Workshops, pp. 387–400. Springer Nature Switzerland, Cham (2023)

8. Tajani, F., Cerullo, G., Stara, F., Sica, F.: Multidimensional models for building decarbonization pathways. Bus. Strategy Environ. n/a (2025). https://doi.org/10.1002/bse.70455
9. Lagonigro, D., et al.: Downscaling NUA: matera new urban structure. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
10. Scorza, F., Gatto, R.V.: Identifying territorial values for tourism development: the case study of calabrian greek area. Sustainability 2023, **15**, 5501 (2023). https://doi.org/10.3390/SU15065501
11. Lacerenza, A., et al.: "Back to the villages": design sustainable development scenarios for in-land areas. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
12. Capodiferro, M., et al.: "University equity": students' facilities in major tourism destination towns. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023 (2023)
13. Florio, E., et al.: SuperABLE: matera accessible for all. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
14. Esposito et al.: Innovation ecosystem: the added value in a unique UNESCO city. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
15. Casas, G.L., Scorza, F.: Sustainable planning: a methodological toolkit. In: Gervasi, O., et al. (eds.) ICCSA 2016. LNCS, vol. 9786, pp. 627–635. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-42085-1_53
16. Gatto, R.V., Corrado, S., Scorza, F.: Taxonomy for specialized tourism ecosystems : new geographies for sustainable territorial planning. Habitat Int. (2025)
17. Murgante, B., Borruso, G., Lapucci, A.: Sustainable development: concepts and methods for its application in urban and environmental planning. Studies in Computational Intelligence **348**, 1–15 (2011). https://doi.org/10.1007/978-3-642-19733-8_1/COVER
18. Santopietro, L., Scorza, F.: Voluntary planning and city networks: a systematic bibliometric review addressing current issues for sustainable and climate-responsive planning. Sustainability **16** (2024). https://doi.org/10.3390/su16198655
19. Sica, F., Tajani, F., Cerullo, G.: An evaluation model for an optimal decarbonisation process in the built environment. Built Environment Project and Asset Management **15**, 51–66 (2024). https://doi.org/10.1108/BEPAM-05-2024-0126
20. Tajani, F., Bologna, A., Cerullo, G., Doko, E., Sica, F.: Upcycling strategies for resilience reconstruction goals: a case study of an italian public building. Buildings **15**, (2025). https://doi.org/10.3390/buildings15203683
21. Pilogallo, A., Scorza, F.: Mapping regulation ecosystem services specialization in Italy. J. Urban Plan. Dev. **148** (2022). https://doi.org/10.1061/(ASCE)UP.1943-5444.0000801
22. Scorza, F., Santopietro, L., Giuzio, B., Amato, F., Murgante, B., Casas, G.: Las: Conflicts between environmental protection and energy regeneration of the historic heritage in the case of the city of matera: Tools for assessing and dimensioning of sustainable energy action plans (SEAP). In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), pp. 527–539 (2017). https://doi.org/10.1007/978-3-319-62407-5_37
23. Santopietro, L., Solimene, S., Lucchese, M., Di Carlo, F., Scorza, F.: An economic appraisal of the SE(C)AP public interventions towards the EU 2050 target: The case study of Basilicata region. Cities. **149** (2024). https://doi.org/10.1016/j.cities.2024.104957
24. Gatto, R.V., Scorza, F.: "Anti-gravity tourism planning": an analytical approach to manage tourism congestion, Seasonality and Overtourism. Urban Science **9** (2025). https://doi.org/10.3390/urbansci9120524
25. Gatto, R., Santopietro, L., Scorza, F.: Roghudi: Developing knowledge of the places in an abandoned inland municipality. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). 13382 LNCS, pp. 48–53 (2022). https://doi.org/10.1007/978-3-031-10592-0_5/COVER

26. Del P. Pablo-Romero, M., Molina, J.A.: Tourism and economic growth: a review of empirical literature. Tour. Manag. Perspect **8**, 28–41 (2013). https://doi.org/10.1016/j.tmp.2013.05.006
27. Gatto, R.V., Scorza, F.: Sustainable tourism ecosystem balancing territorial values: a place-based perspective. In: International Conference on Computational Science and Its Applications, pp. 90–103. Springer Nature Switzerland Cham (2023)
28. Gatto, R.V., Corrado, S., Scorza, F.: A taxonomy of specialized tourism ecosystems (STESY): toward new geographies for sustainable territorial planning. International Journal of E-Planning Research (2025)
29. Anselin, L., Syabri, I., Kho, Y.: GeoDa: an introduction to spatial data analysis. Geogr. Anal. **38**, 5–22 (2006). https://doi.org/10.1111/j.0016-7363.2005.00671.x
30. Humaira, H., Rasyidah, R.: Determining the appropiate cluster number using elbow method for k-means algorithm. Presented at the March 3 (2020). https://doi.org/10.4108/eai.24-1-2018.2292388
31. Lagonigro, D., et al.: Downscaling NUA: Matera New Urban Structure (2023)
32. UNhabitat: The New Urban Agenda (2016). https://doi.org/10.18356/4665f6fb-en
33. Gatto, R.V., Corrado, S., Scorza, F.: Specialized Tourism Ecosystem Workshop Report. University of Basilicata (2026). https://doi.org/10.5281/zenodo.18347608.
34. Annunziata, A., et al.: Climate actions handbook supporting decision making for regional adaptation strategies in Basilicata, Italy. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Lago, M.N.F., Scorza, F., Braga, A. (eds.) 25th International Conference on Computational Science and Its Applications (ICCSA 2025). Springer Nature Switzerland AG, Istanbul, Türkiye (2025)
35. Gatto, R.V., Dale, M.M., Noennig, J.R.: Exploration of a disaster risk management method for tourism destinations: the case of Guatemala. In: Procedia Computer Science, pp. 2047–2056. Elsevier B.V. (2025). https://doi.org/10.1016/j.procs.2025.09.325
36. Tullipani, E.M.P., Gatto, R.V., Scorza, F.: "Croatia 365": a STESY based strategy for tourism destagionalization. In: Lecture Notes in Computer Science, pp. 212–222. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97651-3_15
37. Cascione, F., Musano, A., Pizzolla, P., Salvia, F., Gatto, R.V., Scorza, F.: "NATURE as the way mobility and well-being": STESY based sustainable tourism development strategy in Belgium. In: Lecture Notes in Computer Science, pp. 234–244. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97651-3_17
38. Gatto, R.V., Andrulli, G., Perrone, F., Corrado, S., Cerra, E., Scorza, F.: Enhancing vulture's territorial assets through tourism ecosystems for spatial development. In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), pp. 285–292. Springer Science and Business Media Deutschland GmbH (2024). https://doi.org/10.1007/978-3-031-65318-6_19
39. Randò, L., Scavone, M., Tarantino, S., Gatto, R.V., Scorza, F.: "A journey between sky and sea": investigating tourism ecosystem in Madeira. In: Lecture Notes in Computer Science, pp. 223–233. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97651-3_16
40. Elhabchi, I., Piliero, A., Gatto, R.V., Scorza, F.: "Sherry triangle", investigating tourism ecosystem in Andalusia (ES). In: Lecture Notes in Computer Science, pp. 16–26. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97589-9_2
41. Pappalardi, V., Nolè, R., Gatto, R.V., Scorza, F.: A dismissed train line as a new pillar for sustainable tourism development in Corsica: "The Maquis Way" Strategy. In: Lecture Notes in Computer Science, pp. 40–49. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97589-9_4

42. Gatto, R.V.: Planning for sustainable tourism in protected areas. a policy-oriented spatial evaluation framework . . TeMA - Journal of Land Use, Mobility and Environment **19**, 171–188 (2026)
43. Scorza, F., Fortunato, G., Carbone, R., Murgante, B., Pontrandolfi, P.: Increasing urban walkability through citizens' participation processes. Sustainability (Switzerland) **13** (2021). https://doi.org/10.3390/su13115835
44. Manganelli, B., Murgante, B., Saganeiti, L.: The social cost of urban sprinkling. Sustainability (Switzerland) **12** (2020). https://doi.org/10.3390/su12062236
45. Molaei Qelichi, M., Murgante, B., Yousefi Feshki, M., Zarghamfard, M.: Urbanization patterns in Iran visualized through spatial auto-correlation analysis. Spat. Inf. Res. **25**, 627–633 (2017). https://doi.org/10.1007/s41324-017-0128-0
46. Hendawy, E., et al.: The prediction and assessment of the impacts of soil sealing on agricultural land in the North Nile Delta (Egypt) using satellite data and GIS modeling. Sustainability (Switzerland) **11** (2019). https://doi.org/10.3390/su11174662
47. Murgante, B., Borruso, G.: Cities and smartness: a critical analysis of opportunities and risks. In: Murgante, B., et al. (eds.) Computational Science and Its Applications – ICCSA 2013, pp. 630–642. Springer, Berlin Heidelberg, Berlin, Heidelberg (2013)
48. Murgante, B., Tilio, L., Lanza, V., Scorza, F.: Using participative GIS and e-tools for involving citizens of Marmo Platano-Melandro area in European programming activities. J. Balkan Near East Stud. **13**, 97–115 (2011). https://doi.org/10.1080/19448953.2011.550809
49. Murgante, B., Borruso, G., Balletto, G., Castiglia, P., Dettori, M.: Why Italy first? Health, geographical and planning aspects of the COVID-19 outbreak. Sustainability (Switzerland) **12** (2020). https://doi.org/10.3390/su12125064
50. Scorza, F., et al.: Training for territorial sustainable development design in basilicata remote areas: GEODESIGN workshop. lecture notes in computer science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). 13379 LNCS, pp. 242–252 (2022). https://doi.org/10.1007/978-3-031-10545-6_17/COVER
51. Rizzi, F., et al.: Development of impact model in climate adaptation strategy design: the case study of Basilicata Region, Italy. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Lago, M.N.F., Scorza, F., Braga, A. (eds.) 25th International Conference on Computational Science and Its Applications (ICCSA 2025). Springer Nature Switzerland AG, Istanbul, Türkiye (2025)
52. Iula, G., et al.: Paving the way to Basilicata climate adaptation strategy: a geodesign workshop. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Lago, M.N.F., Scorza, F., Braga, A. (eds.) 25th International Conference on Computational Science and Its Applications (ICCSA 2025). Springer Nature Switzerland AG, Istanbul, Türkiye (2025)

# From Metropolitan Shadow to Territorial Autonomy: A Spatial and Strategic Assessment of the Tourism Ecosystem in North-Holland

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**Abstract.** In North Holland, the main tourism spot is represented by Amsterdam, one of Europe's major tourism destinations. Around it, within the province, surrounding areas show a strong tourism dependence on the metropolitan core. However, the pheripheral areas of the province is also characterized by an emerging tourism specialization increasingly linked to the identity of local places, including windmills, farmsteads, canal landscapes, agricultural fields, ports, and tulip landscapes.

This study investigates the tourism ecosystem of North Holland through the STESY framework, a spatially oriented interpretative framework aimed at identifying territorial imbalances and supporting more sustainable tourism development strategies. The methodology combines the identification of tourism destination areas with the application of indicators, including the Balanced Tourism Supply Index (BTSI), the Diversity Reachability Index (DRI), and the Attraction Potential Index (API), in order to support the assessment of the territorial tourism structure.

The results reveal both weaknesses and potentialities within the tourism system. At the same time, the analysis highlights how targeted interventions can strengthen local identity and support the transition from peripheral day-trip destinations linked to Amsterdam toward more autonomous and alternative forms of stay. Based on these findings, the paper proposes an integrated strategy structured around hard and soft measures. The proposed framework contributes to the development of planning-oriented approaches for strengthening territorial sustainability in metropolitan regions affected by overtourism and uneven tourism distribution.

**Keyword:** Sustainable tourism planning; · spatial analysis; · cluster analysis

## 1 Introduction

Sustainable tourism becomes more and more a core argument in territorial development debate defining local multi-stakeholders' perspectives and global framework for innovation and better management of such complex phenomena [1, 2]. Today tourism is recognized as a dominant driver of economic growth in coastal and heritage destinations, yet its rapid expansion has also generated critical spatial and temporal imbalances

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[3]. In the perspective of the authors, tourism opens to relevant debate in urban and regional planning research as the decision making process connected with tourism management represent a comprehensive framework in which sustainable urban regeneration and transformation, landscape protection actions, economic development issues interacts generating an effective environment to apply sustainable urban development principles, methods and agendas for short term and strategic territorial design [4–8]. Those applications are also oriented to improve the competences of students in academic curricula dealing with territorial design professionals, and this paper comes as a result of a studio in architectural classes following the research tradition [9–14] of sustainable urban planning and design at UNIBAS [15–18].

Tourism as a spatial phenomenon is a multidisciplinary domain where spatial dimension represents a robust analytical dimension for managing information and designs, applying collaborative approach for strategic planning [19–25].

This perspective is particularly relevant in metropolitan regions where the presence of a dominant urban pole tends to organize the broader territory through asymmetrical relationships of attraction and dependency [26].

In such contexts, tourism is rarely distributed in a balanced way [24]. It often concentrates in highly visible and accessible nodes, while nearby landscapes, settlements, and infrastructures remain functionally secondary despite possessing significant cultural, environmental, or experiential value. The resulting imbalance is not simply quantitative; it affects the way territories are perceived, used, and strategically positioned within wider destination systems.

North-Holland provides a paradigmatic case of this condition. The province contains one of the most globally recognized urban destinations in Europe, Amsterdam, while simultaneously encompassing a much broader territorial structure made up of coastal landscapes, dune systems, historic villages, agricultural polder morphologies, infrastructural corridors, and northern port environments. Yet the image, functionality, and tourism logic of the region remain strongly centered on the metropolitan core. As a consequence, Amsterdam acts both as an attractor and as a territorial shadow: it concentrates demand, services, and symbolic capital, while the rest of the province often remains relegated to a supporting role, functioning largely as a space for short excursions or peripheral leisure consumption [27].

This condition produces a double distortion. On the one hand, the concentration of tourism demand in and around the metropolitan core reinforces congestion, short-duration visitation, infrastructural stress, and a progressive loss of territorial balance. On the other hand, the wider province remains structurally under-activated, not because it lacks resources, but because its assets are fragmented, weakly integrated, and insufficiently recognized as part of a coherent tourism system. In this sense, the challenge is not simply to divert visitors away from saturated areas, but to reinterpret the territorial structure of tourism itself.

This paper aims to develop a spatially informed planning framework capable of supporting the transition from a short-duration, high-pressure tourism model toward a more balanced system based on extended stays and territorial redistribution. The study proposes an integrated methodological approach combining spatial analysis, cluster-based interpretation, and policy-oriented design strategies in compliance with NUA

principles. The contribution lies in bridging analytical diagnosis and operational planning within a coherent framework transferable to similar tourism destinations.

Within this framework, the present paper proposes a spatial and strategic reading of North-Holland as a potentially autonomous and polycentric tourism ecosystem. Rather than treating the province as a residual geography surrounding Amsterdam, the study investigates its internal territorial logic through an integrated diagnosis of attractions, services, accessibility, and performance. The objective is to identify where tourism potential is currently concentrated, where it remains latent, and how different territorial configurations can support differentiated development trajectories. In doing so, the paper contributes to the field of sustainable tourism planning by linking spatial diagnosis with strategic design and by demonstrating how territorial interpretation can inform more balanced and place-sensitive tourism policies.

## 2 Study Area

The study area identified in this research is the Province of North-Holland, a territory that can be considered one of the economic and symbolic cores of the Netherlands, yet currently marked by a profound internal dichotomy between the metropolitan area of Amsterdam and its wider peripheral landscapes. This territorial condition makes North-Holland particularly relevant for investigating the spatial imbalances of contemporary tourism systems nearby EU capital cities.

From a morphological point of view, the study area extends from the northern urban edge of the capital to the northern tip of Den Helder and can be interpreted through the coexistence of two major territorial systems.

The first is the western coastal system, composed of dunes, beaches, and leisure-oriented settlements, which functions as a major outlet for recreational demand but is also strongly exposed to seasonal pressure.

The second is the inland historical-productive system of the polders, where the landscape has been radically shaped by an ordered matrix of canals, reclaimed land, and agricultural plots. This inland structure reflects a highly constructed territorial identity, where the preservation of productive landscapes and the valorization of small historic settlements represent key spatial values.

Considering the overall of tourism precence within the different regional contexts, Greater Amsterdam clearly emerges as the dominant tourism pole, concentrating by far the largest share of tourist presence within the provincial system (Fig. 1). This confirms its structural role as the main attractor and the primary gateway of tourism demand in North-Holland. Outside the metropolitan core, the territorial distribution of tourism presence becomes significantly weaker and more fragmented. Among them, Kop van Noord-Holland, Alkmaar and its surroundings, Agglomeration of Haarlem and the Agglomeration of Leiden and Bollenstreek stand out as the most relevant secondary contexts, while, IJmond, Zaanstreek, show comparatively lower levels of tourism presence.

Concerning tourism intensity, Greater Amsterdam remains the most exposed area, confirming not only its quantitative dominance but also the strong territorial burden generated by tourism in relation to local inhabitants (Fig. 2).

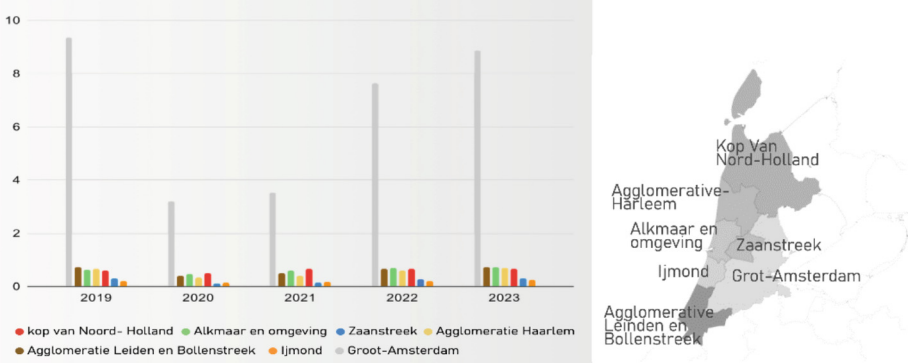


**Fig. 1.** Annual visitor volumes across the main regional contexts of North-Holland (in millions). Source: personal elaboration of EU data - https://tourism-dashboard.ec.europa.eu/

At the same time, the northern part of the province, particularly Kop van Noord-Holland, also records high relative values, indicating that tourism pressure can become highly significant even in areas that are less central in absolute terms.

By contrast, Zaanstreek, IJmond, remain comparatively more balanced, showing lower levels both in terms of tourism presence and relative pressure.

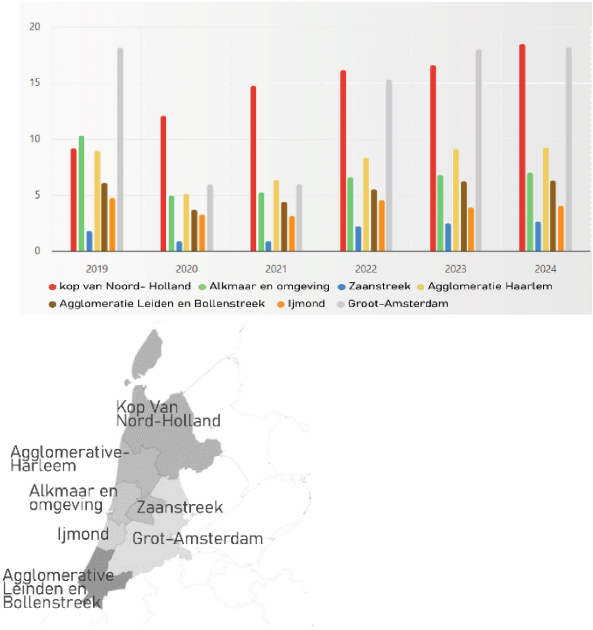


**Fig. 2.** Tourism intensity across North-Holland regions (2019–2024), expressed as the ratio between total overnight stays and resident population. Source: personal elaboration of EU data - https://tourism-dashboard.ec.europa.eu/

The temporal distribution of tourism demand in North-Holland reveals a markedly seasonal structure, characterized by a strong concentration of flows within a limited period of the year (Fig. 3). The monthly pattern shows a progressive increase in tourism activity from early spring, reaching a pronounced peak during the summer months, particularly in July and August, before declining rapidly in the autumn period.

A secondary rise can be observed in the spring period, corresponding to the flower season of tulips. The most critical transition occurs in the autumn months, when tourism demand drops sharply, falling below the average level and marking the end of the main tourism cycle.

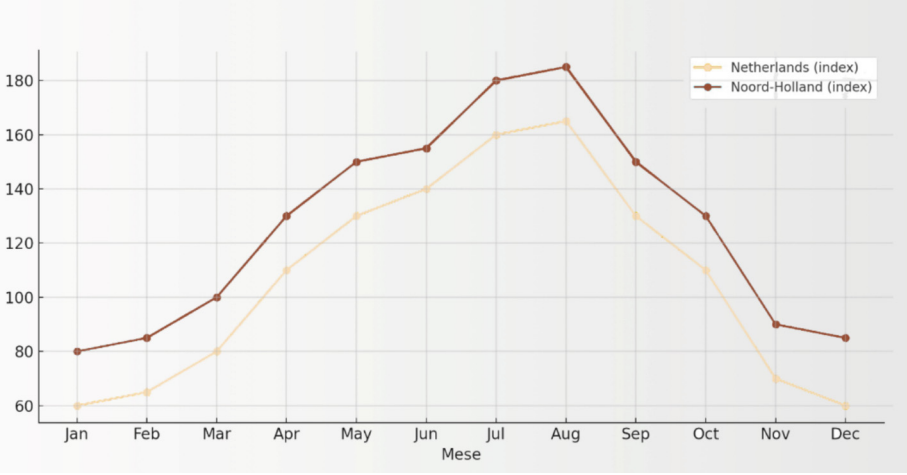


**Fig. 3.** Monthly tourism concentration in North-Holland compared with the national average. Source: personal elaboration of EU data - https://tourism-dashboard.ec.europa.eu/

## 3 Territorial Analysis

The approach adopted in this study is based on the STESY framework [28] conceived as an integrated analytical and interpretative tool for the identification of territorial imbalances and the support of evidence-based planning strategies.

The first phase consists of a contextual analysis of the study area, focusing on the identification and classification of key georeferenced components (PoIs) of the tourism system, including attractors, services, and reachability. The attractors are windmills, tulip fields, and agri-food and craft-related sites, which collectively define a landscape-based tourism specialized value chain rooted in local rural heritage and symbolic imagery. Iconic nodes such as Zaanse Schans further reinforce this configuration by concentrating multiple expressions of rural identity within a single destination.

This specialization is supported by a highly reachability and diffuse territorial structure, where cycling infrastructure plays a central role in enabling slow and immersive forms of landscape exploration. At the same time, a widespread precence of services, including accommodation, restaurants, and information points, ensures the functionality of the system (Fig. 4).

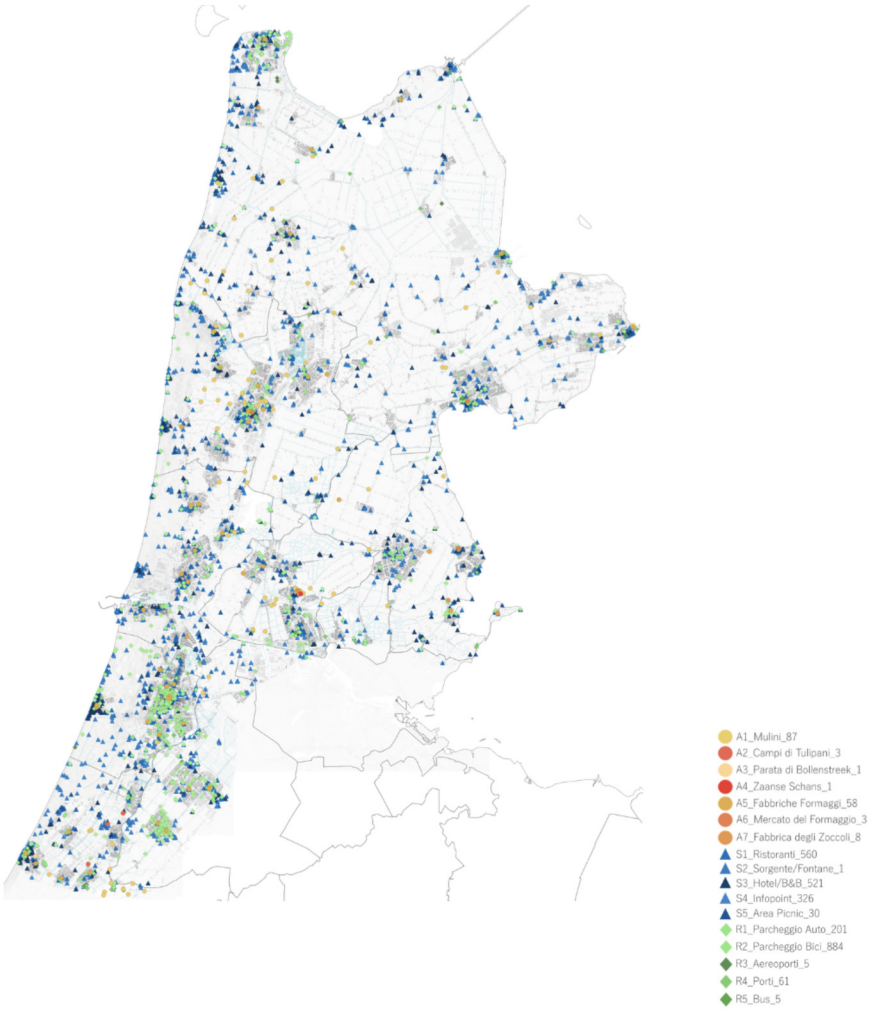


**Fig. 4.** Distribution of Attractors, services and reachability.

The second phase involves the spatial interpretation of these components through a cluster-based approach in order to identifying the Destination Areas of the tourism system in the case study. The territorial system is divided into homogeneous clusters using GeoDA software [29] aimed at identifying distinct spatial patterns. The optimal number of clusters is determined through the application of the Elbow Method [30], ensuring a balance between analytical detail and interpretative clarity (Fig. 5).

The spatial interpretation of these dynamics leads to the identification of four destination areas corresponds to the clusters.

This cluster 1 is considered as consolidated destination area, where the concentration of attractors is the highest within the entire tourism system.

It is characterized by a dense territorial structure supported by a solid base of accommodation and food-related services.

The cluster 2 represents the historical-cultural destination area of the system, characterized by the highest density of services and a well-developed, capillary reachability network. It concentrates the major landmark attractions, including *Zaanse Schans* and the historic windmills, thus configuring a highly attractive area. However, this centrality is also associated with significant phenomena of spatial congestion.

The cluster 3 corresponds to a fringe destination area where the natural landscape of dunes and polders predominates. Its specialization is associated with a slower and more landscape-oriented form of hospitality, in which the protection of environmental and scenic value constitutes the primary planning constraint.

The cluster 4 exhibits the greatest unexpressed destination area potential within the system. Despite the presence of high-quality services and primary transport infrastructure, the area shows a marked identity deficit due to the limited presence of attractors. It can therefore be interpreted as a serving territorial fabric that is functionally efficient but lacking in symbolic and tourism-generating centralities.

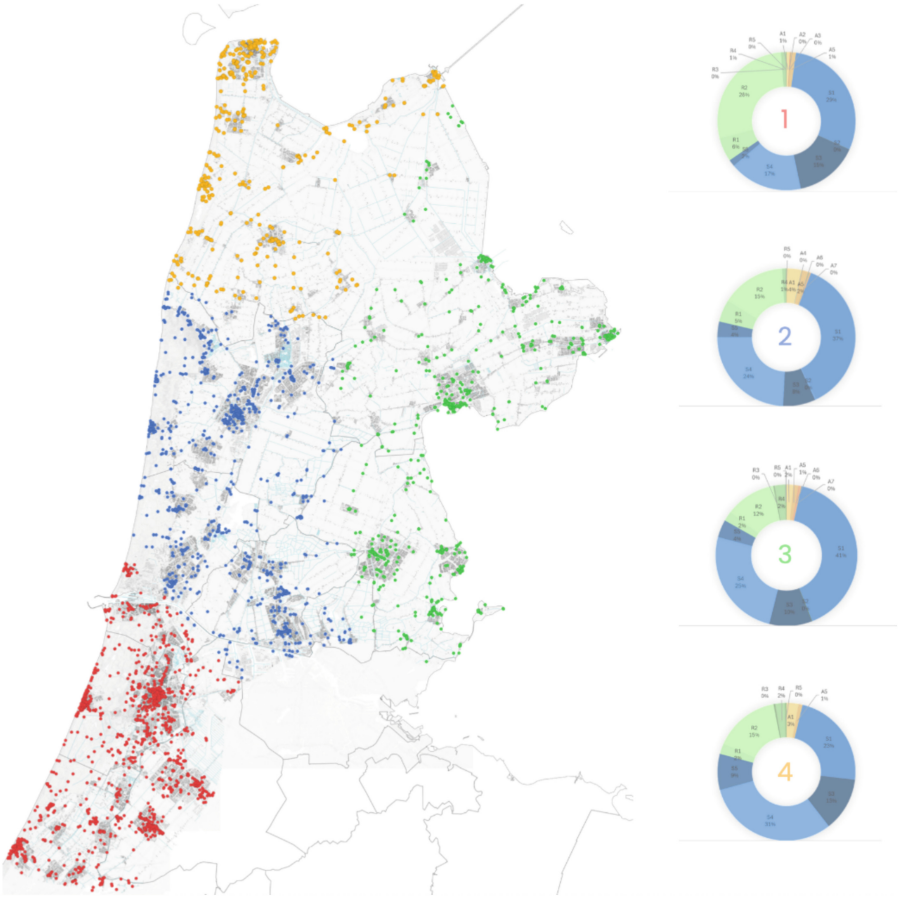


**Fig. 5.** Clusters identified of Attractors, services and reachability.

To quantify the characteristics of each cluster, three composite indicators are employed (Fig. 6). The Balanced Tourism Supply Index (BTSI) measures the relationship between accommodation capacity and consumption services, distinguishing between overnight-oriented and day-trip-oriented areas. The Attraction Potential Index (API) evaluates the strength of attractors based on their relevance and scale, while the Diversity Reachability Index (DRI) assesses accessibility and intramodality within the transport system.

The BTSI reveals a highly mature system in the most central areas and weaker configurations elsewhere. The DRI confirms the overall efficiency of the transport infrastructure, indicating that reachability is not a limiting factor in the system. The API, on the other hand, emphasizes the uneven distribution of attraction potential, with strong concentrations in specific nodes and a significant deficit in peripheral areas.




**Fig. 6.** Indicators applied to each Cluster (Destination Area).

The transition from the assessment of the local context to the analysis of performance indicators was carried out through a high-resolution intra-provincial benchmarking, namely a comparative evaluation of the performances observed across the four clusters. This process made it possible to identify the main territorial criticalities and to interpret the internal structure of the tourism system in a more articulated way.

The four clusters reveal different territorial roles within the provincial tourism system. Cluster 1 emerges as a consolidated destination area with the highest concentration of attractors and a strong support base of tourism services. Cluster 2 represents the historical-cultural destination area, where reachability, service density, and landmark attractions converge, but where the most evident congestion effects also occur. Cluster 3 reflects a more landscape-oriented and environmentally sensitive fringe, characterized

by slower forms of tourism linked to dunes and polders. Cluster 4, despite its infrastructural and service endowment, shows the greatest latent potential, remaining functionally relevant but weak in terms of tourism identity and symbolic centrality.

Overall, the benchmarking highlights that the main structural weakness of the system lies in the fragmentation of the tourism offer, which configures the territory as a constellation of disconnected "islands of attractiveness" rather than as an integrated tourism ecosystem. This condition is further reinforced by a marked polarization of carrying capacity, with evident saturation and territorial concentrated in the most accessible nodes and in the areas closest to Amsterdam.

## 4 Discussion and Planning Strategy

The findings of the analysis support the development of a multi-scalar planning strategy aimed at transforming the existing tourism system. The downscaling of NUA [31, 32] compliance assessment supports the definition of spatial strategies aimed at enhancing the sustainability of the territorial system. The proposed approach is based on the combination of soft measures and hard interventions, designed to influence both visitor behavior and spatial organization.

The proposed strategy identifies three strategic nodes to be transformed into Identity Districts, with the aim of increasing accommodation capacity without additional land consumption, operating through the adaptive reuse of existing built heritage.

Within Cluster 2 (Koedijk), the intervention addresses the mismatch between high landscape value and limited accommodation supply. The proposed "Green-Canal District" is based on the conversion of agricultural warehouses and granaries into water-oriented lofts, following a diffuse hospitality model. This approach preserves the local morphological and cultural identity while integrating services aligned with international tourism demand.

In Cluster 3 (Purmerend), the "Post-Modern Design District" reinterprets the satellite city through a retro-future narrative. The regeneration of 1970s–1980s terraced housing maintains the original architectural identity while enabling a form of immersive hospitality, allowing visitors to experience everyday Dutch life as a cultural asset.

Cluster 4 (Den Helder) represents the northern area most affected by the lack of contemporary attractors. Here, the "Port District" focuses on the regeneration of the former Royal Navy shipyard of Willemsoord. Existing port warehouses are repurposed into spaces for sports, craft breweries, and digital-oriented lofts, while reused shipping containers are introduced as flexible social and resting areas, reinforcing the maritime identity of the site.

To address pronounced seasonality, a travelling music festival is proposed as a territorial activation device. The event unfolds over four days, connecting multiple nodes across the province and encouraging visitors to extend their stay beyond the metropolitan core. By transforming landmarks and public spaces into temporary stages, the initiative activates a distributed network of places, including the Lange Jaap Lighthouse in Den Helder, the historical market square in Purmerend, the castle of Schagen, and the windmill landscapes of Koedijk. This strategy enhances spatial continuity and promotes a more balanced distribution of tourist flows (Fig. 7).




**Fig. 7.** Hard and Soft measures of strategic proposal.

The proposed vision can be interpreted as a territorial governance model aligned with the principles of the New Urban Agenda, translating international guidelines into spatially explicit and context-sensitive interventions. In particular, the regeneration strategies implemented in Koedijk and Purmerend demonstrate how cultural heritage preservation can act as a driver for zero land consumption urban regeneration, fostering an economic cycle based on the valorisation of local resources rather than their extraction.

At the same time, the creation of inclusive public and hospitality spaces, grounded in everyday Dutch life, contributes to ensuring that tourism development remains equitable and accessible. Within this framework, North Holland shifts from being a peripheral extension of Amsterdam to a system of interconnected districts, where residents' quality of life and visitors' experience converge within a shared trajectory of sustainable urban development.

## 5 Conclusions

This study has demonstrated how a spatially explicit and system-oriented approach can support the interpretation and reconfiguration of tourism dynamics in territories characterized by strong landscape identity and proximity to dominant metropolitan destinations. Through the application of the STESY framework, the analysis has highlighted how North Holland is structured as a functionally interconnected yet spatially unbalanced tourism system, where highly attractive nodes coexist with underutilized areas exhibiting significant latent potential.

The results reveal that the main structural weakness lies in the fragmentation of the tourism offer and in the polarization of carrying capacity, with congestion concentrated in the most accessible and symbolically dominant areas, particularly those gravitating around Amsterdam. At the same time, the analysis has shown that the territory possesses a rich and diversified asset base, rooted in rural landscapes, cultural heritage, and

local production systems, that remains only partially activated within current tourism dynamics [33].

The whole application is structured on the STESY framework [28, 34, 35]: a robust spatial analytical framework driving from the early stages the strategic design in sustainable tourism for a specific destination area. The framework had been applied in a number of local studies selected among major destinations (i.e. EU Capitals, UNESCO Sites, Environmental global attractors etc.) [36, 37], minor inland tourism areas (i.e. Vulture, Pollino national Park) [38, 39] and niche tourism sites (i.e. Islands) [40–42].

In this paper the main limitation comes from the lack of discussion with local stakeholders. In facts the research was fully development on desk and remotely. It is also relevant to point out how the STESY method effectively supported the process providing a guide to students to start with effective local analysis, to perform meaningful spatial interpretation of a complex phenomenon, to identify design options/solution for a strategic proposal compliant with NUA international principles [43–49].

The indicator dashboard included in the STESY platform allows to compare this application with other case study in a significant and effective way, supporting the decision making process in identifying intervention priority to better plan tourism sector locally benefitting of multi scale assessment options and accountability management of global objective for sustainable and climate responsive design [50–52].

## References

1. Williams, A.M., Shaw, G.: Internationalization and innovation in tourism. Ann. Tour. Res. **38**, 27–51 (2011). https://doi.org/10.1016/j.annals.2010.09.006
2. Lenzen, M., Sun, Y.-Y., Faturay, F., Ting, Y.-P., Geschke, A., Malik, A.: The carbon footprint of global tourism. Nat. Clim. Chang. **8**, 522–528 (2018). https://doi.org/10.1038/s41558-018-0141-x
3. Stojčić, N., Mikulić, J., Vizek, M.: High season, low growth: the impact of tourism seasonality and vulnerability to tourism on the emergence of high-growth firms. Tour. Manag. **89**, 104455 (2022). https://doi.org/10.1016/j.tourman.2021.104455
4. UN HABITAT: New Urban Agenda. United Nations (2016)
5. Las Casas, G., Scorza, F., Murgante, B.: New Urban Agenda and open challenges for urban and regional planning. In: Calabrò, F., Della Spina, L., Bevilacqua, C. (eds.) New Metropolitan Perspectives. ISHT 2018, pp. 282–288. Springer, Cham (2019). https://doi.org/10.1007/978-3-319-92099-3_33
6. Morphet, J., Morphet, R.: New Urban Agenda: New Urban Analytics: A Report Prepared for the MacArthur Foundation (2019)
7. Tajani, F., Manganelli, B., Cerullo, G., Morano, P., Morente, M.A.: The student housing as a catalyst for virtuous processes of "win-win" revitalization of property assets in disuse. In: Gervasi, O., Murgante, B., Rocha, A.M.A.C., Garau, C., Scorza, F., Karaca, Y., Torre, C.M. (eds.) Computational Science and Its Applications – ICCSA 2023 Workshops, pp. 387–400. Springer Nature Switzerland, Cham (2023)
8. Tajani, F., Cerullo, G., Stara, F., Sica, F.: Multidimensional models for building decarbonization pathways. Bus. Strategy Environ. n/a (2025). https://doi.org/10.1002/bse.70455
9. Lagonigro, D., et al.: Downscaling NUA: matera new urban structure. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)

10. Scorza, F., Gatto, R.V.: Identifying territorial values for tourism development: the case study of Calabrian Greek Area. Sustainability 2023, **15**, 5501 (2023). https://doi.org/10.3390/SU15065501
11. Lacerenza, A., et al.: "Back to the villages": design sustainable development scenarios for in-land areas. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
12. Capodiferro, M., et al.: "University equity": students' facilities in major tourism destination towns. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023 (2023)
13. Florio, E., et al.: SuperABLE: matera accessible for all. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
14. Esposito Loscavo, B., et al.: Innovation ecosystem: the added value in a unique UNESCO city. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
15. Casas, G.L., Scorza, F.: Sustainable planning: a methodological toolkit. In: Gervasi, O., et al. (eds.) ICCSA 2016. LNCS, vol. 9786, pp. 627–635. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-42085-1_53
16. Gatto, R.V., Corrado, S., Scorza, F.: Taxonomy for specialized Tourism Ecosystems : new geographies for sustainable territorial planning. Habitat Int. (2025)
17. Murgante, B., Borruso, G., Lapucci, A.: Sustainable development: concepts and methods for its application in urban and environmental planning. Studies in Computational Intelligence **348**, 1–15 (2011). https://doi.org/10.1007/978-3-642-19733-8_1/COVER
18. Santopietro, L., Scorza, F.: Voluntary planning and city networks: a systematic bibliometric review addressing current issues for sustainable and climate-responsive planning. Sustainability **16** (2024). https://doi.org/10.3390/su16198655
19. Sica, F., Tajani, F., Cerullo, G.: An evaluation model for an optimal decarbonisation process in the built environment. Built Environment Project and Asset Manage. **15**, 51–66 (2024). https://doi.org/10.1108/BEPAM-05-2024-0126
20. Tajani, F., Bologna, A., Cerullo, G., Doko, E., Sica, F.: Upcycling strategies for resilience reconstruction goals: a case study of an italian public building. Buildings **15** (2025). https://doi.org/10.3390/buildings15203683
21. Pilogallo, A., Scorza, F.: Mapping regulation ecosystem services specialization in Italy. J. Urban Plan. Dev. **148** (2022). https://doi.org/10.1061/(ASCE)UP.1943-5444.0000801
22. Scorza, F., Santopietro, L., Giuzio, B., Amato, F., Murgante, B., Casas, G.: Las: conflicts between environmental protection and energy regeneration of the historic heritage in the case of the city of matera: Tools for assessing and dimensioning of sustainable energy action plans (SEAP). In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), pp. 527–539 (2017). https://doi.org/10.1007/978-3-319-62407-5_37
23. Santopietro, L., Solimene, S., Lucchese, M., Di Carlo, F., Scorza, F.: An economic appraisal of the SE(C)AP public interventions towards the EU 2050 target: the case study of Basilicata region. Cities. **149** (2024). https://doi.org/10.1016/j.cities.2024.104957
24. Gatto, R.V., Scorza, F.: "Anti-gravity tourism planning": an analytical approach to manage tourism congestion, seasonality and overtourism. Urban Science **9** (2025). https://doi.org/10.3390/urbansci9120524
25. Gatto, R., Santopietro, L., Scorza, F.: Roghudi: developing knowledge of the places in an abandoned inland municipality. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). 13382 LNCS, pp. 48–53 (2022). https://doi.org/10.1007/978-3-031-10592-0_5/COVER
26. Del P. Pablo-Romero, M., Molina, J.A.: Tourism and economic growth: a review of empirical literature. Tour. Manag. Perspect **8**, 28–41 (2013). https://doi.org/10.1016/j.tmp.2013.05.006

27. Gatto, R.V., Scorza, F.: Sustainable tourism ecosystem balancing territorial values: a place-based perspective. In: International Conference on Computational Science and Its Applications, pp. 90–103. Springer Nature Switzerland Cham (2023)
28. Gatto, R.V., Corrado, S., Scorza, F.: A taxonomy of specialized tourism ecosystems (STESY): toward new geographies for sustainable territorial planning. International Journal of E-Planning Research (2025)
29. Anselin, L., Syabri, I., Kho, Y.: GeoDa: an introduction to spatial data analysis. Geogr. Anal. **38**, 5–22 (2006). https://doi.org/10.1111/j.0016-7363.2005.00671.x
30. Humaira, H., Rasyidah, R.: Determining The Appropiate Cluster Number Using Elbow Method for K-Means Algorithm. Presented at the March 3 (2020). https://doi.org/10.4108/eai.24-1-2018.2292388
31. Lagonigro, D., et al.: Downscaling NUA: Matera New Urban Structure (2023)
32. UNhabitat: The New Urban Agenda (2016). https://doi.org/10.18356/4665f6fb-en
33. Gatto, R.V.: Planning for sustainable tourism in protected areas. a policy-oriented spatial evaluation framework . . TeMA - Journal of Land Use, Mobility and Environment **19**, 171–188 (2026)
34. Gatto, R.V., Corrado, S., Scorza, F.: Specialized Tourism Ecosystem Workshop Report. University of Basilicata (2026). https://doi.org/10.5281/zenodo.18347608.
35. Annunziata, A., et al.: Climate actions handbook supporting decision making for regional adaptation strategies in Basilicata, Italy. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Lago, M.N.F., Scorza, F., Braga, A. (eds.) 25th International Conference on Computational Science and Its Applications (ICCSA 2025). Springer Nature Switzerland AG, Istanbul, Türkiye (2025)
36. Gatto, R.V., Dale, M.M., Noennig, J.R.: Exploration of a disaster risk management method for tourism destinations: the case of Guatemala. In: Procedia Computer Science, pp. 2047–2056. Elsevier B.V. (2025). https://doi.org/10.1016/j.procs.2025.09.325
37. Tullipani, E.M.P., Gatto, R.V., Scorza, F.: "Croatia 365": a STESY based strategy for tourism destagionalization. In: Lecture Notes in Computer Science, pp. 212–222. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97651-3_15
38. Cascione, F., Musano, A., Pizzolla, P., Salvia, F., Gatto, R.V., Scorza, F.: "NATURE as the way mobility and well-being": STESY based sustainable tourism development strategy in Belgium. In: Lecture Notes in Computer Science, pp. 234–244. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97651-3_17
39. Gatto, R.V., Andrulli, G., Perrone, F., Corrado, S., Cerra, E., Scorza, F.: Enhancing vulture's territorial assets through tourism ecosystems for spatial development. In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), pp. 285–292. Springer Science and Business Media Deutschland GmbH (2024). https://doi.org/10.1007/978-3-031-65318-6_19
40. Randò, L., Scavone, M., Tarantino, S., Gatto, R.V., Scorza, F.: "A journey between sky and sea": investigating tourism ecosystem in Madeira. In: Lecture Notes in Computer Science, pp. 223–233. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97651-3_16
41. Elhabchi, I., Piliero, A., Gatto, R.V., Scorza, F.: "Sherry triangle", investigating tourism ecosystem in Andalusia (ES). In: Lecture Notes in Computer Science, pp. 16–26. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97589-9_2
42. Pappalardi, V., Nolè, R., Gatto, R.V., Scorza, F.: A dismissed train line as a new pillar for sustainable tourism development in Corsica: "The Maquis Way" Strategy. In: Lecture Notes in Computer Science, pp. 40–49. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97589-9_4

43. Murgante, B., Borruso, G.: Cities and smartness: a critical analysis of opportunities and risks. In: Murgante, B., et al. (eds.) Computational Science and Its Applications – ICCSA 2013, pp. 630–642. Springer, Berlin Heidelberg, Berlin, Heidelberg (2013)
44. Murgante, B., Tilio, L., Lanza, V., Scorza, F.: Using participative GIS and e-tools for involving citizens of Marmo Platano-Melandro area in European programming activities. J. Balkan Near East Stud. **13**, 97–115 (2011). https://doi.org/10.1080/19448953.2011.550809
45. Murgante, B., Borruso, G., Balletto, G., Castiglia, P., Dettori, M.: Why Italy first? Health, geographical and planning aspects of the COVID-19 outbreak. Sustainability (Switzerland) **12** (2020). https://doi.org/10.3390/su12125064
46. Molaei Qelichi, M., Murgante, B., Yousefi Feshki, M., Zarghamfard, M.: Urbanization patterns in Iran visualized through spatial auto-correlation analysis. Spat. Inf. Res. **25**, 627–633 (2017). https://doi.org/10.1007/s41324-017-0128-0
47. Hendawy, E., et al.: The prediction and assessment of the impacts of soil sealing on agricultural land in the North Nile Delta (Egypt) using satellite data and GIS modeling. Sustainability (Switzerland) **11**, (2019). https://doi.org/10.3390/su11174662
48. Manganelli, B., Murgante, B., Saganeiti, L.: The social cost of urban sprinkling. Sustainability (Switzerland) **12** (2020). https://doi.org/10.3390/su12062236
49. Scorza, F., Fortunato, G., Carbone, R., Murgante, B., Pontrandolfi, P.: Increasing urban walkability through citizens' participation processes. Sustainability (Switzerland) **13**, (2021). https://doi.org/10.3390/su13115835
50. Scorza, F., et al.: Training for territorial sustainable development design in basilicata remote areas: GEODESIGN workshop. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). 13379 LNCS, pp. 242–252 (2022). https://doi.org/10.1007/978-3-031-10545-6_17/COVER
51. Rizzi, F., et al.: Development of impact model in climate adaptation strategy design: the case study of Basilicata Region, Italy. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Lago, M.N.F., Scorza, F., Braga, A. (eds.) 25th International Conference on Computational Science and Its Applications (ICCSA 2025). Springer Nature Switzerland AG, Istanbul, Türkiye (2025)
52. Iula, G., et al.: Paving the way to Basilicata climate adaptation strategy: a GeoDesign workshop. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Lago, M.N.F., Scorza, F., Braga, A. (eds.) 25th International Conference on Computational Science and Its Applications (ICCSA 2025). Springer Nature Switzerland AG, Istanbul, Türkiye (2025)

# The Integration of Strategic Environmental Assessment into Urban Planning in the Emilia-Romagna Region

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**Abstract.** The paper examines the evolution and application of Strategic Environmental Assessment (SEA) within the urban and spatial planning framework of the Emilia-Romagna Region, Italy, highlighting its progressive shift from a procedural compliance tool toward a strategic, integrated decision-support system. SEA in Emilia-Romagna has been conceived since the early 2000s as an embedded component of planning, influencing the formulation of objectives, actions, and implementation pathways. The regional planning reform (LR 24/2017) and its strong focus on urban regeneration and land take reduction led to a reconfiguration of the municipal urban plan (Piano Urbanistico Generale, PUG) that became more strategic, thus influencing the proactive role of SEA. Through the description of a case study, the paper illustrates how SEA supports urban planning by structuring diagnosis, coherence assessment, scenario evaluation, guidance for implementation, and monitoring. The analysis shows SEA's capacity to steer decisions toward sustainability, while also revealing tensions between its strategic ambitions and its increasing responsibility in assessing multidimensional (environmental, social, economic) impacts of redevelopment proposals. The paper concludes by discussing opportunities and limitations of SEA's evolving role and the need for further experimentation to consolidate its effectiveness.

**Keywords:** Strategic Environmental Assessment (SEA) · Urban Regeneration · Sustainable Spatial Planning

## 1 Introduction

In the international discourse on sustainability in urban and regional planning, Strategic Environmental Assessment (SEA) is widely acknowledged as a pivotal instrument for ensuring that decision-making processes are systematically aligned with sustainability objectives. Scholars such as Therivel (2010) and Fischer (2007) demonstrate that SEA functions not merely as a technical compliance mechanism, but as a strategic framework capable of embedding environmental, social, and economic considerations from the earliest stages of planning. Within this perspective, SEA operates as a critical interface between long term strategic vision and operational decision-making, ensuring that spatial plans and programmes remain consistent with the foundational principles of sustainable

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development. Actually, SEA can be conceived as a formalized and systematic process that assesses environmental impacts at strategic level, to be undertaken along with the definition of the plan design and before its implementation. This peculiarity makes SEA quite different from another and previous instrument devoted to evaluating the impact of projects on the environment, namely the Environmental Impact Assessment (EIA).

SEA was introduced in the European policy context in 2001 with the 'SEA directive' (2001/42/EC) that aims to ensure that environmental protection becomes an integral and anticipated part of planning processes, ensuring more sustainable, transparent and informed decisions.

The EC directive required EU member states to introduce a Strategic Environmental Assessment (SEA) procedure in their national legislation to be applied to policies, plans and programs (PPP) with potentially significant environmental impacts. In Italy, the transposition took place organically at the national level through Legislative Decree 152/2006. According to the legislation competences of the Italian Regions, that have the power to define proper laws to tailor and implement national regulatory measures, SEA has been adapted to regional contexts through regional laws that have regulated its application and evaluation objective in a diversified way.

This paper aims to describe the application of SEA in Emilia-Romagna, a Region that has been innovating its urban and spatial planning framework by strengthening the strategic nature of the municipal general plan as well as the effectiveness and reliability of its implementation. The role of SEA in supporting this process, from strategies into actions, has become increasingly relevant, overcoming the mere procedural approach that frequently characterized the practical application of SEA.

## 2 The Evolution of SEA: From Procedural Extension to Strategic Process

The notion of Strategic Environmental Assessment (SEA) was set in the late 1980s, when the European Commission introduced the term 'strategic environmental assessment' in an interim report, but it dates back to 1969, when the US National Environmental Policy Act introduced the need to undertake environmental assessments of proposed federal actions (Fundingsland Tetlow and Hanusch, 2012; Noble and Nwanekezie, 2017). However, its popularity increased considerably in the early 2000s, when it was endorsed by two important acts, namely the European SEA Directive (2001/42/EC) and the United Nations Economic Commission for Europe (UNECE) 2003 SEA Protocol (UNECE, 2003) that clarified its nature, scope, methodologies and possible applications (Noble and Nwanekezie, 2017). During this quite long period, SEA has undergone a substantial conceptual transformation, and a more profound reinterpretation of SEA emerged, influenced by planning theory, governance studies and sustainability science.

In Europe, SEA was initially conceived as an extension of project-level Environmental Impact Assessment (EIA) (Brunetta 2002; Chaker et al. 2006) diminishing the innovation potential inherent in the strategic dimension of the SEA. On the contrary, unlike EIA, SEA is not embedded in an authorization procedure, but operates as an internal, self-evaluative process within decision-making. In this sense, SEA accompanies the entire policy cycle rather than producing a single conclusive judgement.

This interpretation is consistent with later international contributions that conceptualize SEA as a family of approaches (Dalal-Clayton and Sadler 2005, p. 12) rather than a standardized technique. Moreover, Noble and Nwanekezie (2017) see SEA as a tool capable of covering a rather wide spectrum of approaches that differ from each other in terms of their strategic levels. They range from impact assessment-based approaches (derived from EIA) to more recent strategy-based approaches, oriented towards policy formulation and institutional transformation. IA-based SEA is the typical approach adopted for addressing directive-based SEA systems and requirements, where appraising compliance with specific policies, regulatory or program objectives is central as well as the assessment of the PPP's potential impacts. On the other hand, strategic-based SEA is an approach that evaluates environmental implications of strategic objectives and development pathways at the earliest stage of decision-making, helping shape policies or strategies toward sustainable outcomes before detailed plans are developed (Fig. 1).

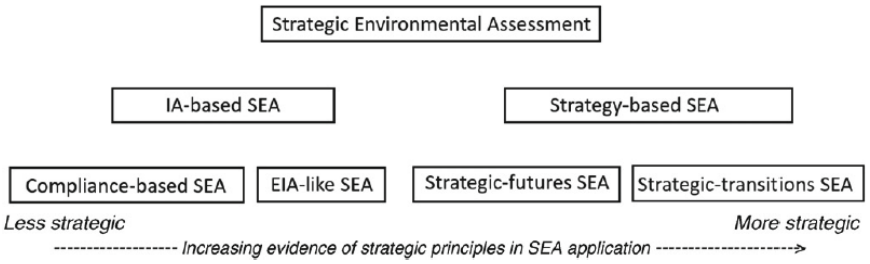


**Fig. 1.** IA-based and strategy-based conceptualization of SEA (source: Noble and Nwanekezie, 2017)

The objectives attributed to SEA have expanded in parallel with its conceptual evolution. Early SEA systems primarily pursued environmental protection goals, seeking to address cumulative effects, large-scale impacts and long-term risks inadequately captured at project level. Effectiveness was therefore initially interpreted in terms of environmental safeguarding and regulatory compliance (Chaker et al. 2006).

Over time, SEA objectives have broadened considerably. Contemporary SEA is increasingly expected to contribute to sustainable development, integrate environmental, social and economic dimensions, enhance transparency and accountability, and facilitate stakeholder participation and inter-institutional coordination (Tetlow and Hanusch, 2012).

In terms of impacts, Rega and Bonifazi (2011) detected that SEA has improved the procedural quality of European planning, but it still struggles to become a real strategic tool. SEA is still frequently conceived as a procedure to meet legislative requirements, rather than a process which adds real value (Fundingsland Tetlow and Hanusch, 2012), therefore the future challenge is not so much regulatory, but operational and cultural in order to make evaluation an integral and anticipated part of decisions, overcoming the logic of administrative compliance and to affirm it as a concrete support for public choices (Rega and Bonifazi, 2011).

This strategic role is further stressed when it comes to new global planning challenges. In addition to its traditional role of integrating sustainability goals, SEA is now

used to incorporate considerations related to new sustainability issues, such as climate change (Isola et al. 2024), urban resilience (Anelli et al. 2025) or biodiversity protection and ecosystem services (Geneletti et al. 2015; Geneletti, 2016). In this sense, SEA is configured as a strategic device capable of linking environmental, social and economic objectives with new global priorities, making urban and territorial planning more resilient, equitable and future-oriented.

## 3 SEA in the Planning Framework of the Emilia-Romagna Region

In Italy SEA was introduced by the Legislative Decree 152/2006 implementing the SEA Directive 2001/42/EC. The directive conceived SEA as an instrument with an endoprocedural nature (Tondelli, 2013) meaning that it should ensure the integration of environmental considerations in the preparation, adoption and approval of plans and programmes, in order to make a more informed and explicit selection of policies and actions in the plan that pursuit sustainability. Later, the Legislative Decree 152/2006, afterwards changed with Legislative Decree 4/2008, has assimilated the SEA process to that of the more consolidated Environmental Impact Assessment (EIA) and thus betraying the original role of the SEA, transforming it into an external and less integrated "plan assessment" (Tondelli, 2013).

This paradigm shift, which took place long after the issuance of the European directive, has made the national interpretation distant from practices already in place at the regional level and much more adherent to the spirit of the directive itself. The case of the Emilia-Romagna Region is emblematic. This Region was a forerunner of the European SEA: already with Regional Law 20/2000 it introduced the Environmental and Territorial Sustainability Assessment (ValSAT) in urban and territorial plans, conceived from the beginning as an assessment "within" the plan, integrated with the decision-making process, rather than as an external authorization act, thus placing itself quite distant form an impact-assessment based approach recalled by Noble and Nwanekezie (2017). ValSAT was conceived as an anticipation of the SEA described in the SEA directive, indeed it was formally recognized as adherent to SEA after its inclusion in the national legislation. Therefore, from now on, we will use the term SEA for indicating the specific instrument adopted in the Emilia Romagna region. The peculiarity of SEA in Emilia-Romagna lies in having been a pioneer and integrated into the planning process, with a strong orientation towards sustainability "within" the choices.

The regional experiences related to the first 15 years of application of Regional Law 20/2000 have often referred to consolidated models (e.g. ENPLAN Guidelines, 2004) based on an assessment process to accompany the plan, providing in particular:

1. selection of relevant sustainability goals.
2. definition of objectives and planning actions.
3. verification of external coherence (with sustainability objectives) and internal coherence (between planning choices), through matrices or checklists.
4. identification of measures: enabling conditions, performance, compensation and mitigations.
5. Monitoring of effects during implementation, which becomes the most innovative lever of the SEA, but which in practice has often been enunciated rather than implemented.

Regional planning then saw a further novelty thanks to the issuance of Regional Law 24/2017, still in force, which promotes urban regeneration and redevelopment as the ordinary ways of developing the urban contexts without further expanding the urban environments according to the "No net land take by 2050" principle (EC, 2021). This development model aims at operating a reorganization and densification of built-up areas in a sustainable and resilient way through the implementation of the general urban plan (PUG, Piano Urbanistico Generale) at municipal level. In fact, the law set a target of net land take of only 3% of the urbanized territory as of 1 January 2018 that may be used by 2050. Moreover, it sets a transitional period of 6 years (from 2018 till 2024) where development plans may be implemented according to the previous urban planning instruments. Since 2024, all the building rights related to urban expansion which were not undertaken were cancelled. Moreover, the PUG must not locate new development areas eroding 3% of the urbanized territory, thus land use rights are assigned later during the implementation phase.

Thanks to these measures, the law aims at concentrating the real estate interests upon regeneration and redevelopment processes. In order to shorten times between the planning and implementation of these interventions, the municipal urban plan was changed, assuming a more strategic nature and freeing it from all those conforming contents linked to large urban transformations, which are delegated to a new instrument called operational agreement (AO, Accordo Operativo). AOs are planning and design tools proposed by private developers, which transform significant areas of the city and the territory (e.g. redevelopment areas or expansion areas within the 3%) and have the important role to detail the planning framework, defined by the PUG and taking care of the implementation of the planning contents at the same time. However, to be accepted by the Municipality, they must prove to be consistent with the PUG by contributing to implementing its strategic framework. Besides the AO, another instrument, called public initiative implementation plan (PAIP, Piano Attuativo di Iniziativa Pubblica), was introduced. It is proposed by the Municipality and considers the implementation of public urban infrastructures, services and facilities and all the changes that need a clear public direction. Similarly to AO, it should be compliant with the PUG but is conceived by the law to have a less important role in implementing the PUG strategy than the AO.

In this context, evaluation processes capable of measuring the benefits and co-benefits related to (private) urban regeneration interventions (i.e. the public, collective benefit that must inspire any intervention in the existing city) take on a great importance. In this framework the law gives the SEA the role not only of assessing the environmental effects of the PUG, but also of guiding the definition of the AOs' contents.

The strategic nature of the PUG has influenced the way SEA is developed. Actually, it weakens the quantitative assessments which were originally based on certain urban planning forecasts, in which the quantities and functions in play were given. In particular, it is no longer possible to assess the effects due to expansions as the PUG can no longer decide on them in terms of location. In this case, SEA can only provide appropriate location criteria to guide the implementation of the 3% of new development.

The result is a breakdown of the traditional SEA into two main phases:

i) the SEA of the PUG, which focuses both on mainly strategic contents and planning decisions linked to smaller regeneration interventions within the existing city and in the rural territory subject to ordinary regulatory discipline.
ii) the SEA of the Operational Agreements, in which it is possible to verify the sustainability of the structural and quantitative component of the agreements resulting through public-private negotiation, as well as the coherence with the strategy of the PUG.

This implies that the SEA of the PUG is conceived as a continuous and coordinated process by:

1. specifying further checks and in-depth analysis to be carried out during the preparation of the operational agreement in the light of the critical issues already emerged and the actual nature and extent of the transformations proposed
2. giving specific indications concerning performance to be achieved, conditions to be respected in urban transformation interventions in compliance with the main goals set by the PUG;
3. defining a robust monitoring system to assess the implementation of the actions and interventions and related effects.

SEA is therefore required to take on a key role not only to assess the effects on the individual environmental components but also to guide the evaluation of the proposals made by private developers, assuming a strategic and proactive role, aimed at pursuing the environmental and territorial sustainability objectives of the plan itself in an integrated manner.

## 4 The Application of the SEA to a Real Case Study

The proposed case study concerns the SEA developed by the Inter Dept. Centre of Building and Constructions of the University of Bologna for the PUG of a Union of four municipalities - Carpi, Soliera, Novi di Modena and Campogalliano - in the province of Modena. The Union is located in the Po Valley and is characterized by a polycentric urban structure. The territory is attractive for production and logistical functions thanks to the presence of considerable infrastructures and its high accessibility to important freight and passenger transport corridors. The area is crossed by numerous artificial watercourses that determine the risk of significant flooding, from which the Union is called Terre d'Argine (TdA – "embarkment lands").

The logical process adopted in setting up the SEA of the PUG is illustrated in this paper, without going too far into the specificities of the plan and the SEA but recalling some fundamental steps relating to the case study to better understand the followed evaluation process.

The SEA adopted a methodology aligned with the different phases of the plan definition, in order to accompany the planning stages and transformation choices ensuring compliance with the conditions of sustainability. At the same time, it defined the criteria and conditions orienting the AOs and their respective SEAs (Fig. 2).

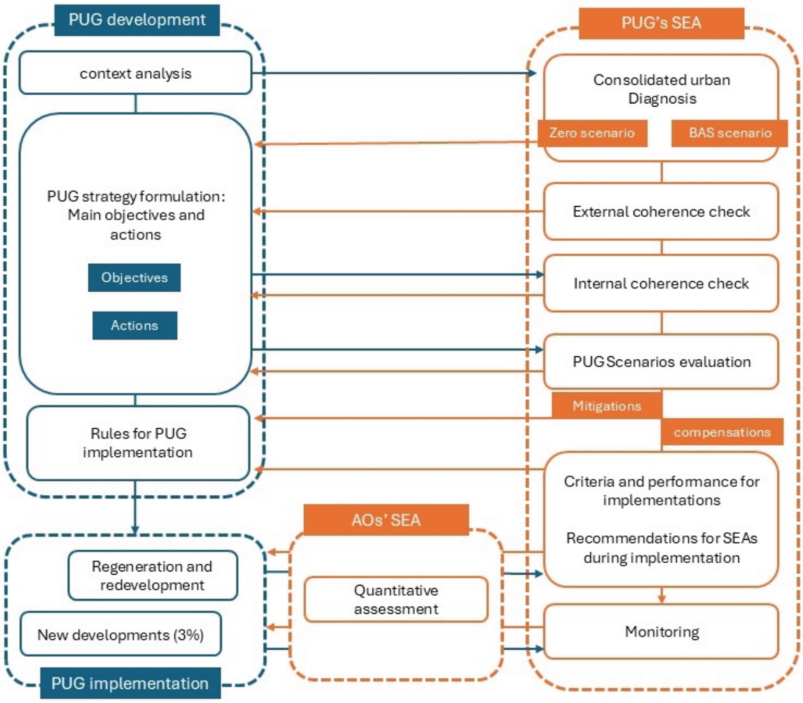


**Fig. 2.** Conceptualization of SEA process undertaken for the TdA PUG (source: Authors' elaboration)

The SEA of the PUG was therefore articulated in the following phases:

- Consolidated urban diagnosis: which synthesizes the context analysis highlighting vulnerability and resilience conditions in the different spatial domains.
- External coherence assessment: which evaluates if the goals of the PUG strategy are in line with overarching and sectoral planning and general sustainability objectives at national and international level.
- Internal coherence assessment: which assesses if the strategy objectives are consistent among themselves and if they respond well to the diagnosis.
- Scenarios of the PUG evaluation: it concerns the assessment of possible alternative planning scenarios highlighting effects on the environment and related measures to mitigate, compensate and reduce negative impacts.
- Criteria for implementation: concerns recommendations and performance to be considered when defining the masterplans for the AOs as well as their SEA contents and investigations.
- monitoring of the Plan: consisting of a set of indicators and targets necessary to monitor the implementation of the actions, including the AOs' implementation effects and the sustainability conditions.

These steps are briefly illustrated, highlighting the most significant elements that characterize the role of the SEA as a decision support system and guidance of planning decisions.

### 4.1 Consolidated Urban Diagnosis

This phase is aimed at diagnosing the socio-economic and environmental conditions of the territory, identifying problems, vulnerabilities to be addressed but also resources and opportunities to be leveraged in the territory. A SWOT analysis was conducted to highlight the strengths (S), weaknesses (W), opportunities (O) and threats (T) of the current and future state of the territory. This phase allowed us to build the baseline scenario, representing the current situation of the territorial context, and the business as usual (BAU) scenario, which reflects the expected future in the absence of interventions Notably, the SWOT framework made it possible to go beyond the traditional siloed approach based on environmental components, providing multidimensional and integrated synthesis of the most relevant phenomena affecting the entire territory. This analysis thus supported the formulation of a concrete and effective territorial diagnosis. The diagnosis is an essential step in the decision-making process, as it distills the information provided by the context analyses, highlights the most relevant territorial factors and trends, and identifies the elements that contribute to increasing vulnerability or strengthening resilience, providing a solid basis for guiding the definition of the strategy.

### 4.2 Coherence Check

Coherence check is an important step in the SEA process, because it allows the objectives of the PUG strategy, that have been defined in the meantime, to be examined with the aim of orienting decisions upon them towards solid sustainability principles. It is divided into external coherence check and internal coherence check.

The external coherence check ensured that the objectives of the new Plan's strategy are consistent with the sustainability objectives of the overarching and sectoral planning and with the SDGs. On an operational level, we initially proceeded with the analysis of international, national, regional and local policies and strategies, identifying the sustainability objectives against which the PUG should be compared. By then resorting to a matrix comparison between the overarching sustainability objectives and the objectives of the PUG being defined, the assessment supported the definition of a coherence judgment for each comparison. For instance, this phase supported effective integration with other sectoral municipal plans such as the Sustainable Energy and Climate Action Plan (SECAP), which was under approval, and the Sustainable Urban Mobility Plan (SUMP), which had already been approved. The coherence check made it possible to better align the policies and actions envisaged within these policy instruments and to select relevant indicators already identified by these plans for their periodic monitoring, thereby reducing the workload of the offices responsible for monitoring the PUG implementation.

The internal coherence check, on the other hand, was responsible for assessing the coherence between the strategies and objectives of the Plan itself as well as between the results of the diagnosis and the strategy of the PUG. Also in this case, two matrix

comparisons were used: the former was built to verify that critical issues and potential that emerged from the analysis had actually been intercepted by the strategy, while the latter support the check about the mutual coherence between the objectives of the Strategy.

This made it possible to adjust the objectives already drafted where coherence was not ensured, in order to better align them with the sustainability objectives considered and help to better define the strategy of the plan. This exercise proved to be very useful in identifying two actions that could lead to conflict situations: regeneration of already urbanized areas versus new developments. In this regard, during the PUG scenarios evaluation phase, we were able to work more precisely to define specific criteria aimed at addressing potential conflicts.

### 4.3 Scenarios of the PUG Evaluation

The evaluation of the scenarios of the PUG served to identify the reasonable alternatives suitable for achieving the established objectives by assessing the effects that these have on the territory and the environment. In this specific case, the scenarios were built starting from the 5 pillars of the strategy of the PUG and were compared to the BAU scenarios and zero scenarios.

A qualitative-quantitative assessment was carried out according to the available data from the context analysis in order to highlight the positive (or not worsening) trend of the plan and the various alternative actions and approaches that the plan proposes on some pillars, providing recommendations on the priority of certain alternatives or identifying sustainability conditions and measures.

A specific scenario that deserved particular attention is the one relating to new developments, even though they will be residual. The assessment of this scenario is particularly critical for highlighting the role of SEA, considering that the PUG cannot identify the areas in which to expand the city using 3% consumable land. The SEA played an important role, helping to provide correct guidance on this aspect. To this end, the SEA has defined a system of criteria and weights that identify the locations suitability to transformation, i.e. parts of the territory that are more favourable to the establishment of new urban functions as well as those locations where such transformations should be inhibited. For instance, favourable locations are those in which there is a limitation of urban sprawl, proximity to relevant services and connections to promote sustainable mobility, while unfavourable locations are those affecting areas that present environmental and landscape values or are affected by environmental risks. The evaluation system assigned scores to the different areas, thus providing information about their suitability for a sustainable development. Meanwhile, two alternative scenarios were compared, as identified in the previous phase: new developments and deep urban regeneration. In this case, the two scenarios could be in conflict. The SEA made it possible to better identify the priority conditions under which urban regeneration should be preferred over new developments, to reduce potential conflicts between the actions of the strategy.

### 4.4 Guidance for the Implementation

As already said, the PUG does not provide building rights in urban developments and redevelopments, to avoid generating urban rents. Consequently the regional law allows (and requires) that these urban changes are detailed (in terms of future urban layout and uses but also building rights and public spaces to be realized and given to the municipality) and proposed by the developers in a later stage, once economic and market related conditions are favourable for operationalize and implement these important urban changes, which take the form of an Operational Agreement. The SEA of the PUG has the role of keeping these two stages (planning and implementation) together under a sustainability framework. This task is addressed by establishing, within the SEA of the PUG, the analysis to be included in the SEA of AOs as well as by setting specific sustainability conditions in relation to specific transformations and/or contexts. Notably the SEA of PUG TdA required: i) a coherence check between the contents of the implementation tools with the strategy of the PUG, accounting how much the project proposal is in line with the objectives and actions of the PUG; ii) a sustainability assessment of the proposals, based on specific in-depth analysis recommended by the SEA of the PUG.

To this end, a checklist has been built based on the dimensions of sustainability and the peculiarities of the territory highlighted by the diagnostic framework and the Plan objectives, which identifies criteria, indicators and aspects to be made explicit in the SEA of the AOs.

The topics identified in the checklist are the following:

- Facilities and public services
- Social housing
- Economic impact (strategic nature)
- Landscape
- Accessibility and mobility services and infrastructures
- Energy consumption
- Seismic risk
- Soil permeability
- Soil quality
- CO2 emissions and air pollution
- Noise
- Hydraulic risk
- Ecosystem performance
- Water resource management
- Waste management

For each of them, the required levels of in-depth analysis and the situations in which these studies are most relevant and decisive have been defined, based on the findings of the previous analyses. Therefore, the checklist was intended as a transparent and effective tool for both developers - to support their decisions regarding performance-based design choices characterizing the AO proposal and the issues influencing the acceptance or rejection of the proposal - and for municipal officials, who are responsible for determining whether the proposal is acceptable based on the most relevant aspects that it should address.

In addition to implementation through major urban interventions, the strategy of the PUG is also carried out through minor urban changes within already built-up areas that do not necessarily require high-impact interventions. In this case, the strategic objectives should be translated into specific planning rules aimed at maintaining or improving existing urban conditions, without altering the urban character of the built-up areas. These areas generally represent the majority of the urbanized territory and therefore need to be considered by the SEA, in terms of the cumulative effects that may be generated. In this context, the SEA plays an important role in supporting decision-making processes aimed at identifying appropriate performance requirements to address the issues emerging from the diagnosis.

### 4.5 Monitoring

Monitoring is the central tool of the PUG evaluation process, capable of effectively assessing the implementation of the Plan itself. It is based on sets of indicators and targets capable of controlling the significant effects on the environment due to the implementation of the plan and verifying the achievement of the sustainability objectives set, in order to identify unforeseen negative effects and consequently adopt corrective measures (Tondelli, 2003).

The monitoring system has been structured based on the objectives of the Plan, according to two main parts:

- Context monitoring, which describes the initial environmental conditions, the dynamics and trends in place and the contribution of the plan to the modification of these trends. Selected indicators and targets are in line with the sustainability objectives and strategies set at supralocal level. Basically, they verify the plan scenarios, recording the cumulative variations due to the implementation of the plan in the local context.
- Plan monitoring, which more properly concerns the Plan itself and therefore records the effects deriving from the implementation of the Plan through indicators that are strictly functional to verify the completion of the actions envisaged in the plan strategy and the degree of achievement of the specific objectives, including the ones deriving from the AOs implementation.

The monitoring system was therefore conceived as a useful working tool for municipal administrations to record the contributions due to the implementation of the plan and to provide for any corrective measures.

## 5 Discussion and Conclusions

This paper discussed how the SEA has been adopted in Emilia-Romagna, Italy, as a decision support tool for ensuring that planning decisions included in an urban or spatial plan are sustainable, clearly comprising not only the environmental domain but also all the other domains affected by urban and territorial decisions. This perspective has given the SEA a very important role, not reduced to the “mere” assessment of the presence of sustainable conditions but rather representing a new way of planning.

As a matter of fact, the SEA in Emilia-Romagna can be conceived as more like a Strategy based model (Noble and Nwanekezie, 2017) based on Strategic futures approach. The SEA of the PUG is designed to influence planning actions and/or other next-level decisions regarding development initiatives, including the EIA or the SEA of plan-projects such as the AOs. The SEA tends to shape the plan rather than adjust the plan, becoming the planning process itself.

Indeed, in the proposed case study, the SEA has demonstrated its potential to support the decision-making process particularly in defining the strategic contents of the plan. In that phase, the SEA was able to easily steer the transition from the diagnosis to the definition of the PUG strategy by anchoring more firmly the strategic lines already drafted by policy makers to the territorial needs and sectoral or supralocal policies.

However, SEA is also responsible of verifying consistency with sustainability principles, adopting an approach closer to compliance-based SEAs, especially when it is carried out to accompany the design of AOs. Important points of concern emerge in this regard. They are linked to the delicate transition to the implementation phase, which occurs outside the framework of a complete and preventive control of the plan, but is instead entrusted to negotiation and assessment of sustainability on a case-by-case basis. On this aspect, the SEA of the PUG is inevitably weak, as it tends to orient rather than constrain decisions, lacking the possibility to define stringent sustainability conditions which are based on clearly identified transformations already envisaged by the plan and quantifiable effects. In this context, monitoring assumes fundamental importance to capture real effects on the territory and enabling corrective actions to be implemented. Monitoring is the real challenge in the transition from the strategic dimension of the plan to its implementation, to ensure the implementation itself is sustainable and consistent with the initial objectives. This critical point is exacerbated by a sort of cross-eyed approach affecting the administrative sphere, given the fact that, by National law, requires the SEA to follow a procedure that is very similar to that of the EIA. This makes the adoption of a strategy-based model still experimental and interpreted differently across regional experiences; on this topic, indeed, there is not yet a shared approach or common set of techniques. However, we believe that the approach presented in this paper can be easily transferred to planning contexts similar to those of the Emilia-Romagna, where the plan is strategic and based on negotiation for the definition of major urban transformations. At the same time, this evaluation scheme can be easily adapted to be applied to more conformative and regulatory plans. It means including the SEA of the AO within the SEA of the PUG, prefiguring assessments and scenarios based on new urban uses and maximum building volumes already envisaged by the plan, in areas where deep urban transformations are envisaged.

This multiplicity of approaches and variations denotes a good versatility of the tool, which is able to adapt to different planning stages, but at the same time it risks overlapping with instruments such as the EIA that, according to the law, is still due as well to assess the sustainability of certain urban projects, such as urban redevelopments involving areas greater than 10 hectares.

There is also another aspect concerning the role of the SEA that is highly topical in the regional scientific and cultural debate: whether it is appropriate to assign to the SEA the task of setting mechanisms for assessing the admissibility of AO proposals

thus inevitably considering multiple aspects, not only the environmental ones. This is due to a concern that the discretion of the plan will be reduced in favour of the SEA, which appears to take on a prominent role in the decision-making process, while this task should be primarily taken on by the planning discipline in dialogue with the political decision-making sphere. Understanding the role of the SEA as subordinate to the role of the plan is the result of a traditional approach to planning that does not yet interpret the SEA as a different way of constructing the plan itself, not as an external process.

In conclusion, experimentations and research on this topic are still needed, in particular on the two main topics. First, it is important to investigate the possible contradictions between the strategic and impact-related dimensions of the SEA that may generate confusion and overwhelm the scoping phases. Applying the SEA to different planning processes (i.e. at different scales other than the municipal level, or for sectorial plans) that combine strategic and structural dimensions would be interesting and useful for assessing the potential and limitations of the SEA itself and try to clarify which are the boundaries between strategic based and impact-assessment based approaches. Second, further studies should aim to overcome the difficulties in interpreting the exact role of the SEA in the planning process, which should be considered more as a different planning approach, rather than an external assessment of the plan.

## References

Anelli, D., Morano, P., Locurcio, M., Tajani, F.: Resilient cities and land take. effective management through sustainable urban planning tools. Land **14**(7), 1335 (2025)

Brunetta, G.: Valutazione ambientale strategica e grandi eventi. Riflessioni a partire dall'esperienza di Torino 2006. Bollettino della Società Geografica Italiana, serie XII, volume VII, 4 (2002)

Chaker, A., El-Fadl, K., Chamas, L., Hatjian, B.: A review of strategic environmental assessment in 12 selected countries. Environ. Impact Assess. Rev. **26**(1), 15–56 (2006)

Dalal-Clayton, B., Sadler, B.: Strategic Environmental Assessment: A Sourcebook and Reference Guide to International Experience. Earthscan, London (2005)

Enplan: Guidelines for the Environmental Assessment of Plans and Programs (2004). https://interreg-enplan.org/guida/index.htm. Accessed 25 Feb 2026

European Commission: EU Soil Strategy for 2030: Reaping the benefits of healthy soils for people, food, nature and climate, COM(2021) 699 (EC, 2021). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A52021DC0699. Accessed 25 Feb 2026

Fischer, T.B.: The Theory and Practice of Strategic Environmental Assessment. Earthscan (2007)

Fundingsland Tetlow, M., Hanusch, M.: Strategic environmental assessment: the state of the art. Impact Assessment and Project Appraisal **30**(1), 15–24 (2012)

Geneletti, D., Bond, A., Russel, D., Turnpenny, J., Sheate, W., Jordan, A.: Chapter 10: Ecosystem services and sustainability assessment: theory and practice. In: Morrison-Saunders, A., Pope, J., Bond, A. (eds.) Handbook of Sustainability Assessment. Edward Elgar, Cheltenham, UK and Northampton, USA, pp. 215–234 (2015)

Geneletti, D.: Chapter 3: Ecosystem services analysis for Strategic Environmental Assessment: concepts and examples. In: Handbook on Biodiversity and Ecosystem Services in Impact Assessment. Edward Elgar Publishing, Cheltenham, UK (2016)

Isola, F., Lai, S., Leone, F., Zoppi, C.: Strategic environmental assessment as a tool to embed climate change adaptation in urban planning. the case of four Italian cities. In: Computational Science and Its Applications – ICCSA 2024 Workshops, Proceedings, Part IV, pp. 275–292. Springer-Verlag, Berlin, Heidelberg (2024)

Noble, B., Nwanekezie, K.: Conceptualizing strategic environmental assessment: principles, approaches and research directions. Environ. Impact Assess. Rev. **62**, 165–173 (2017)

Therivel, R.: Strategic Environmental Assessment in Action. 2nd edn. Routledge (2010)

Tondelli, S.: L'esperienza della VAS in Emilia-Romagna. IN_BO. Ricerche E Progetti Per Il Territorio, La Città E l'architettura **4**(6), 245–254 (2013)

United Nations Economic Commission for Europe: Protocol on Strategic Environmental Assessment to the Convention on Environmental Impact Assessment in a Transboundary Context, Kyiv (UNECE, 2003)

# Integrating Wine Specialization into a Territorial Tourism Dimension: A STESY-Based Interpretation of La Rioja

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**Abstract.** La Rioja represents one of the most distinctive wine-producing regions in Southern Europe, where agricultural specialization, territorial identity, and cultural heritage converge into a highly recognizable regional system. Although wine production constitutes the primary structural driver of the local economy and the main source of international visibility, its tourism development remains only partially integrated at the territorial scale.

This study applies the STESY framework in order to investigate how wine specialization may be interpreted not only as a productive asset, but as a territorial structure capable of supporting a more integrated tourism dimension. The methodology combines territorial interpretation, spatial mapping of attractors, services, and reachability, cluster-based subdivision into Destination Areas, and the use of composite indicators including the Balanced Tourism Supply Index (BTSI), Attraction Potential Index (API), and Diversity Reachability Index (DRI). The results reveal a region with a strong and coherent identity, but with uneven integration between its productive specialization, tourism services, and mobility system.

Based on these findings, the paper proposes a strategic framework entitled "The Rioja Experience: Slope & Cellar", aimed at transforming wine specialization into a territorial tourism infrastructure through slow mobility, adaptive reuse, intermodal accessibility, and distributed experiential nodes. The study contributes to the development of policy-oriented approaches for sustainable tourism planning in specialized inland regions, where sectoral excellence can become the basis for a broader territorial tourism model.

**Keyword:** Sustainable tourism planning · spatial analysis · cluster analysis

## 1 Introduction

Sustainable tourism becomes more and more a core argument in territorial development debate defining local multi-stakeholders' perspectives and global framework for innovation and better management of such complex phenomena [1, 2]. Today tourism is

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recognized as a dominant driver of economic growth in coastal and heritage destinations, yet its rapid expansion has also generated critical spatial and temporal imbalances [3]. In the perspective of the authors, tourism opens to relevant debate in urban and regional planning research as the decision making process connected with tourism management represent a comprehensive framework in which sustainable urban regeneration and transformation, landscape protection actions, economic development issues interacts generating an effective environment to apply sustainable urban development principles, methods and agendas for short term and strategic territorial design [4–8]. Those applications are also oriented to improve the competences of students in academic curricula dealing with territorial design professionals, and this paper comes as a result of a studio in architectural classes following the research tradition [9–14] of sustainable urban planning and design at UNIBAS [15–18].

Tourism as a spatial phenomenon is a multidisciplinary domain where spatial dimension represents a robust analytical dimension for managing information and designs, applying collaborative approach for strategic planning [19–25].

Within this perspective, tourism planning becomes especially significant in regions characterized by a strong sectoral specialization. In such cases, the issue is often not whether the territory possesses recognizable resources, but whether these resources are effectively capable of structuring a wider and more integrated territorial tourism system. Productive excellence, even when internationally acknowledged, does not automatically generate a coherent tourism ecosystem. Rather, it may remain spatially concentrated, functionally fragmented, or only partially connected with the broader territorial structure [26].

There are good reasons why wine districts can be considered appropriate settings to examine the topic in question. Indeed, their identity tends to consist of an array of factors, including agriculture, landscapes, cultural memory, gastronomy, and territorial symbolic value. At the same time, however, in many situations wine-related tourism is still restricted to a rather limited list of experiences like visiting cellars, tasting, and consumption events, instead of becoming more territorialized, which would allow for more time spent in the area and more utilization of peripheral regions [24].

La Rioja, in northern Spain, represents a particularly relevant case for exploring this transition. Internationally recognized for its wine production and deeply associated with viticultural identity [27], the region possesses all the conditions to support a high-value tourism model. However, despite its international reputation and dense concentration of wine-related resources, the tourism system still appears only partially integrated at the regional scale. Some areas concentrate the main functions of attraction, service, and access, while others remain more weakly connected despite their environmental and cultural potential.

This paper aims to develop a spatially informed planning framework capable of supporting the transition from a short-duration, high-pressure tourism model toward a more balanced system based on extended stays and territorial redistribution. The study proposes an integrated methodological approach combining spatial analysis, cluster-based interpretation, and policy-oriented design strategies in compliance with NUA principles. The contribution lies in bridging analytical diagnosis and operational planning within a coherent framework transferable to similar tourism destinations.

## 2 Study Area

This paper revolves around La Rioja, which is one of the autonomous communities situated in the north of Spain, and it enjoys great reputation across the globe as a very distinctive wine region within Europe. Though restricted by its geographical territory, La Rioja occupies an exceptional geopolitical-economic position, thanks mainly to the significant impact of viticulture on its production system, landscape, and identity.

The regional geography is clearly defined by the presence of the Ebro Valley, which shapes the north-central portion of the region in such a way as to create a good environment for vine growing. This agricultural structure is supplemented with a slightly more complex structure in the south, with the addition of mountain scenery and settlements in the interior that add to the complexity of the territorial framework. There is, therefore, a clear duality of morphology and environment in the region that includes vine-growing plains and rural landscapes.

Against this background, the wine industry goes well beyond being an agricultural specialization in its own right. Rather, it is a territorial matrix that exerts influence over the local economy, settlement pattern, land use and even the image of the region itself. One of the main nodes in the system is Haro, a city located in the upper Rioja area. Its significance as part of the system is closely associated with the Barrio de la Estación, which features several historically important wineries in terms of its production capabilities and symbolic meaning of bringing together wine production, logistics and territoriality. The role played by Logroño, the capital of the region, complements the above as far as tourism in La Rioja is concerned since it can be seen as the key urban center of the region. While it does not specialize in the production of wines, the city's importance lies in terms of its infrastructure and central role within the region.

Haro emerges as the tourism core of Rioja Alta, attracting between 180,000 and 200,000 visitors annually (Fig. 1) through a territorially embedded wine-based system, with the Barrio de la Estación acting as its main international gateway. The area is characterized by a very high density of tourism resources, particularly wineries, which clearly shape its specialization and strategic orientation.

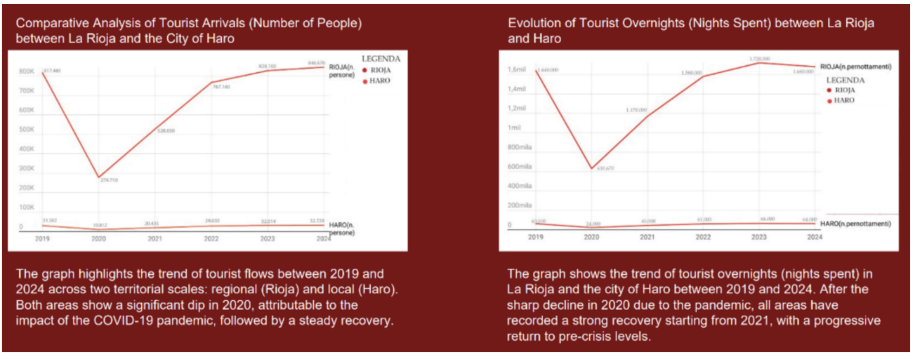


**Fig. 1.** Comparative overview of tourism dynamics in Haro and Rioja. Source: Personal elaboration of data from https://www.larioja.org/estadistica/es.

The GDP composition of the Rioja region highlights a service-oriented economy, with the tertiary sector accounting for 69.4% of total value added, supported by a balanced mix of consumer services and industry-related services. The secondary sector contributes 24.5%, driven by manufacturing, while the primary sector, though limited to 6.1%, remains strategically significant. The defining feature of the regional economy is the wine value chain, which operates as an integrated system across all sectors: viticulture alone accounts for 3.8% of GDP, while related manufacturing, tourism, and advanced services further amplify its impact. Overall, Rioja represents a model of integrated development in which the wine industry functions as a key economic multiplier, linking agriculture, industry, and services into a cohesive territorial system.

## 3 Territorial Analysis

The approach adopted in this study is based on the STESY framework [28] conceived as an integrated analytical and interpretative tool to support evidence-based planning strategies.

The first phase consists of a contextual analysis of the study area, focusing on the identification and classification of key georeferenced components (PoIs) of the tourism system, including attractors, services, and reachability (Fig. 2). Attractors include wineries and wine-related facilities, historical, cultural, religious, and landscape elements that contribute to the regional tourism identity. Services include accommodation, food and beverage facilities, and complementary visitor functions, while reachability is assessed through the presence and articulation of infrastructures supporting territorial access and internal mobility. Beyond its wine-related identity, the region also includes a broader set of resources that reinforce its tourism potential. These include the Camino de Santiago, which crosses part of the region and contributes to its wider experiential and symbolic dimension.

The second phase involves the spatial interpretation of these components through a cluster-based approach in order to identifying the Destination Areas of the tourism system in the case study. The territorial system is divided into homogeneous clusters using GeoDA software [29] aimed at identifying distinct spatial patterns. The optimal number of clusters is determined through the application of the Elbow Method [30], ensuring a balance between analytical detail and interpretative clarity (Fig. 3). Cluster analysis in La Rioja identifies four macro-destination areas with a heterogeneous distribution. Logroño (DA 1) stands as the primary hub with over 1,200 points of interest, followed by the wine tourism center of Haro (DA 2). The map highlights a clear polarization of services along the east-west axis, driven by the reachability of the rail network and the Camino de Santiago.

To quantify the characteristics of each cluster, three composite indicators are employed (Fig. 4). The Balanced Tourism Supply Index (BTSI) measures the relationship between accommodation capacity and consumption services, distinguishing between overnight-oriented and day-trip-oriented areas. The Attraction Potential Index (API) evaluates the strength of attractors based on their relevance and scale, while the Diversity Reachability Index (DRI) assesses accessibility and intramodality within the transport system.

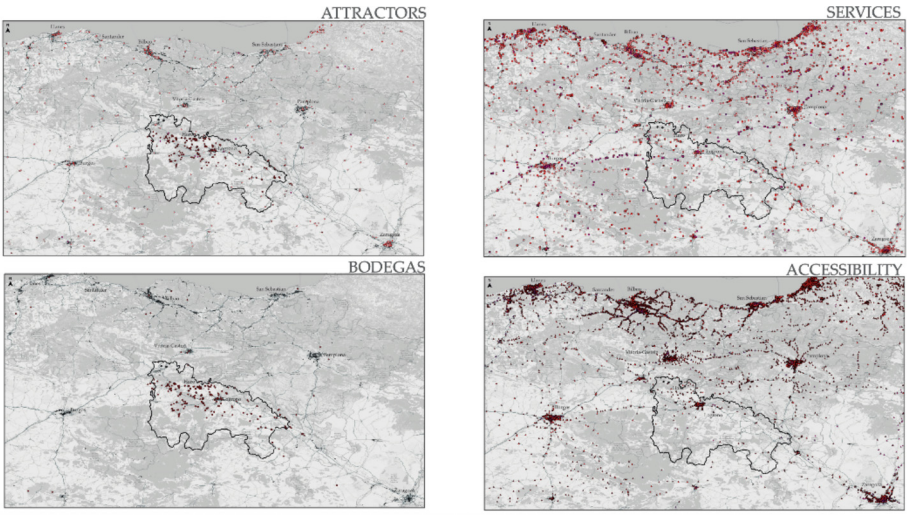


**Fig. 2.** Distribution of Attractors, services and reachability.

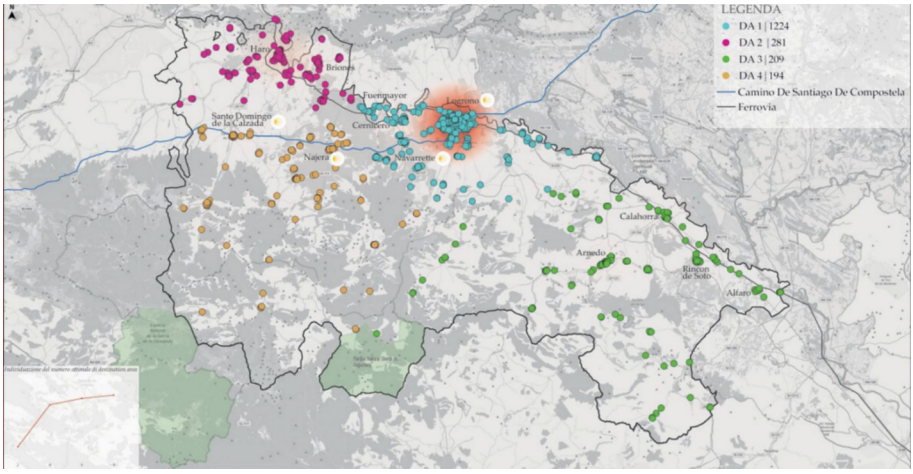


**Fig. 3.** Map of Clusters identified.

The territorial analysis highlights a structurally unbalanced tourism system. The Balanced Tourism Supply Index (BTSI), which measures the integration between accommodation and food services, shows generally very low values across most of the region, indicating a configuration that mainly supports day trips rather than longer stays.

The only significant exception is Destination Area 4, with a BTSI of 0.32, which reflects a relatively more balanced supply despite operating in a less dense tourism context. In terms of accessibility, the Diversity Reachability Index (DRI) reveals a strong concentration of connectivity in the central part of DA 1, which reaches the maximum score of 6/6 and functions as the primary access node for the region, while surrounding

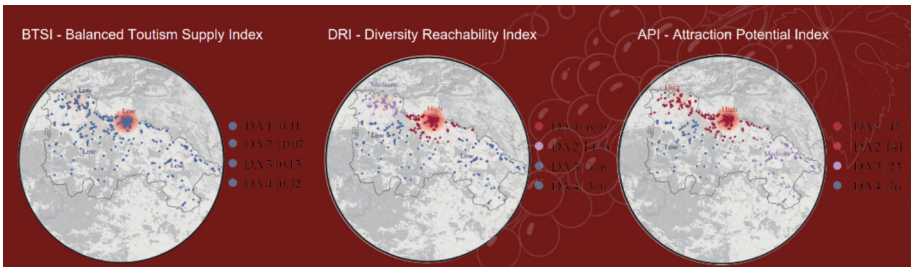


**Fig. 4.** Indicators applied to each Cluster (Destination Area).

areas remain weaklier connected and dependent on the main multimodal poles. Similarly, the Attraction Potential Index (API) confirms a clear polarization of tourism attractiveness, with DA 1 (Logroño) and DA 2 (Haro/Rioja Alta) both scoring 41, far above DA 3 (23) and DA 4 (16).

Taken together, the results do not describe a weak tourism system, but rather a selectively integrated one. The wine specialization is clear and highly effective in generating attractiveness, but its territorial effects remain uneven. The BTSI highlights a structural tendency toward service concentration rather than hospitality consolidation, confirming that the system is more oriented toward visitability than inhabitation. The DRI reveals a dependence on a limited number of access structures, while the API confirms the strong polarization of attraction around a few key nodes.

In summary, the results indicate that there is an excursion-type model of tourism in this region. Attractive and accessible territories are not yet accompanied by an adequate infrastructure that can maintain tourists for a long period of time.

It becomes clear from the above analysis that the territory of La Rioja already has all elements necessary to be competitive in the tourism environment; however, these elements have not yet been transformed into a territorial model of tourism development. In other words, the problem is not about lack of identity and attractiveness, but rather about the underdevelopment of specialization into a territorial tourism form.

## 4 Discussion and Planning Strategy

The findings of the analysis support the development of a multi-scalar planning strategy aimed at transforming the existing tourism system. The downscaling of NUA [31, 32] compliance assessment supports the definition of spatial strategies aimed at enhancing the sustainability of the territorial system. The proposed approach is based on the combination of soft measures and hard interventions, designed to influence both visitor behavior and spatial organization.

Key challenge lies in broadening the territorial meaning of wine specialization, transforming it from a highly concentrated and sector-specific tourism driver into a more distributed and connective territorial experience.

This approach is based on a basic premise that in La Rioja, wine already speaks its own language. Nevertheless, this language is still limited in terms of tourism consumption in concentrated ways, such as visiting vineyards, tasting wine, and staying for short

periods of time for food and wine tourism experiences. What has not been developed yet is the ability of this specialization to generate a tourism story at the territorial level. This is why the proposed idea moves from wine as destination to wine as territory.

This shift will be facilitated by the design of the intervention that is aimed at creating a slow mobility network, where cycling tourism is the primary tool used for territorial integration. Unlike conventional approaches, where the introduction of cycling is seen as one of the possible transportation means, this strategy employs cycling as an experience and space-making approach that can help connect different pieces of the regional tourism industry together. With the help of slow mobility, wineries, villas, cultural places, scenic views, accommodation venues, and mountains can be integrated into one continuous territory.

The strategy is articulated through four thematic cycling routes, each designed not simply as an itinerary, but as a narrative and spatial framework for integrating different territorial vocations.

The first route, "The Rails of Rioja," links Logroño and Haro, reinforcing the relationship between the main service hub and the symbolic heart of the regional wine system. This itinerary translates the structural axis of the region into an experiential corridor where the tourism value of wine is extended through movement, stopovers, and territorial continuity.

The second route, "The Path of the Future Vine," combines viticultural landscapes with the symbolic and cultural dimension of the Camino de Santiago, opening the wine experience to a broader cultural and spiritual interpretation of the territory. This route allows the regional wine identity to interact with slower and more reflective forms of travel.

The third route, "Vertical Vineyards," explores the more elevated and marginal parts of the region, emphasizing the relationship between viticulture, mountain landscapes, and environmental specificity. In doing so, it broadens the spatial expression of wine tourism beyond its most established and accessible nodes.

The fourth route, "Along the Must Riverbanks," follows the Ebro corridor, connecting lower-density areas and integrating agricultural landscapes, small settlements, and riverine environments into the regional tourism structure. This route supports the emergence of a more continuous territorial experience, in which the wine landscape is not limited to iconic points, but becomes a readable and accessible regional condition (Fig. 5).

These itineraries are supported by a wider system of territorial nodes and infrastructures designed to make the tourism experience more inhabitable and territorially embedded. In this sense, the strategy includes the adaptive reuse of existing buildings and disused structures, such as former railway buildings, agricultural service spaces, and small infrastructural artifacts, converting them into tasting points, accommodation facilities, information centers, and interpretative spaces. This approach reinforces the territorial continuity between productive heritage and tourism development, while reducing the need for new land consumption.

A key role within this network is assigned to the "Vitis Pavilion – Rioja Hub," conceived as an intermodal and multifunctional structure able to support visitor orientation,

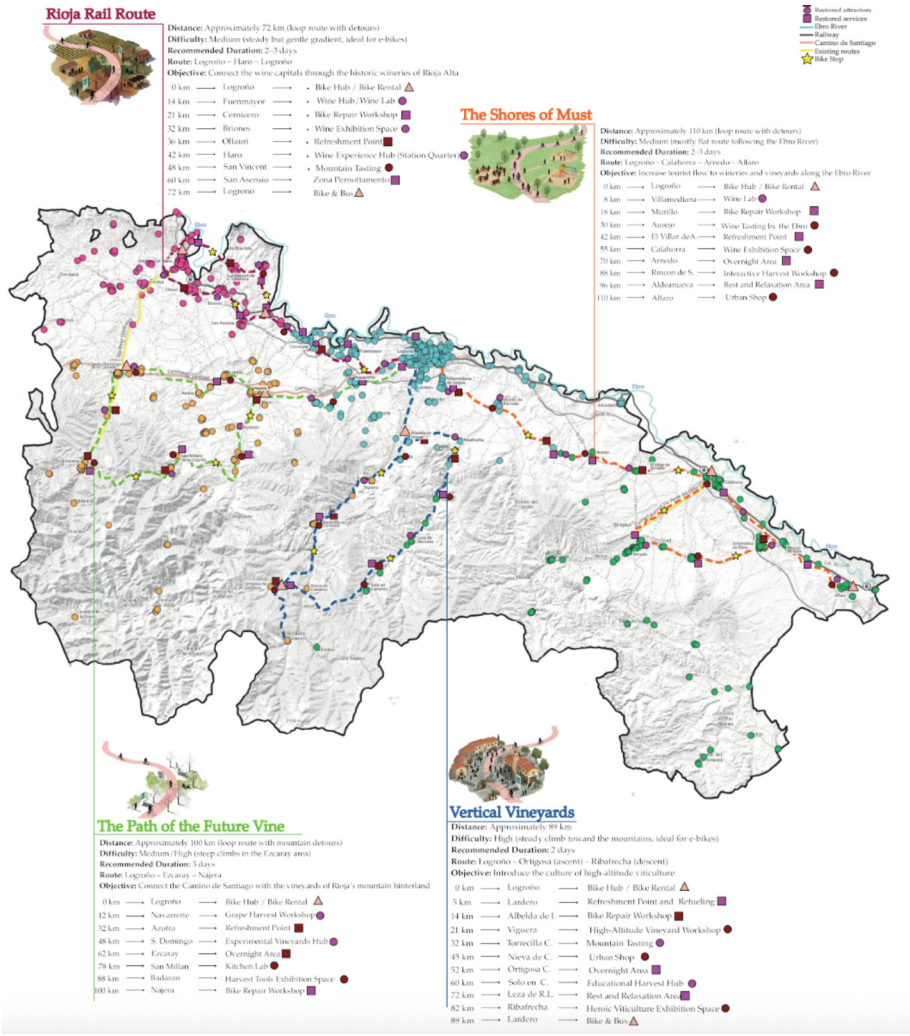


**Fig. 5.** Map of hard interventions

mobility exchange, and territorial interpretation. Alongside this central node, the introduction of Smart Hubs for e-bike support, service assistance, and route accessibility helps consolidate the practical dimension of the slow mobility network.

The strategy is further reinforced by a set of soft territorial devices aimed at enhancing the coherence and continuity of the visitor experience. These include the "Rioja Passport," designed as a cumulative and exploratory mechanism encouraging visitors to move through different nodes of the region; integrated Wine & Ride packages linking wineries, hospitality, and mobility; and a digital support system capable of improving route legibility, real-time accessibility, and visitor orientation (Fig. 6).

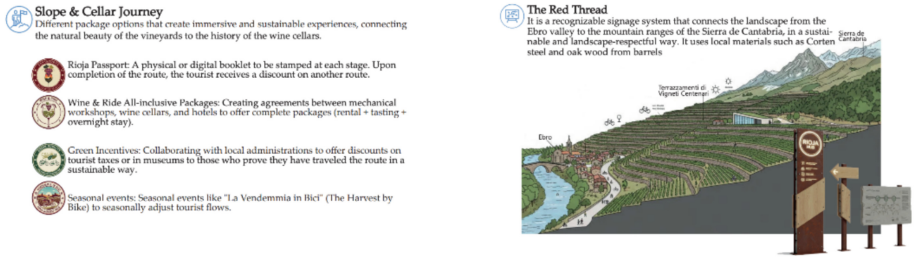


**Fig. 6.** Map of soft interventions

From a strategic standpoint, what is important about this plan is that it is not just the incorporation of individual attractions, but the creation of an overall territorial tourism syntax in which wine specialization becomes more readable, more livable, and more connected to the regional framework in general. In this context, the project will not be about diluting the wine identity of La Rioja, but rather about reinforcing its territorial ability.

## 5 Conclusions

This study has explored the case of La Rioja as a specialized inland region in which a strong productive identity, centered on viticulture and wine culture, constitutes the main foundation of territorial recognition and tourism appeal.

The application of the STESY framework has shown that the region already possesses the essential components of a highly competitive tourism ecosystem. Wine specialization clearly functions as the principal structuring element of attraction, symbolic value, and territorial distinction. At the same time, however, the analysis reveals that this specialization has not yet been fully translated into a broader and more territorially integrated tourism model.

The issue emerging from the case study is therefore not a lack of resources, nor the absence of a recognizable tourism identity. Rather, it concerns the limited integration between the wine system and the wider territorial dimensions of tourism development, including mobility, permanence, hospitality, and the activation of complementary areas. In this sense, the study suggests that the strategic value of La Rioja lies precisely in its possibility to evolve from a region visited for wine into a region experienced through wine.

In this regard, the suggested strategy of "The Rioja Experience: Slope & Cellar" addresses this problem by understanding wine specialization as a kind of territorial infrastructure instead of a tourism product per se. This intervention describes some possibilities as to how this infrastructure, through slow mobility, adaptive reuse, distributed experience nodes, and intermodal accessibility, could provide a potential way for the development of the economy of wine into a more continuous tourism environment.

Furthermore, the case of La Rioja provides an additional perspective in relation to planning of sustainable tourism. For many specialized regions, the main problem of tourism planning is not about attracting more tourists, but about understanding what

already exists as excellence and how it could be transformed into territorial sustainability. With this in mind, wine tourism can be considered not only as an activity within some niche or thematic sphere, but also as a planning field itself [33–40].

The whole application is structured on the STESY framework [28, 41, 42]: a robust spatial analytical framework driving from the early stages the strategic design in sustainable tourism for a specific destination area. The framework had been applied in a number of local studies selected among major destinations (i.e. EU Capitals, UNESCO Sites, Environmental global attractors etc.) [43, 44], minor inland tourism areas (i.e. Vulture, Pollino national Park) [45, 46] and niche tourism sites (i.e. Islands) [47–49].

In this paper the main limitation comes from the lack of discussion with local stakeholders. In facts the research was fully development on desk and remotely. It is also relevant to point out how the STESY method effectively supported the process providing a guide to students to start with effective local analysis, to perform meaningful spatial interpretation of a complex phenomenon, to identify design options/solution for a strategic proposal compliant with NUA international principles.

The indicator dashboard included in the STESY platform allows to compare this application with other case study in a significant and effective way, supporting the decision-making process in identifying intervention priority to better plan tourism sector locally benefitting of multi scale assessment options and accountability management of global objective for sustainable and climate responsive design [50–52].

## References

1. Williams, A.M., Shaw, G.: Internationalization and innovation in tourism. Ann. Tour. Res. **38**, 27–51 (2011). https://doi.org/10.1016/j.annals.2010.09.006
2. Lenzen, M., Sun, Y.-Y., Faturay, F., Ting, Y.-P., Geschke, A., Malik, A.: The carbon footprint of global tourism. Nat. Clim. Chang. **8**, 522–528 (2018). https://doi.org/10.1038/s41558-018-0141-x
3. Stojčić, N., Mikulić, J., Vizek, M.: High season, low growth: The impact of tourism seasonality and vulnerability to tourism on the emergence of high-growth firms. Tour. Manag. **89**, 104455 (2022). https://doi.org/10.1016/j.tourman.2021.104455
4. UN HABITAT: New Urban Agenda. United Nations (2016)
5. Las Casas, G., Scorza, F., Murgante, B.: New urban agenda and open challenges for urban and regional planning. In: Calabrò, F., Della Spina, L., and Bevilacqua, C. (eds.) New Metropolitan Perspectives. ISHT 2018. pp. 282–288. Springer, Cham (2019). https://doi.org/10.1007/978-3-319-92099-3_33
6. Morphet, J., Morphet, R.: New Urban Agenda: New Urban Analytics: A Report Prepared for the MacArthur Foundation (2019)
7. Tajani, F., Manganelli, B., Cerullo, G., Morano, P., Morente, M.A.: The student housing as a catalyst for virtuous processes of "win-win" revitalization of property assets in disuse. In: Gervasi, O., Murgante, B., Rocha, A.M.A.C., Garau, C., Scorza, F., Karaca, Y., Torre, C.M. (eds.) Computational Science and Its Applications – ICCSA 2023 Workshops. pp. 387–400. Springer Nature Switzerland, Cham (2023)
8. Tajani, F., Cerullo, G., Stara, F., Sica, F.: Multidimensional Models for Building Decarbonization Pathways. Bus. Strategy Environ. n/a (2025). https://doi.org/10.1002/bse.70455
9. Lagonigro, D., Cazzati, V., Viggiano, N., Andrulli, G., Gatto, R.V., Mininni, M., Scorza, F.: Downscaling NUA: matera new urban structure. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)

10. Scorza, F., Gatto, R.V.: Identifying territorial values for tourism development: the case study of calabrian greek area. Sustainability 2023 **15**, 5501 (2023). https://doi.org/10.3390/SU15065501
11. Lacerenza, A., et al.: "Back to the villages": design sustainable development scenarios for in-land areas. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
12. Capodiferro, M., et al.: "University equity": students' facilities in major tourism destination towns. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023 (2023)
13. Florio, E., et al.: SuperABLE: matera accessible for all. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
14. Esposito Loscavo, B., et al.: Innovation ecosystem: the added value in a unique UNESCO city. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
15. Casas, G.L., Scorza, F.: Sustainable planning: a methodological toolkit. In: Gervasi, O., et al. (eds.) ICCSA 2016. LNCS, vol. 9786, pp. 627–635. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-42085-1_53
16. Gatto, R.V., Corrado, S., Scorza, F.: Taxonomy for specialized Tourism Ecosystems : new geographies for sustainable territorial planning. Habitat Int. (2025)
17. Murgante, B., Borruso, G., Lapucci, A.: Sustainable development: Concepts and methods for its application in urban and environmental planning. Studies in Computational Intelligence **348**, 1–15 (2011). https://doi.org/10.1007/978-3-642-19733-8_1/COVER
18. Santopietro, L., Scorza, F.: Voluntary planning and city networks: a systematic bibliometric review addressing current issues for sustainable and climate-responsive planning. Sustainability **16** (2024). https://doi.org/10.3390/su16198655
19. Sica, F., Tajani, F., Cerullo, G.: An evaluation model for an optimal decarbonisation process in the built environment. Built Environment Project and Asset Management **15**, 51–66 (2024). https://doi.org/10.1108/BEPAM-05-2024-0126
20. Tajani, F., Bologna, A., Cerullo, G., Doko, E., Sica, F.: Upcycling strategies for resilience reconstruction goals: a case study of an italian public building. Buildings **15** (2025). https://doi.org/10.3390/buildings15203683
21. Pilogallo, A., Scorza, F.: Mapping regulation ecosystem services specialization in Italy. J. Urban Plan. Dev. **148** (2022). https://doi.org/10.1061/(ASCE)UP.1943-5444.0000801
22. Scorza, F., Santopietro, L., Giuzio, B., Amato, F., Murgante, B., Casas, G.: Las: conflicts between environmental protection and energy regeneration of the historic heritage in the case of the city of matera: Tools for assessing and dimensioning of sustainable energy action plans (SEAP). In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), pp. 527–539 (2017). https://doi.org/10.1007/978-3-319-62407-5_37
23. Santopietro, L., Solimene, S., Lucchese, M., Di Carlo, F., Scorza, F.: An economic appraisal of the SE(C)AP public interventions towards the EU 2050 target: the case study of Basilicata region. Cities **149** (2024). https://doi.org/10.1016/j.cities.2024.104957
24. Gatto, R.V., Scorza, F.: "Anti-gravity tourism planning": an analytical approach to manage tourism congestion, seasonality and overtourism. Urban Science **9** (2025). https://doi.org/10.3390/urbansci9120524
25. Gatto, R., Santopietro, L., Scorza, F.: Roghudi: developing knowledge of the places in an abandoned inland municipality. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). 13382 LNCS, pp. 48–53 (2022). https://doi.org/10.1007/978-3-031-10592-0_5/COVER
26. Del P. Pablo-Romero, M., Molina, J.A.: Tourism and economic growth: a review of empirical literature. Tour. Manag. Perspect **8**, 28–41 (2013). https://doi.org/10.1016/j.tmp.2013.05.006

27. Gatto, R.V., Scorza, F.: Sustainable tourism ecosystem balancing territorial values: a place-based perspective. In: International Conference on Computational Science and Its Applications. pp. 90–103. Springer Nature Switzerland Cham (2023)
28. Gatto, R.V., Corrado, S., Scorza, F.: A taxonomy of specialized tourism ecosystems (STESY): toward new geographies for sustainable territorial planning. International Journal of E-Planning Research (2025)
29. Anselin, L., Syabri, I., Kho, Y.: GeoDa: an introduction to spatial data analysis. Geogr. Anal. **38**, 5–22 (2006). https://doi.org/10.1111/j.0016-7363.2005.00671.x
30. Humaira, H., Rasyidah, R.: Determining The Appropiate Cluster Number Using Elbow Method for K-Means Algorithm. Presented at the March 3 (2020). https://doi.org/10.4108/eai.24-1-2018.2292388
31. Lagonigro, D., et al.: Downscaling NUA: Matera New Urban Structure (2023)
32. UNhabitat: The New Urban Agenda (2016). https://doi.org/10.18356/4665f6fb-en
33. Gatto, R.V.: Planning for sustainable tourism in protected areas. a policy-oriented spatial evaluation framework . . TeMA - Journal of Land Use, Mobility and Environment **19**, 171–188 (2026)
34. Scorza, F., Fortunato, G., Carbone, R., Murgante, B., Pontrandolfi, P.: Increasing urban walkability through citizens' participation processes. Sustainability (Switzerland) **13**, (2021). https://doi.org/10.3390/su13115835
35. Manganelli, B., Murgante, B., Saganeiti, L.: The social cost of urban sprinkling. Sustainability (Switzerland) **12** (2020). https://doi.org/10.3390/su12062236
36. Molaei Qelichi, M., Murgante, B., Yousefi Feshki, M., Zarghamfard, M.: Urbanization patterns in Iran visualized through spatial auto-correlation analysis. Spat. Inf. Res. **25**, 627–633 (2017). https://doi.org/10.1007/s41324-017-0128-0
37. Hendawy, E., et al.: The prediction and assessment of the impacts of soil sealing on agricultural land in the North Nile Delta (Egypt) using satellite data and GIS modeling. Sustainability (Switzerland) **11** (2019). https://doi.org/10.3390/su11174662
38. Murgante, B., Borruso, G.: Cities and smartness: a critical analysis of opportunities and risks. In: Murgante, B., et al. (eds.) Computational Science and Its Applications – ICCSA 2013, pp. 630–642. Springer, Berlin Heidelberg, Berlin, Heidelberg (2013)
39. Murgante, B., Tilio, L., Lanza, V., Scorza, F.: Using participative GIS and e-tools for involving citizens of Marmo Platano-Melandro area in European programming activities. J. Balkan Near East Stud. **13**, 97–115 (2011). https://doi.org/10.1080/19448953.2011.550809
40. Murgante, B., Borruso, G., Balletto, G., Castiglia, P., Dettori, M.: Why Italy first? Health, geographical and planning aspects of the COVID-19 outbreak. Sustainability (Switzerland) **12** (2020). https://doi.org/10.3390/su12125064
41. Gatto, R.V., Corrado, S., Scorza, F.: Specialized Tourism Ecosystem Workshop Report. University of Basilicata (2026). https://doi.org/10.5281/zenodo.18347608.
42. Annunziata, A., et al.: Climate actions handbook supporting decision making for regional adaptation strategies in Basilicata, Italy. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Lago, M.N.F., Scorza, F., Braga, A. (eds.) 25th International Conference on Computational Science and Its Applications (ICCSA 2025). Springer Nature Switzerland AG, Istanbul, Türkiye (2025)
43. Gatto, R.V., Dale, M.M., Noennig, J.R.: Exploration of a disaster risk management method for tourism destinations: the case of guatemala. In: Procedia Computer Science, pp. 2047–2056. Elsevier B.V. (2025). https://doi.org/10.1016/j.procs.2025.09.325
44. Tullipani, E.M.P., Gatto, R.V., Scorza, F.: "Croatia 365": A STESY based strategy for tourism destagionalization. In: Lecture Notes in Computer Science. pp. 212–222. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97651-3_15

45. Cascione, F., Musano, A., Pizzolla, P., Salvia, F., Gatto, R.V., Scorza, F.: “NATURE as the Way Mobility and Well-Being”: STESY Based Sustainable Tourism Development Strategy in Belgium. In: Lecture Notes in Computer Science, pp. 234–244. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97651-3_17
46. Gatto, R.V., Andrulli, G., Perrone, F., Corrado, S., Cerra, E., Scorza, F.: Enhancing vulture’s territorial assets through tourism ecosystems for spatial development. In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), pp. 285–292. Springer Science and Business Media Deutschland GmbH (2024). https://doi.org/10.1007/978-3-031-65318-6_19
47. Randò, L., Scavone, M., Tarantino, S., Gatto, R.V., Scorza, F.: “A journey between sky and sea”: investigating tourism ecosystem in Madeira. In: Lecture Notes in Computer Science. pp. 223–233. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97651-3_16
48. Elhabchi, I., Piliero, A., Gatto, R.V., Scorza, F.: “Sherry triangle”, investigating tourism ecosystem in Andalusia (ES). In: Lecture Notes in Computer Science, pp. 16–26. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97589-9_2
49. Pappalardi, V., Nolè, R., Gatto, R.V., Scorza, F.: A dismissed train line as a new pillar for sustainable tourism development in corsica: “the maquis way” strategy. In: Lecture Notes in Computer Science, pp. 40–49. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97589-9_4
50. Scorza, F., et al.: Training for territorial sustainable development design in basilicata remote areas: GEODESIGN workshop. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). 13379 LNCS, pp. 242–252 (2022). https://doi.org/10.1007/978-3-031-10545-6_17/COVER
51. Rizzi, F., et al.: Development of impact model in climate adaptation strategy design: the case study of Basilicata Region, Italy. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Lago, M.N.F., Scorza, F., Braga, A. (eds.) 25th International Conference on Computational Science and Its Applications (ICCSA 2025). Springer Nature Switzerland AG, Istanbul, Türkiye (2025)
52. Iula, G., et al.: Paving the way to basilicata climate adaptation strategy: a geodesign workshop. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Lago, M.N.F., Scorza, F., Braga, A. (eds.) 25th International Conference on Computational Science and Its Applications (ICCSA 2025). Springer Nature Switzerland AG, Istanbul, Türkiye (2025)

# Rebalancing Tourism Flows in Kotor, Montenegro: Application of STESY Framework for Transitioning from Cruise-Based Pressure to Extended Stay

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**Abstract.** Kotor, Montenegro, represents a highly sensitive tourism destination where cruise-based visitation, spatial concentration of flows, and extremely short average stays generate significant territorial imbalances. Despite its unique integration of coastal landscapes and mountainous environments, tourism demand remains largely confined to the historic core and port area. This study applies STESY framework in order to support the transition from a high-pressure, short-stay tourism model toward a more balanced and sustainable system based on extended stays. The methodology integrates territorial analysis, spatial mapping of attractors, services, and reachability, cluster-based classification, and the interpretation of indicators, including the Balanced Tourism Supply Index (BTSI), Attraction Potential Index (API), and Diversity Reachability Index (DRI). The results highlight a structural mismatch between tourism potential and actual demand distribution, revealing the under-exploitation of inland areas and the saturation of coastal zones. Based on these findings, the study proposes a multi-scalar intervention strategy combining soft measures, such as an integrated guest card system, with hard infrastructural actions structured around a network of thematic hubs. The proposed framework contributes to the development of replicable, policy-oriented approaches for sustainable tourism planning in complex coastal–mountain heritage destinations.

**Keyword:** Sustainable tourism planning · spatial analysis · cluster analysis

## 1 Introduction

Sustainable tourism becomes more and more a core argument in territorial development debate defining local multi-stakeholders' perspectives and global framework for innovation and better management of such complex phenomena [1, 2]. Today tourism is

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recognized as a dominant driver of economic growth in coastal and heritage destinations, yet its rapid expansion has also generated critical spatial and temporal imbalances [3]. In the perspective of the authors, tourism opens to relevant debate in urban and regional planning research as the decision making process connected with tourism management represent a comprehensive framework in which sustainable urban regeneration and transformation, landscape protection actions, economic development issues interacts generating an effective environment to apply sustainable urban development principles, methods and agendas for short term and strategic territorial design [4–8]. Those applications are also oriented to improve the competences of students in academic curricula dealing with territorial design professionals, and this paper comes as a result of a studio in architectural classes following the research tradition [9–14] of sustainable urban planning and design at UNIBAS [15–18].

Tourism as a spatial phenomenon is a multidisciplinary domain where spatial dimension represents a robust analytical dimension for managing information and designs, applying collaborative approach for strategic planning [19–25].

Destinations endowed with a strong cultural identity and environmental vulnerability are subject to intense visitor fluxes, seasonalities, and types of tourist consumption that create minimal value for the local economy [26]. Cruise tourism is a typical example of such a scenario, as it involves intense visitation over limited periods, without significantly benefiting the local economy. Such processes are especially pronounced in destinations with a heterogeneous distribution of accessibility, attractiveness, and services.

In such destinations, tourism demand tends to concentrate in highly iconic areas [24], leaving peripheral or inland zones under-exploited despite their potential.

This imbalance results in environmental pressure, infrastructural overload, and reduced quality of life for residents, while limiting opportunities for more sustainable and diversified tourism development [27].

Kotor, Montenegro, represents a paradigmatic case of this condition. Its geographical configuration, characterized by the coexistence of coastal and mountainous systems, combined with its UNESCO-listed historic center, has positioned the destination as a major node in Mediterranean cruise tourism itineraries.

However, the predominance of short-stay and cruise-based tourism has led to a strong spatial congestion of visitors around the historic urban area and port area, generating significant overtourism and limiting the effective development of the broader territorial system.

This paper aims to develop a spatially informed planning framework capable of supporting the transition from a short-duration, high-pressure tourism model toward a more balanced system based on extended stays and territorial redistribution. The study proposes an integrated methodological approach combining spatial analysis, cluster-based interpretation, and policy-oriented design strategies in compliance with NUA principles. The contribution lies in bridging analytical diagnosis and operational planning within a coherent framework transferable to similar tourism destinations.

## 2 Study Area

This study examines the municipality of Kotor, which lies in the Bay of Kotor, or Boka Kotorska, in Montenegro. It's quite a unique part of the Mediterranean, known for a striking contrast in its landscape. On one hand, there are rugged coastal areas, and on the other, towering mountain ranges. Even though the area isn't very large, it brings together steep limestone mountains that rise over 2,000 m alongside deeply indented coastline stretching along the Adriatic Sea.

The old town of Kotor with its Venetian fortifications and walls dating back hundreds of years has been recognized as a UNESCO World Heritage Site since 1979. The cultural monument represents a significant part of tourist demand, especially for cruise tourism. The town's layout is adapted to the surrounding mountains with a long, linear arrangement along the shoreline and a high concentration of activities across a small area.

Recently, Kotor has emerged as a new Mediterranean tourism destination, but it has become highly dependent on cruise tourism due to the massive seasonal inflows of cruise ships arriving Kotor in the summer months. The length of stay of visitors is predominantly low as a result of a predominance of day-trip visitors coupled with a lack of overnight tourism (Fig. 1).

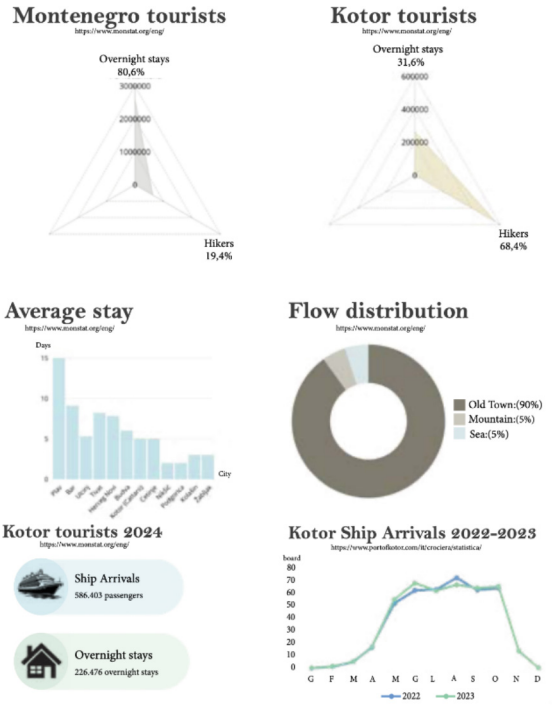



**Fig. 1.** Comparative overview of tourism dynamics in Kotor and Montenegro.

The figure synthesizes key tourism indicators, including the distribution of tourist activities, average length of stay, spatial concentration of visitor flows, annual tourist volumes, and cruise ship arrivals.

## 3 Territorial Analysis

The approach adopted in this study is based on the STESY framework [28] conceived as an integrated analytical and interpretative tool for the identification of territorial imbalances and the support of evidence-based planning strategies.

The first phase consists of a contextual analysis of the study area, focusing on the identification and classification of key georeferenced components (PoIs) of the tourism system, including attractors, services, and reachability (Fig. 2). Attractors are grouped into cultural, architectural, and natural, while services are examined on the basis of lodging, food, and visitor assistance. Reachability is analyzed with respect to the existence and integration of transport systems.

The second phase involves the spatial interpretation of these components through a cluster-based approach in order to identifying the Destination Areas of the tourism system in the case study. The territorial system is divided into homogeneous clusters using GeoDA software [29] aimed at identifying distinct spatial patterns. The optimal number of clusters is determined through the application of the Elbow Method [30], ensuring a balance between analytical detail and interpretative clarity (Fig. 3).

To quantify the characteristics of each cluster, three composite indicators are employed (Fig. 4). The Balanced Tourism Supply Index (BTSI) measures the relationship between accommodation capacity and consumption services, distinguishing between overnight-oriented and day-trip-oriented areas. The Attraction Potential Index (API) evaluates the strength of attractors based on their relevance and scale, while the Diversity Reachability Index (DRI) assesses accessibility and intramodality within the transport system.

Cluster 1 emerges as the core of the tourism system, combining the highest accommodation capacity (325 units) with a strong integration between cultural assets and food-related services. Although the cluster records the highest attractiveness and quality values across the entire analysis (API 3744; DRI 0.86), a marked imbalance persists between its accommodation capacity and the actual patterns of visitor interests. Despite a BTSI value that would suggest a vocation for longer overnight stays, the area appears structurally saturated due to the predominance of cruise passengers. This form of short-duration tourism places excessive pressure on urban infrastructure and limits the effective use of the accommodation and hospitality services already available.

A similar dynamic can be observed in Cluster 3, where the cultural and landscape components, together accounting for more than 59% of the local tourism offer, are not matched by an equally developed accommodation sector, which remains marginal at 10.7%. Here too, the strong influence of cruise tourism turns what could function as a stay-oriented destination into an area largely dominated by day visitors. As a result, the cluster maintains a relatively low API value (2487), while the tourism offer remains mostly confined to a local and short-term dimension.

By contrast, Cluster 2 is characterised by a profile strongly oriented toward mobility, with a very high share of land-based transport infrastructure, including rail and bus

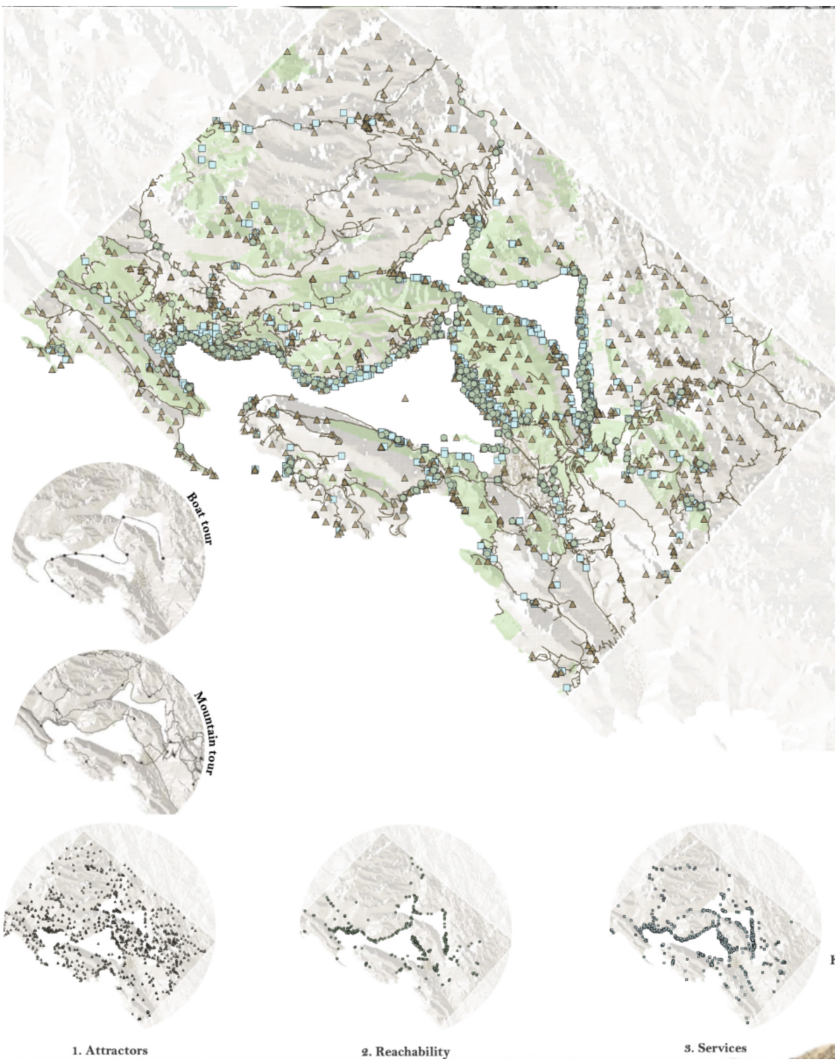



**Fig. 2.** Distribution of Attractors, services and reachability in Kotor.

services (31.1%), alongside a relevant cultural tourism component. While the cluster still shows high attractiveness (API 3181) and a relatively good demand response (DRI 0.71), it appears to be in a transitional phase. Its BTSI value of 0.90 confirms its current role as an excursion-based destination, where visitors tend to consume the tourism offer within a single day, without generating a stable impact on the accommodation sector. This suggests that the average length of stay has not yet been effectively consolidated.

Cluster 4 shows the characteristics of a more balanced area, where cultural and landscape tourism are distributed more evenly and supported by a relatively good degree of transport intermodality. Although this cluster records the lowest market performance

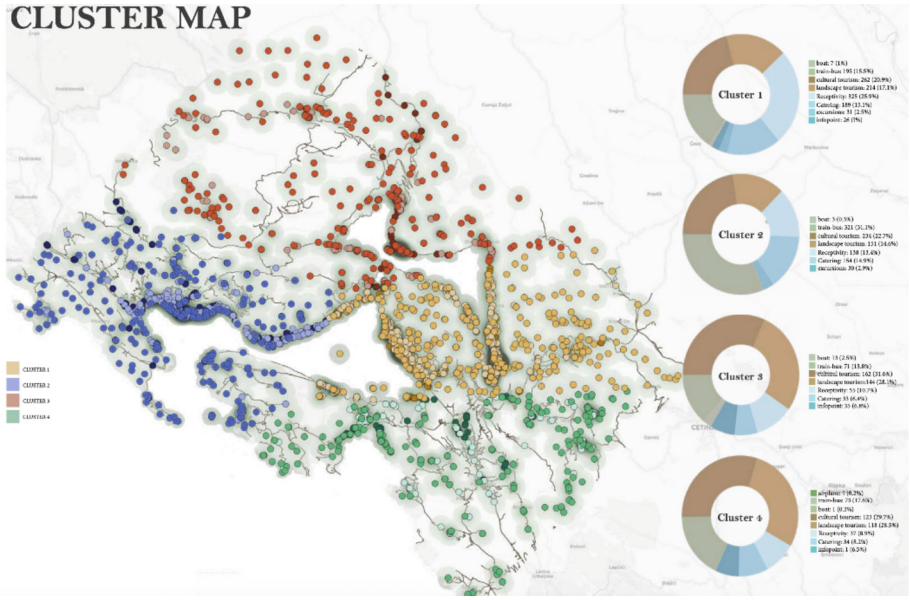



**Fig. 3.** Clusters identified of Attractors, services and reachability.

indicators in the dataset (API 1937), it appears to be structurally more stable. The relationship between accommodation and food services is more balanced, allowing for a more coherent and manageable orientation toward overnight tourism.

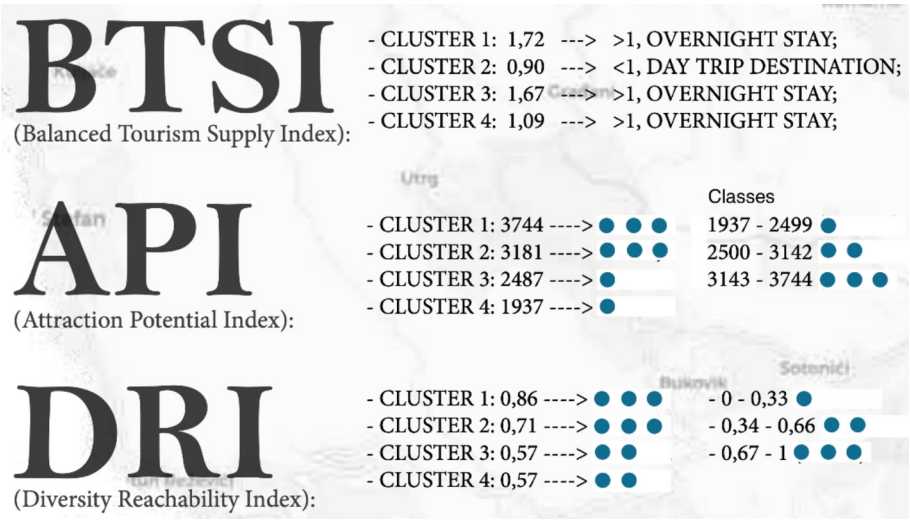


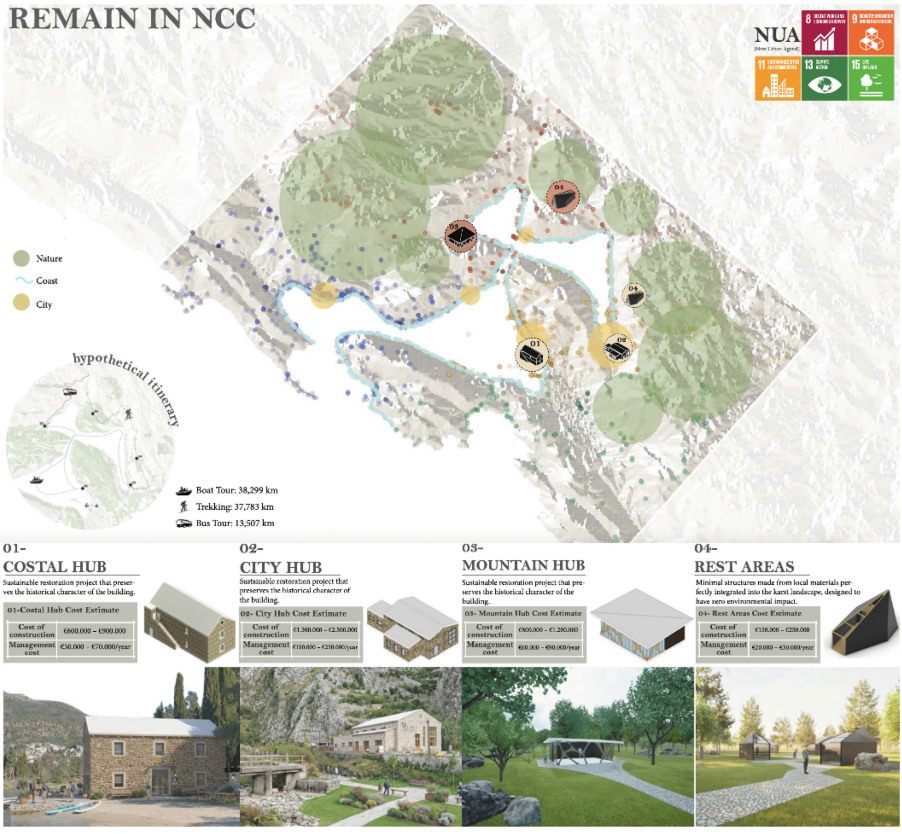

**Fig. 4.** Indicators applied to each Cluster (Destination Area).

Overall, the results highlight the coexistence of over-concentrated and underutilized areas within the same territorial system, emphasizing the need for integrated planning strategies capable of addressing these imbalances.

## 4 Discussion and Planning Strategy

The findings of the analysis support the development of a multi-scalar planning strategy aimed at transforming the existing tourism system. The downscaling of NUA [31, 32]compliance assessment supports the definition of spatial strategies aimed at rebalancing tourism flows and enhancing the sustainability of the territorial system. The proposed approach is based on the combination of soft measures and hard interventions, designed to influence both visitor behavior and spatial organization.

Hard interventions are structured around the development of a network of thematic hubs distributed across the territory. These hubs function as strategic nodes connecting coastal, urban, and mountain environments, facilitating the integration of different components of the tourism system. Each hub is designed to enhance specific territorial functions, including mobility management, cultural experience, and access to natural areas.



Soft measures focus on the introduction of incentive-based mechanisms to encourage longer stays and more balanced spatial distribution of visitors. In this context, the implementation of an integrated guest card system represents a key tool. By linking access to mobility services and tourism experiences to a minimum length of stay, the system aims to transform short-term visitors into overnight tourists while promoting the exploration of less frequented areas (Fig. 5).

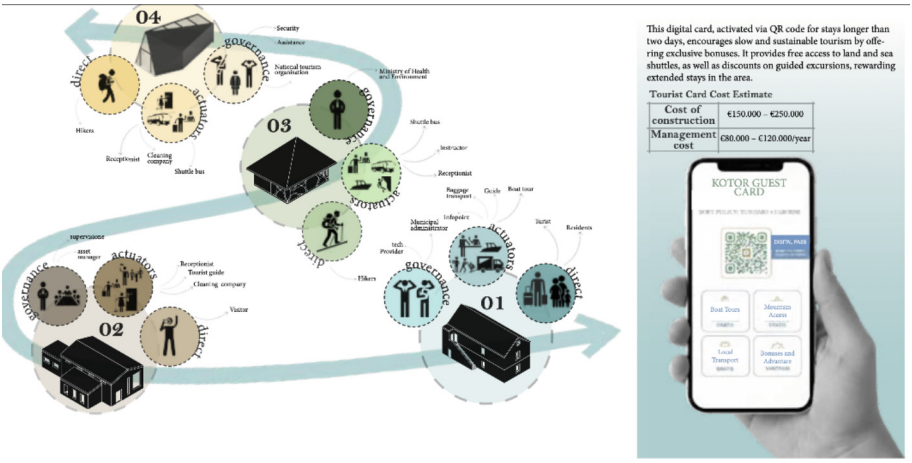



**Fig. 5.** Guest card system

The combined effect of these measures is expected to generate a significant transformation of the tourism system. The average length of stay is projected to increase substantially, while visitor flows are redistributed from highly congested areas toward peripheral zones. This shift supports the extension of the tourism season and the creation of a more resilient and diversified local economy.

## 5 Conclusions

This study has developed a spatially informed planning framework for addressing tourism imbalances in complex coastal–mountain destinations, using Kotor as a representative case. The integration of territorial analysis, cluster-based interpretation, and composite indicators has enabled the identification of structural mismatches between tourism potential and actual demand distribution [33–36].

The proposed strategy demonstrates how the combination of soft and hard measures can support the transition from a short-stay, high-pressure tourism model toward a more balanced system based on extended stays and territorial redistribution. By enhancing the role of underutilized areas and improving the integration of mobility, services, and attractors, the framework contributes to the development of more sustainable and resilient tourism systems.

The approach is designed to be replicable and adaptable to other destinations facing similar challenges, offering a practical contribution to the field of sustainable tourism planning and territorial governance.

The whole application is structured on the STESY framework [28, 37, 38]: a robust spatial analytical framework driving from the early stages the strategic design in sustainable tourism for a specific destination area. The framework had been applied in a number of local studies selected among major destinations (i.e. EU Capitals, UNESCO Sites, Environmental global attractors etc.) [39, 40], minor inland tourism areas (i.e. Vulture, Pollino national Park) [41, 42] and niche tourism sites (i.e. Islands) [43–45].

In this paper the main limitation comes from the lack of discussion with local stakeholders. In facts the research was fully development on desk and remotely. It is also relevant to point out how the STESY method effectively supported the process providing a guide to students to start with effective local analysis, to perform meaningful spatial interpretation of a complex phenomenon, to identify design options/solution for a strategic proposal compliant with NUA international principles.

The indicator dashboard included in the STESY platform allows to compare this application with other case study in a significant and effective way, supporting the decision-making process in identifying intervention priority to better plan tourism sector locally benefitting of multi scale assessment options and accountability management of global objective for sustainable and climate responsive design [46–48].

## References


1. Williams, A.M., Shaw, G.: Internationalization and innovation in tourism. Ann. Tour. Res. **38**, 27–51 (2011). https://doi.org/10.1016/j.annals.2010.09.006
2. Lenzen, M., Sun, Y.-Y., Faturay, F., Ting, Y.-P., Geschke, A., Malik, A.: The carbon footprint of global tourism. Nat. Clim. Chang. **8**, 522–528 (2018). https://doi.org/10.1038/s41558-018-0141-x
3. Stojčić, N., Mikulić, J., Vizek, M.: High season, low growth: the impact of tourism seasonality and vulnerability to tourism on the emergence of high-growth firms. Tour. Manag. **89**, 104455 (2022). https://doi.org/10.1016/j.tourman.2021.104455
4. UN HABITAT: New Urban Agenda. United Nations (2016)
5. Las Casas, G., Scorza, F., Murgante, B.: New urban agenda and open challenges for urban and regional planning. In: Calabrò, F., Della Spina, L., Bevilacqua, C. (eds.) New Metropolitan Perspectives. ISHT 2018, pp. 282–288. Springer, Cham (2019). https://doi.org/10.1007/978-3-319-92099-3_33
6. Morphet, J., Morphet, R.: New Urban Agenda: New Urban Analytics: A Report Prepared for the MacArthur Foundation (2019)
7. Tajani, F., Manganelli, B., Cerullo, G., Morano, P., Morente, M.A.: The student housing as a catalyst for virtuous processes of "win-win" revitalization of property assets in disuse. In: Gervasi, O., Murgante, B., Rocha, A.M.A.C., Garau, C., Scorza, F., Karaca, Y., Torre, C.M. (eds.) Computational Science and Its Applications – ICCSA 2023 Workshops, pp. 387–400. Springer Nature Switzerland, Cham (2023)
8. Tajani, F., Cerullo, G., Stara, F., Sica, F.: Multidimensional Models for Building Decarbonization Pathways. Bus. Strategy Environ. n/a (2025). https://doi.org/10.1002/bse.70455
9. Lagonigro, D., et al.: Downscaling NUA: matera new urban structure. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)

10. Scorza, F., Gatto, R.V.: Identifying territorial values for tourism development: the case study of Calabrian Greek Area. Sustainability 2023, **15**, 5501 (2023). https://doi.org/10.3390/SU15065501
11. Lacerenza, A., et al.: "Back to the villages": design sustainable development scenarios for in-land areas. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
12. Capodiferro, M., et al.: "University equity": students' facilities in major tourism destination towns. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023 (2023)
13. Florio, E., et al.: SuperABLE: matera accessible for all. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
14. Esposito Loscavo, B., et al.: Innovation ecosystem: the added value in a unique UNESCO city. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
15. Casas, G.L., Scorza, F.: Sustainable planning: a methodological toolkit. In: Gervasi, O., et al. (eds.) ICCSA 2016. LNCS, vol. 9786, pp. 627–635. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-42085-1_53
16. Gatto, R.V., Corrado, S., Scorza, F.: Taxonomy for specialized Tourism Ecosystems : new geographies for sustainable territorial planning. Habitat Int. (2025)
17. Murgante, B., Borruso, G., Lapucci, A.: Sustainable development: concepts and methods for its application in urban and environmental planning. Studies in Computational Intelligence **348**, 1–15 (2011). https://doi.org/10.1007/978-3-642-19733-8_1/COVER
18. Santopietro, L., Scorza, F.: Voluntary planning and city networks: a systematic bibliometric review addressing current issues for sustainable and climate-responsive planning. Sustainability **16** (2024). https://doi.org/10.3390/su16198655
19. Sica, F., Tajani, F., Cerullo, G.: An evaluation model for an optimal decarbonisation process in the built environment. Built Environment Project and Asset Manage. **15**, 51–66 (2024). https://doi.org/10.1108/BEPAM-05-2024-0126
20. Tajani, F., Bologna, A., Cerullo, G., Doko, E., Sica, F.: Upcycling strategies for resilience reconstruction goals: a case study of an italian public building. Buildings **15** (2025). https://doi.org/10.3390/buildings15203683
21. Pilogallo, A., Scorza, F.: Mapping regulation ecosystem services specialization in Italy. J. Urban Plan. Dev. **148** (2022). https://doi.org/10.1061/(ASCE)UP.1943-5444.0000801
22. Scorza, F., Santopietro, L., Giuzio, B., Amato, F., Murgante, B., Casas, G. Las: Conflicts between environmental protection and energy regeneration of the historic heritage in the case of the city of matera: Tools for assessing and dimensioning of sustainable energy action plans (SEAP). In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), pp. 527–539 (2017). https://doi.org/10.1007/978-3-319-62407-5_37
23. Santopietro, L., Solimene, S., Lucchese, M., Di Carlo, F., Scorza, F.: An economic appraisal of the SE(C)AP public interventions towards the EU 2050 target: the case study of Basilicata region. Cities. **149** (2024). https://doi.org/10.1016/j.cities.2024.104957
24. Gatto, R.V., Scorza, F.: "Anti-gravity tourism planning": an analytical approach to manage tourism congestion, seasonality and overtourism. Urban Science **9** (2025). https://doi.org/10.3390/urbansci9120524
25. Gatto, R., Santopietro, L., Scorza, F.: Roghudi: developing knowledge of the places in an abandoned inland municipality. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). 13382 LNCS, pp. 48–53 (2022). https://doi.org/10.1007/978-3-031-10592-0_5/COVER
26. Del P. Pablo-Romero, M., Molina, J.A.: Tourism and economic growth: a review of empirical literature. Tour. Manag. Perspect **8**, 28–41 (2013). https://doi.org/10.1016/j.tmp.2013.05.006

27. Gatto, R.V., Scorza, F.: Sustainable tourism ecosystem balancing territorial values: a place-based perspective. In: International Conference on Computational Science and Its Applications, pp. 90–103. Springer Nature Switzerland Cham (2023)
28. Gatto, R.V., Corrado, S., Scorza, F.: A taxonomy of specialized tourism ecosystems (STESY): toward new geographies for sustainable territorial planning. International Journal of E-Planning Research (2025)
29. Anselin, L., Syabri, I., Kho, Y.: GeoDa: an introduction to spatial data analysis. Geogr. Anal. **38**, 5–22 (2006). https://doi.org/10.1111/j.0016-7363.2005.00671.x
30. Humaira, H., Rasyidah, R.: Determining The Appropiate Cluster Number Using Elbow Method for K-Means Algorithm. Presented at the March 3 (2020). https://doi.org/10.4108/eai.24-1-2018.2292388
31. Lagonigro, D., et al.: Downscaling NUA: Matera New Urban Structure (2023)
32. UNhabitat: The New Urban Agenda (2016). https://doi.org/10.18356/4665f6fb-en
33. Gatto, R.V.: Planning for sustainable tourism in protected areas. a policy-oriented spatial evaluation framework . . TeMA - Journal of Land Use, Mobility and Environment **19**, 171–188 (2026)
34. Scorza, F., Fortunato, G., Carbone, R., Murgante, B., Pontrandolfi, P.: Increasing urban walkability through citizens' participation processes. Sustainability (Switzerland) **13** (2021). https://doi.org/10.3390/su13115835
35. Murgante, B., Borruso, G.: Cities and smartness: a critical analysis of opportunities and risks. In: Murgante, B., et al. (eds.) Computational Science and Its Applications – ICCSA 2013, pp. 630–642. Springer, Berlin Heidelberg, Berlin, Heidelberg (2013)
36. Murgante, B., Tilio, L., Lanza, V., Scorza, F.: Using participative GIS and e-tools for involving citizens of Marmo Platano-Melandro area in European programming activities. J. Balkan Near East Stud. **13**, 97–115 (2011). https://doi.org/10.1080/19448953.2011.550809
37. Gatto, R.V., Corrado, S., Scorza, F.: Specialized Tourism Ecosystem Workshop Report. University of Basilicata (2026). https://doi.org/10.5281/zenodo.18347608.
38. Annunziata, A., et al.: Climate actions handbook supporting decision making for regional adaptation strategies in Basilicata, Italy. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Lago, M.N.F., Scorza, F., Braga, A. (eds.) 25th International Conference on Computational Science and Its Applications (ICCSA 2025). Springer Nature Switzerland AG, Istanbul, Türkiye (2025)
39. Gatto, R.V., Dale, M.M., Noennig, J.R.: Exploration of a disaster risk management method for tourism destinations: the case of Guatemala. In: Procedia Computer Science, pp. 2047–2056. Elsevier B.V. (2025). https://doi.org/10.1016/j.procs.2025.09.325
40. Tullipani, E.M.P., Gatto, R.V., Scorza, F.: "Croatia 365": a STESY based strategy for tourism destagionalization. In: Lecture Notes in Computer Science, pp. 212–222. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97651-3_15
41. Cascione, F., Musano, A., Pizzolla, P., Salvia, F., Gatto, R.V., Scorza, F.: "NATURE as the way mobility and well-being": STESY based sustainable tourism development strategy in belgium. In: Lecture Notes in Computer Science, pp. 234–244. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97651-3_17
42. Gatto, R.V., Andrulli, G., Perrone, F., Corrado, S., Cerra, E., Scorza, F.: Enhancing vulture's territorial assets through tourism ecosystems for spatial development. In: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), pp. 285–292. Springer Science and Business Media Deutschland GmbH (2024). https://doi.org/10.1007/978-3-031-65318-6_19
43. Randò, L., Scavone, M., Tarantino, S., Gatto, R.V., Scorza, F.: "A journey between sky and sea": investigating tourism ecosystem in madeira. In: Lecture Notes in Computer Science,

pp. 223–233. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97651-3_16
44. Elhabchi, I., Piliero, A., Gatto, R.V., Scorza, F.: “Sherry triangle”, investigating tourism ecosystem in Andalusia (ES). In: Lecture Notes in Computer Science, pp. 16–26. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97589-9_2
45. Pappalardi, V., Nolè, R., Gatto, R.V., Scorza, F.: A dismissed train line as a new pillar for sustainable tourism development in Corsica: “the maquis way” strategy. In: Lecture Notes in Computer Science, pp. 40–49. Springer Science and Business Media Deutschland GmbH (2026). https://doi.org/10.1007/978-3-031-97589-9_4
46. Scorza, F., et al.: Training for territorial sustainable development design in basilicata remote areas: GEODESIGN workshop. Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics). 13379 LNCS, pp. 242–252 (2022). https://doi.org/10.1007/978-3-031-10545-6_17/COVER
47. Rizzi, F., et al.: Development of impact model in climate adaptation strategy design: the case study of Basilicata Region, Italy. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Lago, M.N.F., Scorza, F., Braga, A. (eds.) 25th International Conference on Computational Science and Its Applications (ICCSA 2025). Springer Nature Switzerland AG, Istanbul, Türkiye (2025)
48. Iula, G., et al.: Paving the way to basilicata climate adaptation strategy: a geodesign workshop. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Lago, M.N.F., Scorza, F., Braga, A. (eds.) 25th International Conference on Computational Science and Its Applications (ICCSA 2025). Springer Nature Switzerland AG, Istanbul, Türkiye (2025)

# From Linear Accessibility to Distributed Territorial Activation: A STESY-Based Approach for the Lofoten Islands

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**Abstract.** The Lofoten Islands, Norway, represent a fragile Arctic tourism destination characterized by exceptional environmental attractiveness, strong cultural identity, and limited infrastructural capacity. The main challenge of the archipelago is the spatial fragmentation and uneven accessibility of its territorial components. Tourism demand is primarily structured along a linear infrastructural corridor defined by the main road, resulting in localized pressure phenomena and the underutilization of peripheral areas with high latent potential. This study applies the STESY framework in order to support the transition from a linear and infrastructure-dependent tourism model toward a more integrated and spatially distributed territorial system. The methodology combines territorial analysis, spatial mapping of attractors, services, and reachability, cluster-based classification, and the interpretation of composite indicators, including the Balanced Tourism Supply Index (BTSI), Attraction Potential Index (API), and Diversity Reachability Index (DRI). The results reveal a structural mismatch between attraction potential and effective accessibility, highlighting the coexistence of highly attractive but weakly connected clusters and more accessible but functionally saturated nodes. Based on these findings, the study proposes a multi-scalar strategy focused on multimodal accessibility, slow tourism infrastructures, and the activation of marginal territories. The proposed framework contributes to the development of policy-oriented approaches for sustainable tourism planning in fragile, low-density, and environmentally sensitive destinations.

**Keywords:** Sustainable tourism planning · spatial analysis · cluster analysis

## 1 Introduction

Sustainable tourism becomes more and more a core argument in territorial development debate defining local multi-stakeholders' perspectives and global framework for innovation and better management of such complex phenomena [1, 2]. Today tourism is

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recognized as a dominant driver of economic growth in coastal and heritage destinations, yet its rapid expansion has also generated critical spatial and temporal imbalances [3]. In the perspective of the authors, tourism opens to relevant debate in urban and regional planning research as the decision making process connected with tourism management represent a comprehensive framework in which sustainable urban regeneration and transformation, landscape protection actions, economic development issues interacts generating an effective environment to apply sustainable urban development principles, methods and agendas for short term and strategic territorial design [4–8]. Those applications are also oriented to improve the competences of students in academic curricula dealing with territorial design professionals, and this paper comes as a result of a studio in architectural classes following the research tradition [9–14] of sustainable urban planning and design at UNIBAS [15–18].

Tourism as a spatial phenomenon is a multidisciplinary domain where spatial dimension represents a robust analytical dimension for managing information and designs, applying collaborative approach for strategic planning [19–25].

It is possible that not all tourism pressure influenced all tourism locations the same way. Many sensitive locations experience pressure from tourism demand that is spatially focused and uneven [26].

For example, Areas with tourism pressure that has low connectivity and tourism offerings are not faced with other tourism location challenges, such as congestion, overtourism, and other tourism supply shortfalls [27].

A better understanding of demand concentration and offer supply tourism networks is needed to address the challenges faced by the spaced out weakly connected tourism locations. [28].

In emerging tourism destinations, such as the Lofoten islands in Northern Norway, the location is characterized by high scenic beauty. However, because of poor connectivity and weak infrastructure, demand is concentrated in specific tourism destinations which creates uneven distribution of tourism and stifles the development of the tourism potential in the less visited periphery.

The archipelago combines extraordinary landscape values, globally recognizable environmental identity, strong maritime heritage, and a deeply rooted fishing culture. Yet, the territorial organization of tourism is strongly conditioned by the morphology of the islands and by the dependence on a limited infrastructural backbone, primarily structured along the E10 road corridor.

The adoption of monitoring-oriented approaches remains relevant in order to detect temporary concentration patterns, support adaptive management over time, and inform strategic actions aimed at improving the visitor experience while better orienting the experience of territorial opportunities.

This paper aims to develop a spatially informed planning framework capable of supporting the transition from a short-duration, high-pressure tourism model toward a more balanced system based on extended stays and territorial redistribution. The study proposes an integrated methodological approach combining spatial analysis, cluster-based interpretation, and policy-oriented design strategies in compliance with NUA principles. The contribution lies in bridging analytical diagnosis and operational planning within a coherent framework transferable to similar tourism destinations.

## 2 Study Area

This research will be undertaken within the Lofoten archipelago region located within Northern Norway and above the Arctic circle. The group of islands constitutes an exceptionally unique island system covering an area of about 1,200 square kilometers, whose uniqueness is brought out by the striking interplay of sea and mountains where reliefs, fjords, narrow coastal plains, and exposed Atlantic coasts create a unique land morphology. Such an environment contributes greatly to the distinctive landscape of the archipelago and increases its international appeal to tourists. In addition, there are several unique natural occurrences in the region like the Northern lights in the winter months and the Midnight sun during the summer that add to the appeal of this destination.

The territorial identity of the Lofoten Islands has also been influenced by an important historical interaction between settlement, seafaring economic activity, and fishing. The history of human settlements in the islands goes back to prehistoric times, while the evolution of more organized territoriality was especially significant during the Viking Age and in the context of the cod fishing economy. This historical evolution resulted in the creation of a unique cultural landscape where production, settlement, and adaptation to the environment are strongly linked together. The rorbuer, traditional fishermen's cabins located on the coast, can be seen as some of the most representative elements of this cultural landscape.

The administrative structure of the islands consists of six municipalities, namely Vågan, Vestvågøy, Flakstad, Moskenes, Værøy, and Røst. These municipalities have very distinctive demographic and functional features. Vestvågøy and Vågan serve as the principal demographic centers of this archipelago, whereas the rest of the municipali-ties demonstrate low demographic density, growing marginalization, and poor infrastructural facilities. From the perspective of tourism, such demographic polarization within the archipelago has significant implications.

The evolution of tourism flows in the Lofoten Islands in relation to the broader regional context of Nordland and the national tourism system of Norway, focusing on the comparison between 2019 and 2023 (Fig. 1).

The data suggest a clear strengthening of the archipelago's role within both the regional and national tourism context. While the seasonal structure remains largely unchanged, with tourism demand concentrated during the summer months, the comparison between the two years highlights an overall increase in visitor volumes and a greater visibility of the Lofoten Islands within the tourism geography of Northern Norway.

In both years, tourism flows show a pronounced seasonal pattern, with a gradual increase from winter to summer followed by a decline during the autumn months. However, the 2023 data indicate a more consolidated tourism dynamic compared to the pre-pandemic baseline of 2019, confirming the growing attractiveness of the archipelago.

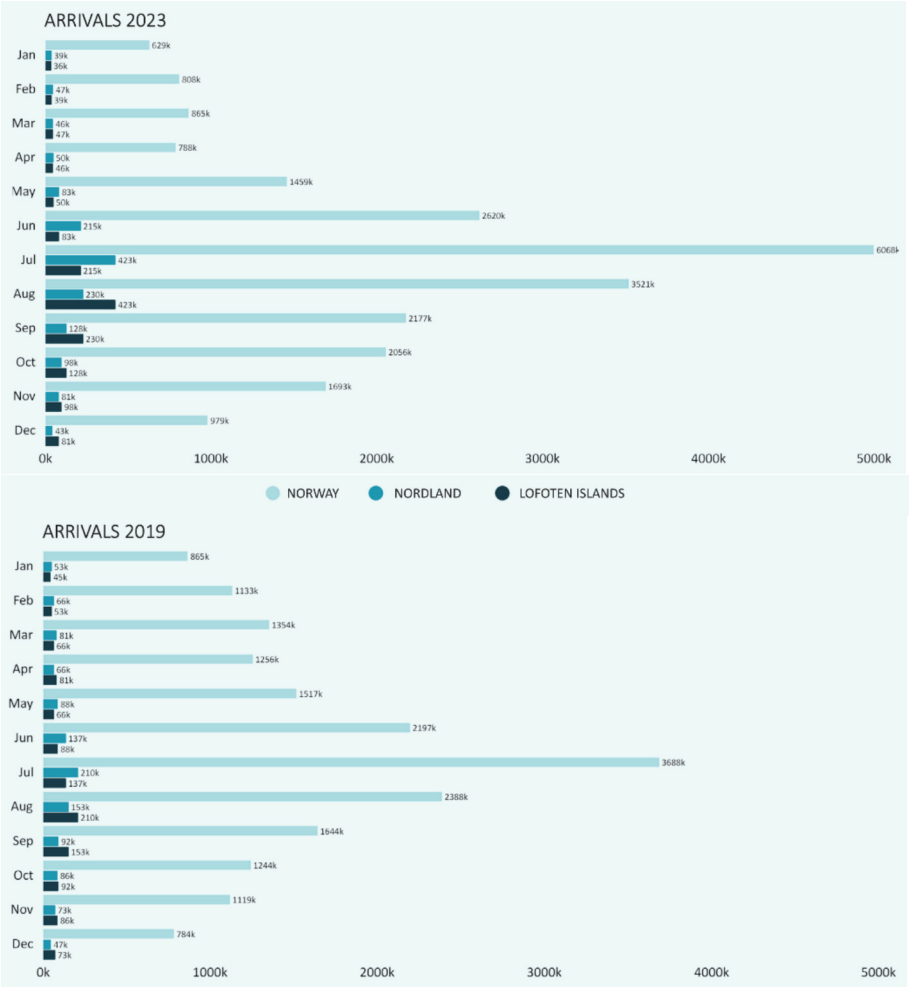


**Fig. 1.** Comparative overview of tourism dynamics in Norway, Norland and Lofoten Islands

## 3 Territorial Analysis

The approach adopted in this study is based on the STESY framework [29] conceived as an integrated analytical and interpretative tool for the identification of territorial imbalances and the support of evidence-based planning strategies.

The first phase consists of a contextual analysis of the study area, focusing on the identification and classification of key georeferenced components (PoIs) of the tourism system, including attractors, services, and reachability (Fig. 2). Attractors are categorized according to their cultural, historical, environmental, and landscape characteristics. The analysis reveals a territorial structure in which the environmental dimension clearly dominates the tourism ecosystem. A very large number of attractors are associated with outdoor and nature-based experiences, including trekking routes, viewpoints, cycling

itineraries, and panoramic landscapes. Alongside this environmental structure, the cultural dimension is articulated through museums, Viking-related heritage, fishing culture, churches, galleries, festivals, and traditional settlement patterns, all of which contribute to the narrative and symbolic depth of the tourism experience. Services are analyzed in relation to accommodation, food provision, logistics, and support functions for visitors. The results show a diversified but territorially uneven hospitality system, with a strong presence of motels, hotels, cafés, restaurants, parking areas, camping facilities, and a more limited provision of complementary services such as e-bike rental and visitor-oriented infrastructures. Reachability is evaluated through the presence and integration of transport infrastructures, including airports, ferry terminals, and bus stations. The analysis highlights the strategic importance of the maritime system and the E10 corridor as the main territorial backbone of the archipelago.

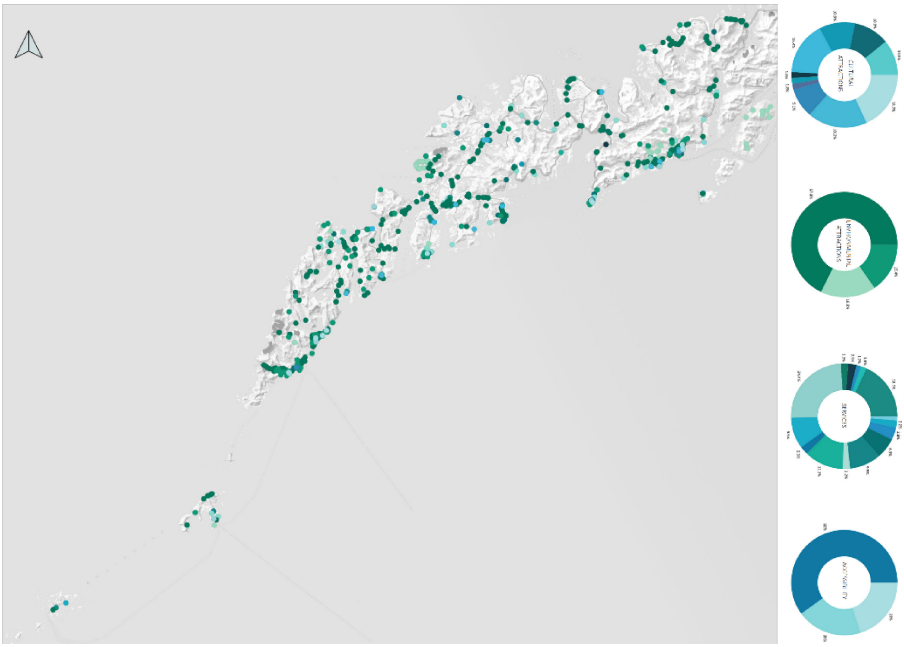

**Fig. 2.** Distribution of Attractors, services and reachability in Lofoten Islands.

The second phase involves the spatial interpretation of these components through a cluster-based approach in order to identifying the Destination Areas of the tourism system in the case study. The territorial system is divided into homogeneous clusters using GeoDA software [30] aimed at identifying distinct spatial patterns. The optimal number of clusters is determined through the application of the Elbow Method [31], ensuring a balance between analytical detail and interpretative clarity (Fig. 3).

The analysis identifies four clusters**,** corresponding to four Destination Areas characterized by different degrees of maturity, accessibility, tourism specialization, and infrastructural support.

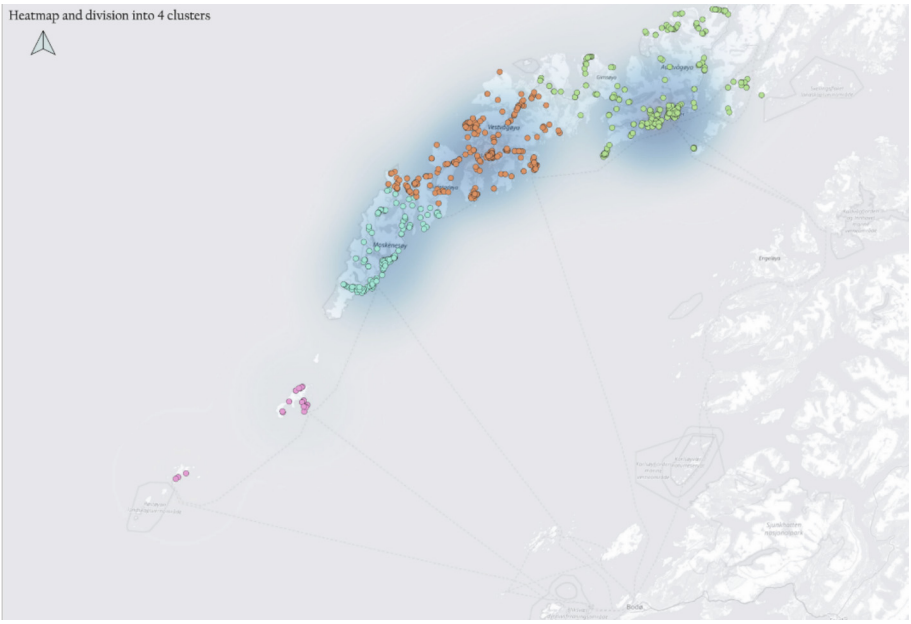


**Fig. 3.** Clusters of Attractors, services and reachability.

To quantify the characteristics of each cluster, three composite indicators are employed: the Balanced Tourism Supply Index (BTSI), the Attraction Potential Index (API), and the Diversity Reachability Index (DRI).

The Balanced Tourism Supply Index (BTSI) is used to evaluate the balance between the tourism accommodation system and the broader territorial support structure. The results reveal that the archipelago is generally configured for forms of extended stay rather than purely transient tourism, but internal differences between clusters remain significant. The first Destination Area shows a relatively balanced and consolidated structure, confirming its role as the principal support node of the system. The second cluster exhibits the lowest BTSI value, suggesting a more open and less saturated territorial condition, potentially suitable for quality-oriented development. The third Destination Area, by contrast, records the highest BTSI value, indicating a strong concentration of accommodation functions and a localized condition of structural pressure. The fourth cluster, although more peripheral and sparse, also presents a relatively high BTSI, revealing that tourism density can become significant even in marginal areas when infrastructural support is weak.

The Diversity Reachability Index (DRI) measures the capacity of each cluster to connect its different resources, identities, and functions through the accessibility system. This indicator reveals one of the most relevant criticalities of the Lofoten tourism system. The first Destination Area records a modest value, while the second cluster achieves the highest DRI, suggesting a stronger capacity for integrating different components of the territorial experience. However, both the third and fourth Destination Areas record a value equal to zero, indicating a condition of functional isolation and

poor systemic accessibility. This result is particularly important because it demonstrates that high tourism value and attraction potential are not necessarily supported by adequate reachability.

The Attraction Potential Index (API) evaluates the density and quality of attractors within each cluster. The first Destination Area records the highest API value, confirming its role as the principal generator of territorial image and tourism demand within the archipelago. The second cluster maintains a significant but more balanced attraction potential, indicating a more gradual and integrated form of territorial value. The third cluster also records a high API, but in this case the strong attractiveness appears to be in tension with environmental fragility and infrastructural limitations. The fourth Destination Area, although characterized by the lowest API, still presents a relevant identity value linked to marginality, remoteness, and selective experiential potential (Fig. 4).

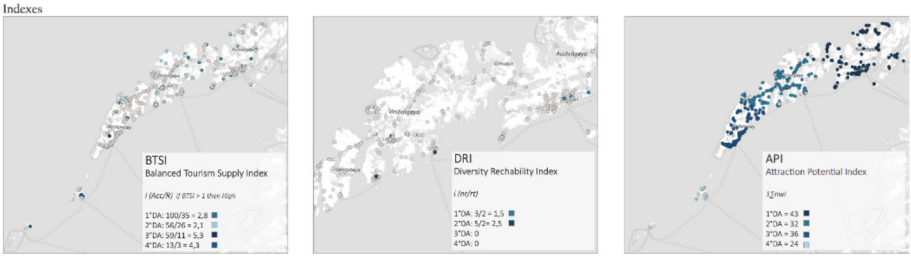


**Fig. 4.** Indicators applied to each Cluster (Destination Area).

The two identified clusters show the systemic versatility of the first and the potential landscape resilience of the second. The third shows the most critical situation, as tourism potential and attraction intensity are poorly supported infrastructurally and systemically. The fourth shows the most fragile and peripherally isolated conditions, needing soft systems to activate tourism density, but to enable selected system structures. The findings point to the necessity of planning for systems not aimed at minimizing tourism, but at integrating the system and improving distributed accessibility.

## 4 Discussion and Planning Strategy

The findings of the analysis support the development of a multi-scalar planning strategy aimed at strengthening territorial integration and enabling a more distributed and resilient tourism system. In this case, the objective is not to reduce tourism pressure in absolute terms, but to reconfigure the spatial logic of access and experience, improving the relationship between tourism demand, mobility systems, and territorial structure. The downscaling of New Urban Agenda (NUA) principles supports the definition of spatial strategies capable of addressing the structural weaknesses of the archipelago while preserving its environmental and cultural identity [32, 33].

The strategic proposal is developed under the project vision “Between Sky and Ocean”, conceived as a territorial framework for redefining the relationship between infrastructure, landscape, and tourism experience in the Lofoten Islands. In this perspective, reachability becomes not only a technical issue, but also a planning tool for territorial diversification and resilience.

The proposed planning strategy is structured around two main directions (Fig. 5).

The first concerns the strengthening of Destination Area 3, which currently functions as the terminal and most fragile segment of the E10 axis. The strategy proposes the introduction of an integrated public transport system capable of ensuring more continuous and distributed accessibility beyond the end of the primary road corridor. This intervention aims to reduce the dependency on private vehicles, improve the continuity of movement between settlements, and support both visitors and local communities through a more efficient and coherent territorial mobility structure.

This intervention is reinforced through the design of a Cultural and Environmental Route connecting Hamnøy and Å. The route is conceived as a slow tourism infrastructure integrating cultural heritage, landscape experience, and environmental accessibility. It links the traditional fishing villages, the rorbuer landscape, the cod-related heritage system, and the trekking infrastructure through a sequence of strategically located nodes. These nodes include arrival and departure hubs, scenic viewpoints, regulated camping points, visitor services, and environmental interpretation devices. The objective is to transform movement itself into a structured tourism experience while reducing the concentration of use on a few isolated hotspots.

The second strategic direction concerns the reconnection of Destination Area 4, the most peripheral and infrastructurally isolated component of the archipelago. In this case, the main issue is the territorial marginality and lack of accessibility. To address this condition, the strategy introduces a new system of maritime connections aimed at extending the infrastructural logic of the archipelago beyond the limits of the road network. A strategic ferry line from Svolvær is proposed to reconnect marginal settlements and integrate them more effectively into the broader territorial system. This intervention is further strengthened by the proposal of additional maritime links toward Bodø, allowing the peripheral islands to gain a more direct relationship with the regional accessibility network.

The proposal for Destination Area 4 is based on the selective enhancement of identity, accessibility, and experiential quality.

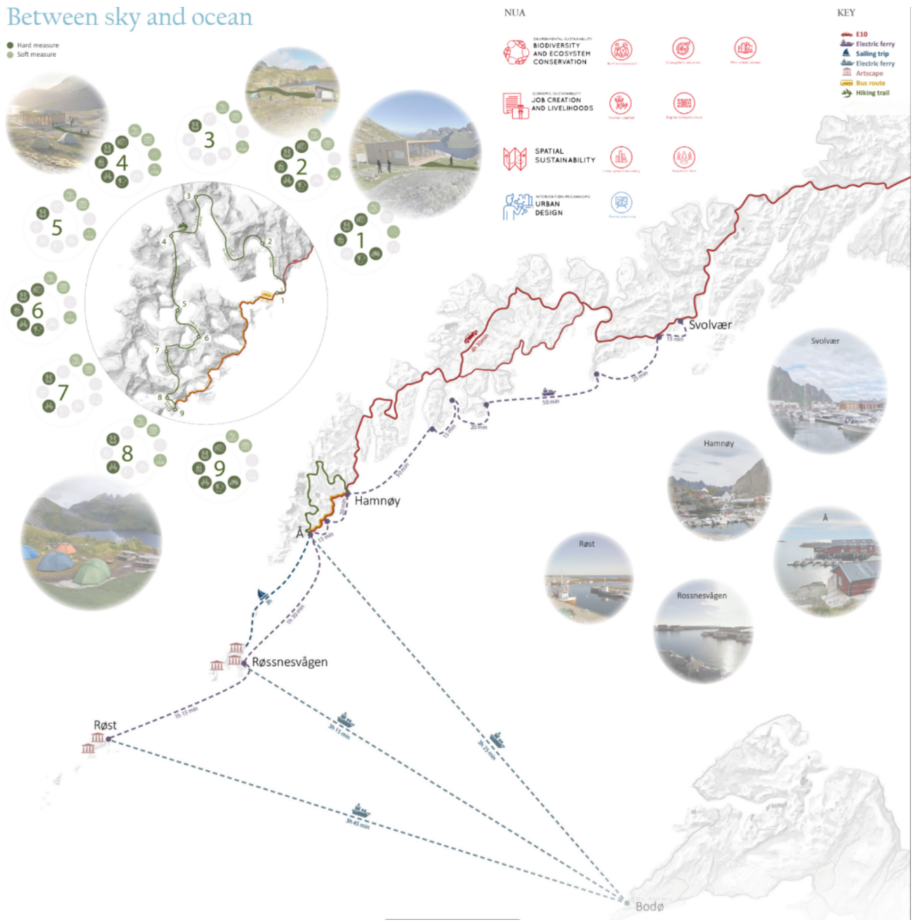


**Fig. 5.** Plan of interventions

## 5 Conclusions

Looking at regions differently, using clusters and blended measures revealed distinct patterns across the islands, showing that tourist activity depends less on attractions alone and more on how well transport, amenities, and local layouts connect. What stands out is how boosting various travel modes, building low-speed tourism facilities, while gently linking outer areas helps shift away from rigid, road-heavy tourism toward a looser yet unified land use setup. Instead of just spreading visitors around, the idea works by strengthening the islands' ability to manage visits through tighter area links, sturdier access routes, and matching visitor needs more closely with local character. The whole application is structured on the STESY framework [29, 34, 35]: a robust spatial analytical framework driving from the early stages the strategic design in sustainable tourism for a specific destination area. The framework had been applied in a number of local studies selected among major destinations (i.e. EU Capitals, UNESCO Sites, Environmental

global attractors etc.) [36, 37], minor inland tourism areas (i.e. Vulture, Pollino national Park) [38, 39] and niche tourism sites (i.e. Islands) [40–42].

In this paper the main limitation comes from the lack of discussion with local stakeholders. In facts the research was fully development on desk and remotely. It is also relevant to point out how the STESY method effectively supported the process providing a guide to students to start with effective local analysis, to perform meaningful spatial interpretation of a complex phenomenon, to identify design options/solution for a strategic proposal compliant with NUA international principles [43–50].

The indicator dashboard included in the STESY platform allows to compare this application with other case study in a significant and effective way, supporting the decision making process in identifying intervention priority to better plan tourism sector locally benefitting of multi scale assessment options and accountability management of global objective for sustainable and climate responsive design [51–53].

## References

1. Williams, A.M., Shaw, G.: Internationalization and innovation in tourism. Ann. Tour. Res. **38**, 27–51 (2011). https://doi.org/10.1016/j.annals.2010.09.006
2. Lenzen, M., Sun, Y.-Y., Faturay, F., Ting, Y.-P., Geschke, A., Malik, A.: The carbon footprint of global tourism. Nat. Clim. Chang. **8**, 522–528 (2018). https://doi.org/10.1038/s41558-018-0141-x
3. Stojčić, N., Mikulić, J., Vizek, M.: High season, low growth: the impact of tourism seasonality and vulnerability to tourism on the emergence of high-growth firms. Tour. Manag. **89**, 104455 (2022). https://doi.org/10.1016/j.tourman.2021.104455
4. UN HABITAT: New Urban Agenda. United Nations (2016)
5. Las Casas, G., Scorza, F., Murgante, B.: New urban agenda and open challenges for urban and regional planning. In: Calabrò, F., Della Spina, L., Bevilacqua, C. (eds.) New Metropolitan Perspectives. ISHT 2018. Smart Innovation, Systems and Technologies, vol. 100, pp. 282–288. Springer, Cham (2019). https://doi.org/10.1007/978-3-319-92099-3_33
6. Morphet, J., Morphet, R.: New urban agenda: new urban analytics: a report prepared for the MacArthur Foundation (2019)
7. Tajani, F., Manganelli, B., Cerullo, G., Morano, P., Morente, M.A.: The student housing as a catalyst for virtuous processes of "*win-win*" revitalization of property assets in disuse. In: Gervasi, O., *et al.* Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol 14109, pp. 387–400. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37120-2_25
8. Tajani, F., Cerullo, G., Stara, F., Sica, F.: Multidimensional models for building decarbonization pathways. Bus. Strategy Environ. (2025). https://doi.org/10.1002/bse.70455
9. Lagonigro, D., et al.: Downscaling NUA: matera new urban structure. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol. 14110, pp. 14–24. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37123-3_2
10. Scorza, F., Gatto, R.V.: Identifying territorial values for tourism development: the case study of calabrian greek area. Sustainability **15**, 5501 (2023). https://doi.org/10.3390/SU15065501
11. Lacerenza, A., et al.: "Back to the Villages": design sustainable development scenarios for in-land areas. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol. 14110, pp. 162–176. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37123-3_14

12. Capodiferro, M., et al.: "University equity": students' facilities in major tourism destination towns. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023 (2023)
13. Florio, E., Marcosano, S.R., Parrulli, R., Andrulli, G., Gatto, R.V., Mininni, M., Scorza, F.: SuperABLE: Matera accessible for all. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023. Springer (2023)
14. Loscavo, B.E., et al.: Innovation ecosystem: the added value in a unique UNESCO city. In: Gervasi, O., *et al.* Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol. 14110, pp. 129–137. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37123-3_11
15. Casas, G.L., Scorza, F.: Sustainable planning: a methodological toolkit. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2016. ICCSA 2016. Lecture Notes in Computer Science, vol. 9786, pp. 627–635. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-42085-1_53
16. Gatto, R.V., Corrado, S., Scorza, F.: Taxonomy for specialized tourism ecosystems: new geographies for sustainable territorial planning. Habitat Int. (2025)
17. Murgante, B., Borruso, G., Lapucci, A.: Sustainable development: concepts and methods for its application in urban and environmental planning. Stud. Comput. Intell. **348**, 1–15 (2011). https://doi.org/10.1007/978-3-642-19733-8_1/COVER
18. Santopietro, L., Scorza, F.: Voluntary planning and city networks: a systematic bibliometric review addressing current issues for sustainable and climate-responsive planning. Sustainability **16** (2024). https://doi.org/10.3390/su16198655
19. Sica, F., Tajani, F., Cerullo, G.: An evaluation model for an optimal decarbonisation process in the built environment. Built Environ. Proj. Asset Manage. **15**, 51–66 (2024). https://doi.org/10.1108/BEPAM-05-2024-0126
20. Tajani, F., Bologna, A., Cerullo, G., Doko, E., Sica, F.: Upcycling strategies for resilience reconstruction goals: a case study of an Italian public building. Buildings **15** (2025). https://doi.org/10.3390/buildings15203683
21. Pilogallo, A., Scorza, F.: Mapping regulation ecosystem services specialization in Italy. J. Urban Plan. Dev. **148** (2022). https://doi.org/10.1061/(ASCE)UP.1943-5444.0000801
22. Scorza, F., Santopietro, L., Giuzio, B., Amato, F., Murgante, B., Casas, G.L.: Conflicts between environmental protection and energy regeneration of the historic heritage in the case of the city of matera: tools for assessing and dimensioning of sustainable energy action plans (SEAP). In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2017. ICCSA 2017. Lecture Notes in Computer Science, vol. 10409, pp. 527–539. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-62407-5_37
23. Santopietro, L., Solimene, S., Lucchese, M., Di Carlo, F., Scorza, F.: An economic appraisal of the SE(C)AP public interventions towards the EU 2050 target: the case study of Basilicata region. Cities **149** (2024). https://doi.org/10.1016/j.cities.2024.104957
24. Gatto, R.V., Scorza, F.: "Anti-gravity tourism planning": an analytical approach to manage tourism congestion, seasonality and overtourism. Urban Sci. **9** (2025). https://doi.org/10.3390/urbansci9120524
25. Gatto, R., Santopietro, L., Scorza, F.: Roghudi: developing knowledge of the places in an abandoned inland municipality. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds.) Computational Science and Its Applications – ICCSA 2022 Workshops. ICCSA 2022. Lecture Notes in Computer Science, vol. 13382, pp. 48–53. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-10592-0_5
26. Del P. Pablo-Romero, M., Molina, J.A.: Tourism and economic growth: a review of empirical literature. Tour. Manag. Perspect. **8**, 28–41 (2013). https://doi.org/10.1016/j.tmp.2013.05.006
27. Gatto, R.V., Scorza, F.: "Anti-gravity tourism planning": an analytical approach to manage tourism congestion, seasonality and overtourism (2025)

28. Gatto, R.V., Scorza, F.: Sustainable tourism ecosystem balancing territorial values: a place-based perspective. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol. 14110, pp. 90–103. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37123-3_8
29. Gatto, R.V., Corrado, S., Scorza, F.: A taxonomy of specialized tourism ecosystems (STESY): toward new geographies for sustainable territorial planning. Int. J. E-Plann. Res. (2025)
30. Anselin, L., Syabri, I., Kho, Y.: GeoDa: an introduction to spatial data analysis. Geogr. Anal. **38**, 5–22 (2006). https://doi.org/10.1111/j.0016-7363.2005.00671.x
31. Humaira, H., Rasyidah, R.: Determining the appropiate cluster number using elbow method for K-means algorithm. Presented at the March 3 (2020). https://doi.org/10.4108/eai.24-1-2018.2292388
32. Lagonigro, D., Cazzati, V., Viggiano, N., Andrulli, G., Gatto, R.V., Mininni, M., Scorza, F.: Downscaling NUA: Matera new urban structure (2023)
33. UNhabitat: The new urban agenda (2016). https://doi.org/10.18356/4665f6fb-en
34. Gatto, R.V., Corrado, S., Scorza, F.: Specialized Tourism Ecosystem Workshop Report. University of Basilicata (2026). https://doi.org/10.5281/zenodo.18347608
35. Annunziata, A., et al.: Climate actions handbook supporting decision making for regional adaptation strategies in Basilicata, Italy. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 304–320. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_22
36. Gatto, R.V., Dale, M.M., Noennig, J.R.: Exploration of a disaster risk management method for tourism destinations: the case of guatemala. Procedia Comput. Sci., 2047–2056 (2025). Elsevier B.V. https://doi.org/10.1016/j.procs.2025.09.325
37. Tullipani, E.M.P., Gatto, R.V., Scorza, F.: "Croatia 365": a STESY based strategy for tourism destagionalization. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 212–222. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_15
38. Cascione, F., et al.: "NATURE as the way mobility and well-being": STESY based sustainable tourism development strategy in Belgium. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 234–244. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_17
39. Gatto, R.V., Andrulli, G., Perrone, F., Corrado, S., Cerra, E., Scorza, F.: Enhancing vulture's territorial assets through tourism ecosystems for spatial development. In: Gervasi, O., Murgante, B., Garau, C., Taniar, D., C. Rocha, A.M.A., Faginas Lago, M.N. (eds.) Computational Science and Its Applications – ICCSA 2024 Workshops. ICCSA 2024. Lecture Notes in Computer Science, vol. 14822, pp. 285–292. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-65318-6_19
40. Randò, L., Scavone, M., Tarantino, S., Gatto, R.V., Scorza, F.: "A journey between sky and sea": investigating tourism ecosystem in Madeira. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 223–233. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_16
41. Elhabchi, I., Piliero, A., Gatto, R.V., Scorza, F.: "Sherry triangle", investigating tourism ecosystem in Andalusia (ES). In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15887, pp. 16–26. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97589-9_2
42. Pappalardi, V., Nolè, R., Gatto, R.V., Scorza, F.: A dismissed train line as a new pillar for sustainable tourism development in Corsica: "the maquis way" strategy. In: Gervasi, O., et al.

Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15887, pp. 40–49. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97589-9_4

43. Gatto, R.V., Perrone, F., Scorza, F.: Planning for sustainable tourism in protected areas. A policy-oriented spatial evaluation framework. . TeMA – J. Land Use Mobility Environ. **19**, 171–188 (2026)
44. Scorza, F., Fortunato, G., Carbone, R., Murgante, B., Pontrandolfi, P.: Increasing urban walkability through citizens' participation processes. Sustainability (Switz.) **13** (2021). https://doi.org/10.3390/su13115835
45. Manganelli, B., Murgante, B., Saganeiti, L.: The social cost of urban sprinkling. Sustainability (Switz.) **12** (2020). https://doi.org/10.3390/su12062236
46. Molaei Qelichi, M., Murgante, B., Yousefi Feshki, M., Zarghamfard, M.: Urbanization patterns in Iran visualized through spatial auto-correlation analysis. Spat. Inf. Res. **25**, 627–633 (2017). https://doi.org/10.1007/s41324-017-0128-0
47. Hendawy, E., et al.: The prediction and assessment of the impacts of soil sealing on agricultural land in the North Nile Delta (Egypt) using satellite data and GIS modeling. Sustainability (Switz.) **11** (2019). https://doi.org/10.3390/su11174662
48. Murgante, B., Borruso, G.: Cities and smartness: a critical analysis of opportunities and risks. In: Murgante, B., et al. Computational Science and Its Applications – ICCSA 2013. ICCSA 2013. Lecture Notes in Computer Science, vol. 7973, pp. 630–642. Springer, Heidelberg (2013). https://doi.org/10.1007/978-3-642-39646-5_46
49. Murgante, B., Tilio, L., Lanza, V., Scorza, F.: Using participative GIS and e-tools for involving citizens of Marmo Platano-Melandro area in European programming activities. J. Balkan Near East Stud. **13**, 97–115 (2011). https://doi.org/10.1080/19448953.2011.550809
50. Murgante, B., Borruso, G., Balletto, G., Castiglia, P., Dettori, M.: Why Italy first? Health, geographical and planning aspects of the COVID-19 outbreak. Sustainability (Switz.) **12** (2020). https://doi.org/10.3390/su12125064
51. Scorza, F., et al.: Training for territorial sustainable development design in Basilicata remote areas: GEODESIGN workshop. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds.) Computational Science and Its Applications – ICCSA 2022 Workshops. ICCSA 2022. Lecture Notes in Computer Science, vol. 13379, pp. 242–252. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-10545-6_17
52. Rizzi, F., et al.: Development of an impact model for climate adaptation strategy design: the case study of Basilicata Region, Italy. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 260–277. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_19
53. Iula, G., et al.: Paving the way to basilicata climate adaptation strategy: a geodesign workshop. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 289–303. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_21

# Symbiotic Territories: Application of the STESY Framework for Rebalancing Tourism Flows Between Granada and Sierra Nevada

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**Abstract.** Granada and Sierra Nevada constitute a highly sensitive tourism system characterized by the spatial coexistence of two differentiated tourism environments: an urban heritage destination and a mountain tourism area. Within this configuration, Granada concentrates cultural tourism flows within its historic core, producing localized pressure on urban services, housing dynamics, and public space. Conversely, Sierra Nevada is characterized by a strongly seasonal tourism regime, marked by a pronounced concentration of demand during the winter period. In this context, the present study applies the STESY framework to support the spatial interpretation and strategic assessment of the territorial system. The methodological approach integrates territorial analysis and the application of composite indicators, including the Attraction Potential Index (API), the Balanced Tourism Supply Index (BTSI), and the Diversity Reachability Index (DRI), in order to examine the distribution of tourism functions, territorial performance, and spatial complementarities across the study area.

The results reveal differentiated territorial configurations and uneven patterns of tourism specialization, reflecting the coexistence of heterogeneous functional structures and distinct pressure regimes. On this basis, the study outlines a planning strategy structured around thematic hubs, sustainable mobility interventions, and a digital incentive system aimed at improving stay distribution, supporting a more balanced use of territorial resources, and enhancing the overall performance of the Granada–Sierra Nevada tourism system.

Overall, the proposed framework contributes to the advancement of policy-oriented and transferable approaches for the spatial planning of tourism in complex urban–mountain destinations.

**Keywords:** Sustainable tourism planning · spatial analysis · cluster analysis

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## 1 Introduction

Sustainable tourism becomes more and more a core argument in territorial development debate defining local multi-stakeholders' perspectives and global framework for innovation and better management of such complex phenomena [1, 2]. Today tourism is recognized as a dominant driver of economic growth in coastal and heritage destinations, yet its rapid expansion has also generated critical spatial and temporal imbalances [3]. In the perspective of the authors, tourism opens to relevant debate in urban and regional planning research as the decision making process connected with tourism management represent a comprehensive framework in which sustainable urban regeneration and transformation, landscape protection actions, economic development issues interacts generating an effective environment to apply sustainable urban development principles, methods and agendas for short term and strategic territorial design [4–8]. Those applications are also oriented to improve the competences of students in academic curricula dealing with territorial design professionals, and this paper comes as a result of a studio in architectural classes following the research tradition [9–14] of sustainable urban planning and design at UNIBAS [15–18].

Tourism as a spatial phenomenon is a multidisciplinary domain where spatial dimension represents a robust analytical dimension for managing information and designs, applying collaborative approach for strategic planning [19–25].

This issue becomes especially relevant in territorial contexts characterized by marked internal differentiation, where multiple tourism environments coexist within the same regional system while expressing distinct functional profiles, temporal rhythms, and development patterns. In such configurations, tourism demand often tends to concentrate within a limited number of highly attractive nodes, while surrounding areas may remain comparatively less activated despite the presence of significant territorial resources and latent tourism potential. These dynamics may contribute to uneven spatial development, localized pressure on specific areas, and limited redistribution of tourism-related opportunities across the wider territory [26].

Granada and Sierra Nevada provide a relevant case study within this perspective. The system combines one of the most significant historic urban destinations in southern Spain with a major mountain tourism area associated with winter sports and high-value natural landscapes [27]. Within this territorial configuration, Granada concentrates cultural tourism flows within its historic urban fabric, whereas Sierra Nevada is characterized by a strongly seasonal tourism regime. The coexistence of these differentiated tourism environments gives rise to a complex territorial structure, shaped by heterogeneous forms of tourism use, distinct spatial pressures, and uneven functional organization [28].

This paper aims to develop a spatially informed planning framework capable of supporting the transition from a short-duration, high-pressure tourism model toward a more balanced system based on extended stays and territorial redistribution. The study proposes an integrated methodological approach combining spatial analysis, cluster-based interpretation, and policy-oriented design strategies in compliance with NUA principles. The contribution lies in bridging analytical diagnosis and operational planning within a coherent framework transferable to similar tourism destinations.

## 2 Study Area

The study area is located in the province of Granada, in the Andalusian region of southern Spain, and includes the urban system of Granada together with the mountain environment of Sierra Nevada. The territory is characterized by an exceptional morphological and functional duality, where in a relatively limited spatial extent it is possible to move from the dense and historically stratified urban core of Granada to the high-altitude natural landscapes of one of the most important mountain systems of the Iberian Peninsula.

The territorial reading highlights the coexistence of two highly differentiated tourism models. This polarization is also reflected in the temporal structure of tourism demand and in the differentiated pressure patterns affecting the two components of the system. As shown by the monthly distribution of tourist arrivals (Fig. 1) and overnight stays (Fig. 2), Granada maintains a relatively stable tourism profile throughout the year, with moderate seasonal variation and consistently high accommodation demand across multiple months. This condition is associated with an intense and continuous use of the urban tourism system, which in recent years has been increasingly exposed to overtourism-related dynamics. In particular, the concentration of more than 2.6 million annual visitors, the progressive expansion of short-term rental accommodation, and the prevalence of short-stay visitation patterns have contributed to increasing pressure on housing availability, urban services, public space, and the socio-spatial balance of the historic fabric, particularly in the Albaicín area. By contrast, Sierra Nevada exhibits a markedly concentrated temporal pattern, with tourist flows and overnight stays strongly clustered in the winter season and sharply reduced during the rest of the year. This seasonal concentration intensifies the use of mountain infrastructure and accessibility systems during peak months, producing localized congestion and significant management pressures. Overall, these dynamics highlight the coexistence of two distinct tourism regimes within the same territorial system: a more continuous and diversified urban demand in Granada, and a highly seasonal mountain demand in Sierra Nevada, characterized by a limited temporal utilization of tourism infrastructure and services.




**Fig. 1.** Comparative Tourist Arrivals in Granada and Sierra Nevada. Source: Personal elaboration of data from Instituto Nacional de Estadistica.

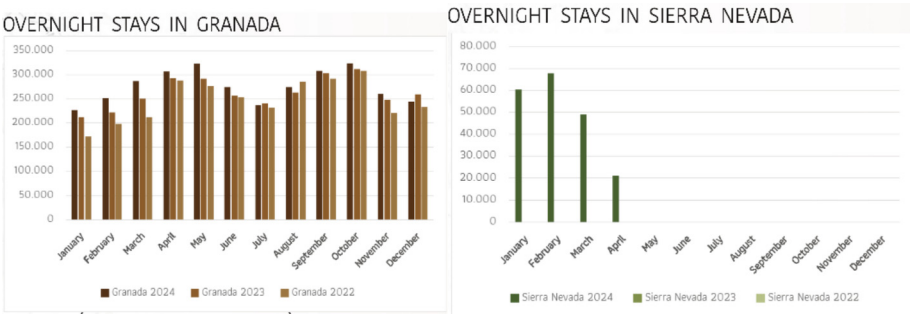


**Fig. 2.** Comparative Overnight stays in Granada and Sierra Nevada. Source: Personal elaboration of data from Instituto Nacional de Estadistica.

## 3 Territorial Analysis

The approach adopted in this study is based on the STESY framework [29] conceived as an integrated analytical and interpretative tool for the identification of territorial imbalances and the support of evidence-based planning strategies.

The first phase consists of a contextual analysis of the study area, focusing on the identification and classification of key georeferenced components (PoIs) of the tourism system, including attractors, services, and reachability (Fig. 3).

Granada represents a consolidated cultural tourism destination whose identity is strongly rooted in its historic and architectural heritage. The urban structure is dominated by the monumental complex of the Alhambra and by the historical districts of Moorish origin, particularly Albaicín, both recognized as UNESCO heritage assets. These elements constitute the primary attractors of tourism demand and define the city as a destination with strong symbolic and experiential value.

In contrast, Sierra Nevada constitutes a valuable environmental system and an important node of winter tourism in the south of Spain. The region includes protected natural territories and contains one of the most popular ski resorts in the country, located in Pradollano and the nearby high-altitude structures. Regarding its relevance to tourism, the mountain complex is linked to winter sports, but it remains underutilized outside of winter.

The attraction dimension incorporates cultural, historical, scenic, and experiencial assets that add value to a tourist destination in terms of castles, towers, monu-ments, churches, museums, galleries of arts, theaters, artworks, ancient ruins, squares, quarters, villages, rivers, bridges, waterfalls, observation points, observatories, mountains, and hiking trails. Such factors embody the main spatial elements of tourism attractiveness and form the basis for distinct identity features of both urban and mountain territories.

The service dimension encompasses tourism-oriented infrastructure that enables accommodation and hospitality services, such as hotels, hostels, restaurants, camp-ing sites, mountain lodges, recreational areas for caravans, gift stores, markets, picnicking grounds, public lavatories, fountains, and maps of tourist routes. This category was used to assess the functional capacity of the territory to host and support tourism demand across different spatial contexts.

Finally, the reachability dimension refers to the accessibility structure of the tourism system and includes strategic transport and mobility infrastructures such as the airport, railway station, bus station, highways, and local bus connections. This component was considered in order to evaluate the degree of territorial accessibility and the potential connectivity between the main tourism environments.

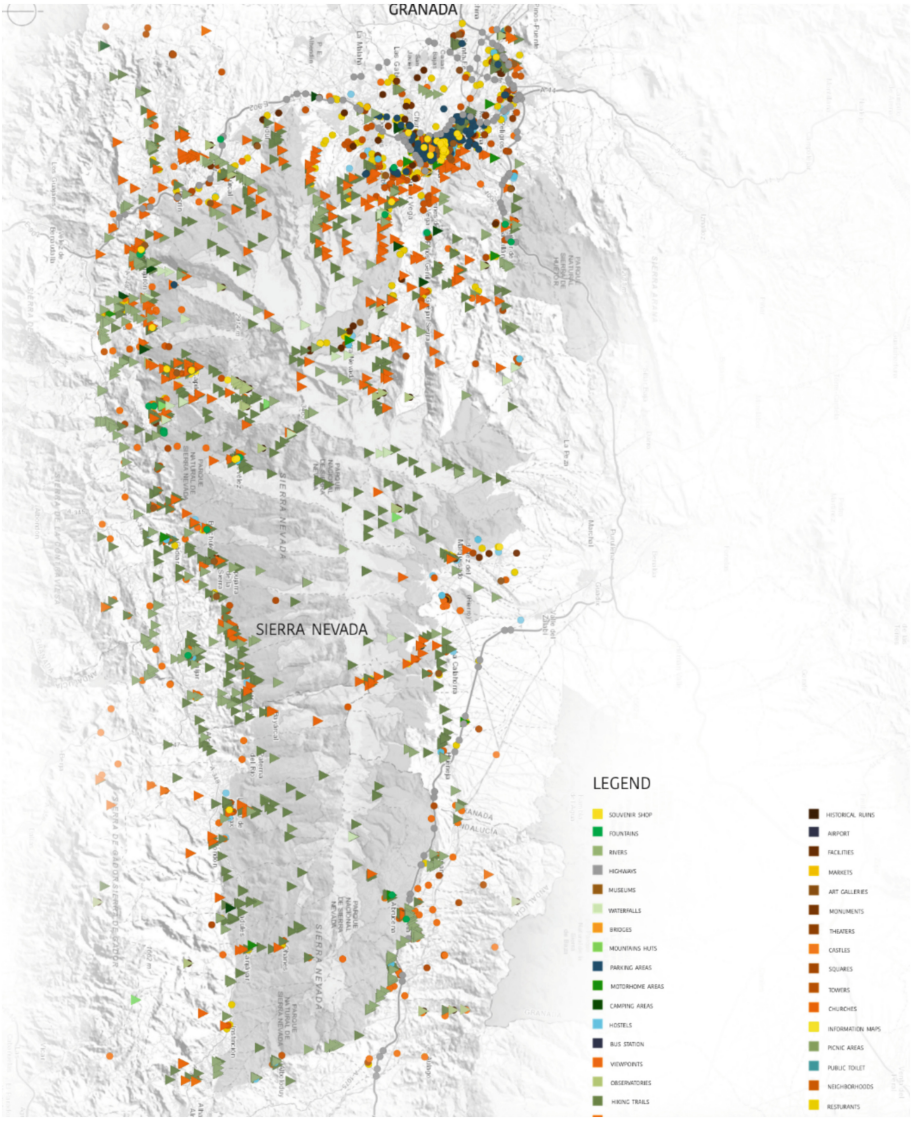


**Fig. 3.** Distribution of Attractors, services and reachability in Sierra Nevada e Granada

The second phase involves the spatial interpretation of these components through a cluster-based approach in order to identifying the Destination Areas of the tourism system in the case study. The territorial system is divided into homogeneous clusters using GeoDA software[30] aimed at identifying distinct spatial patterns. The optimal number of clusters is determined through the application of the Elbow Method[31], ensuring a balance between analytical detail and interpretative clarity (Fig. 4).

The three clusters therefore represent: (1) the urban Destination Area associated with Granada, (2) the transition Destination Area corresponding to the intermediate foothill belt, and (3) the mountain Destination Area centered on Sierra Nevada and the ski-related environment.

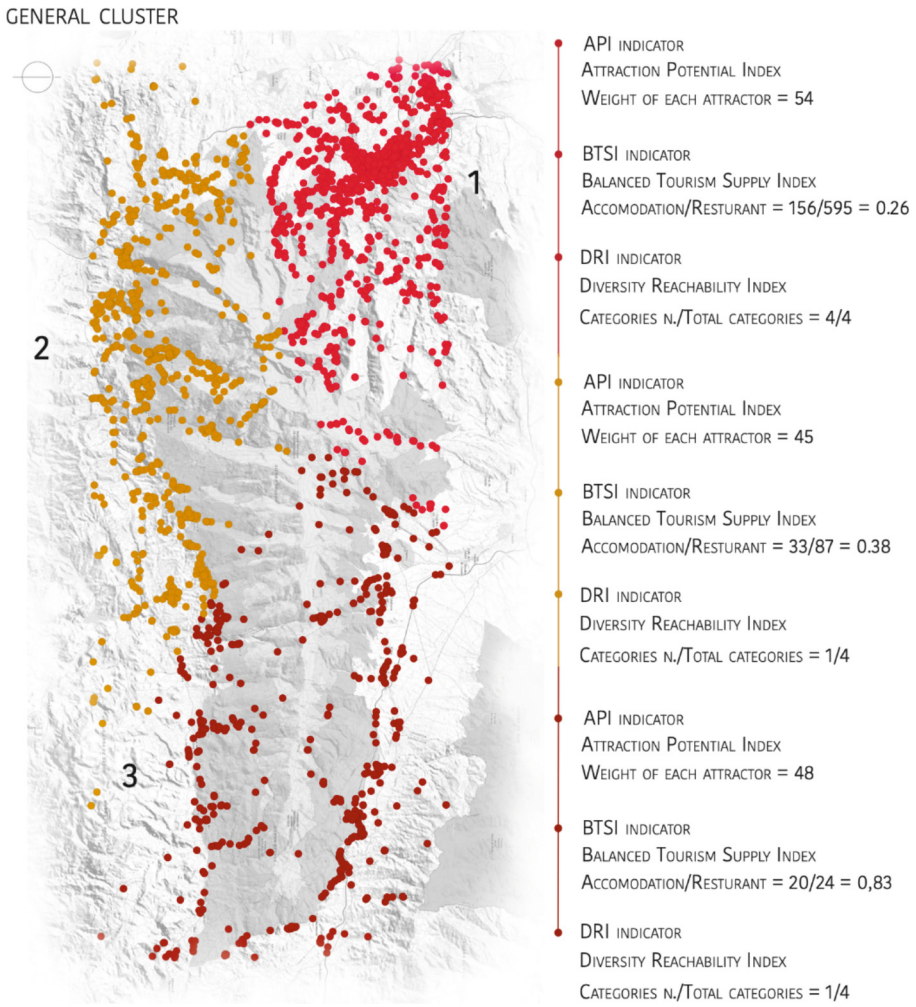


**Fig. 4.** Clusters identified of Attractors, services and reachability and Indicators.

To quantify the characteristics of each cluster, three indicators are employed (Fig. 4): The Balanced Tourism Supply Index (BTSI), The Attraction Potential Index (API) and the Diversity Reachability Index (DRI).

The API evaluates the territorial strength of the attractors present in each cluster. The results show a relatively high attraction potential across the entire system, with the urban detsination area reaching the highest value (54), followed by the mountain destination area (48) and the transition destination area (45). These values indicate that even the non-central areas possess a significant intrinsic tourism potential. However, the inability of these areas to attract proportionate tourism demand suggests that attraction alone is insufficient when not supported by a coherent system of services and mobility infrastructures.

The BTSI measures the balance between accommodation and food-related services, offering insight into the type of tourism structure that characterizes each destination area. The urban destination area presents the most critical condition, with a highly unbalanced ratio between accommodation and restaurants (156/595), corresponding to an index value of 0.26. This result indicates a tourism economy disproportionately oriented toward day-use consumption and short-duration visits. The transition Destination Area shows a slightly less critical but still unbalanced value (33/87; 0.38), while the mountain Destination Area presents the highest equilibrium (20/24; 0.83), suggesting a more stay-oriented tourism structure, although limited in scale and seasonal in operation.

The DRI assesses the diversity of service categories in relation to their effective accessibility. In this case, the urban Destination Area reaches a maximum value of 4/4, confirming the high diversity and availability of services within Granada. By contrast, both the transition and mountain Destination Areas record extremely low values (1/4), revealing a strong lack of diversification and complementary functions. In particular, the foothill area appears to operate merely as a transit corridor toward the mountain, while the high-altitude Destination Area remains functionally dependent on winter sports and unable to support alternative forms of tourism such as hiking, cycling, or night-based environmental experiences.

## 4 Discussion and Planning Strategy

The findings of the analysis support the development of a multi-scalar planning strategy aimed at transforming the existing tourism system. The downscaling of NUA [32, 33]compliance assessment supports the definition of spatial strategies designed to address both the physical disconnection between Granada and Sierra Nevada and the behavioral dynamics that currently reinforce tourism concentration and short stays. The overall strategy is coherent with the broader sustainability goals related to mobility transition, territorial resilience, environmental quality, and more inclusive and balanced urban-tourism relationships.

Instead of suggesting separate tourism infrastructures, the intervention is set up as a holistic transformation of territorial relations, to convert proximity into complementarity and tourism demand into value for territorial space.

The proposed approach is based on the combination of soft measures and hard interventions, designed to influence both visitor behavior and spatial organization.

The first group of interventions focuses on infrastructural strengthening and deseasonalization (Fig. 5). In order to address the lack of service diversity and the rigid seasonality of the mountain destination area, the strategy proposes the implementation of specialized high-altitude hubs. These include a hiking hub designed to operate from spring to autumn and equipped with basic but strategic facilities such as lockers, water refill stations, and light food services; an astronomical hub aimed at extending the temporal use of the mountain environment into evening and nighttime hours; and a ski hub conceived as a retrofitting intervention for rationalizing winter tourism infrastructure and reducing dysfunctional car-based occupation of public space.

The second group of interventions addresses alternative mobility and the valorization of marginal areas, particularly the transition Destination Area, which currently functions as an infrastructural void (Fig. 5). In order to transform this area from a mere transit corridor into a place of pause and activation, the project introduces a cycling hub equipped with self-service repair facilities and e-bike charging stations, capable of supporting soft mobility and intercepting visitors before they reach the upper mountain system. This is complemented by the introduction of a cultural hub and a dedicated shuttle service linking the city with foothill stations, with the dual objective of reducing private car dependence and redistributing tourist attention across intermediate territorial nodes.

The third component of the strategy concerns territorial marketing and systemic integration through the implementation of a digital incentive infrastructure. Coherently with the Copenhagen precedent, the project introduces the app-based system “Tapas Currency”, conceived as a gamified territorial reward mechanism. Through this tool, tourists accumulate points by walking or cycling across the various hubs and routes, and can subsequently redeem them within Granada’s food and hospitality system. In this way, the project establishes a circular relationship between outdoor tourism and the urban economy, encouraging visitors to remain in the city after mountain-based experiences and thereby increasing the probability of overnight stays and more distributed expenditure patterns.

The expected impacts of the proposed scenario are significant. The DRI values of the transition and mountain clusters are projected to improve through the introduction of new functions and services, while the average length of stay is expected to increase from the current short-stay pattern toward a more stable overnight-oriented tourism structure. At the same time, the reorganization of access and the introduction of collective mobility systems are expected to reduce private traffic toward Sierra Nevada, especially during winter peaks, contributing to lower congestion and reduced environmental pressure. The strategy therefore supports a transition from a polarized and extractive tourism model toward a more diversified, resilient, and territorially integrated ecosystem.

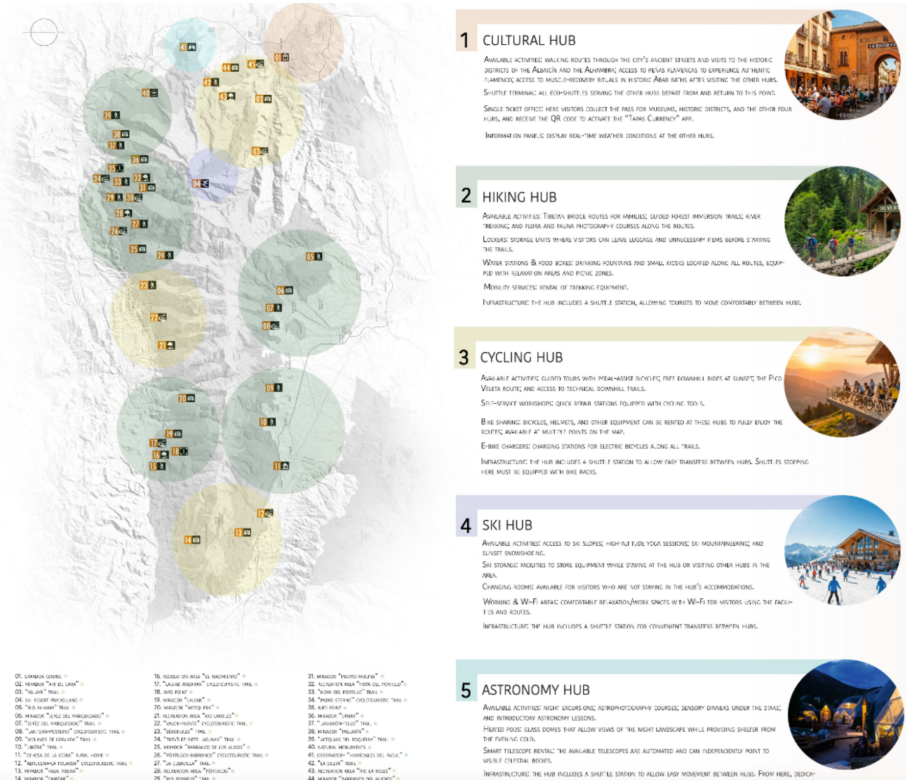


**Fig. 5.** Frist two group of Interventions.

## 5 Conclusions

This study has developed a spatially informed planning framework for addressing tourism imbalances in a complex urban–mountain destination, using Granada and Sierra Nevada as a representative case. The integration of territorial analysis, cluster-based interpretation, and composite indicators has enabled the identification of structural mismatches between tourism potential and actual demand distribution[34–41].

The proposed strategy demonstrates how the combination of soft and hard measures can support the transition from a fragmented, high-pressure, and seasonally polarized tourism model toward a more balanced system based on territorial complementarity, extended stays, and distributed value creation. By strengthening the role of currently marginal areas and improving the integration between mobility, services, and attractors, the framework contributes to the development of a more resilient tourism ecosystem.

The approach is designed to be replicable and adaptable to other destinations facing similar challenges, offering a practical contribution to the field of sustainable tourism planning and territorial governance.

The whole application is structured on the STESY framework [29, 42, 43]: a robust spatial analytical framework driving from the early stages the strategic design in sustainable tourism for a specific destination area. The framework had been applied in a number

of local studies selected among major destinations (i.e. EU Capitals, UNESCO Sites, Environmental global attractors etc.) [44, 45], minor inland tourism areas (i.e. Vulture, Pollino national Park) [46, 47] and niche tourism sites (i.e. Islands) [48–50].

In this paper the main limitation comes from the lack of discussion with local stakeholders. In facts the research was fully development on desk and remotely. It is also relevant to point out how the STESY method effectively supported the process providing a guide to students to start with effective local analysis, to perform meaningful spatial interpretation of a complex phenomenon, to identify design options/solution for a strategic proposal compliant with NUA international principles.

The indicator dashboard included in the STESY platform allows to compare this application with other case study in a significant and effective way, supporting the decision making process in identifying intervention priority to better plan tourism sector locally benefitting of multi scale assessment options and accountability management of global objective for sustainable and climate responsive design [51–53].

## References


1. Williams, A.M., Shaw, G.: Internationalization and innovation in tourism. Ann. Tour. Res. **38**, 27–51 (2011). https://doi.org/10.1016/j.annals.2010.09.006
2. Lenzen, M., Sun, Y.-Y., Faturay, F., Ting, Y.-P., Geschke, A., Malik, A.: The carbon footprint of global tourism. Nat. Clim. Chang. **8**, 522–528 (2018). https://doi.org/10.1038/s41558-018-0141-x
3. Stojčić, N., Mikulić, J., Vizek, M.: High season, low growth: the impact of tourism seasonality and vulnerability to tourism on the emergence of high-growth firms. Tour. Manag. **89**, 104455 (2022). https://doi.org/10.1016/j.tourman.2021.104455
4. UN HABITAT: New Urban Agenda. United Nations (2016)
5. Las Casas, G., Scorza, F., Murgante, B.: New urban agenda and open challenges for urban and regional planning. In: Calabrò, F., Della Spina, L., Bevilacqua, C. (eds.) New Metropolitan Perspectives. ISHT 2018. Smart Innovation, Systems and Technologies, vol. 100, pp. 282–288. Springer, Cham (2019). https://doi.org/10.1007/978-3-319-92099-3_33
6. Morphet, J., Morphet, R.: New Urban Agenda: New Urban Analytics: A Report Prepared for the MacArthur Foundation (2019)
7. Tajani, F., Manganelli, B., Cerullo, G., Morano, P., Morente, M.A.: The student housing as a catalyst for virtuous processes of "*win-win*" revitalization of property assets in disuse. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol. 14109, pp. 387–400. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37120-2_25
8. Tajani, F., Cerullo, G., Stara, F., Sica, F.: Multidimensional models for building decarbonization pathways. Bus. Strategy Environ. (2025). https://doi.org/10.1002/bse.70455
9. Lagonigro, D., et al.: Downscaling NUA: matera new urban structure. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol. 14110, pp. 14–24. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37123-3_2
10. Scorza, F., Gatto, R.V.: Identifying territorial values for tourism development: the case study of calabrian greek area. Sustainability **15**, 5501 (2023). https://doi.org/10.3390/SU15065501
11. Lacerenza, A., et al.: "Back to the Villages": design sustainable development scenarios for in-land areas. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol. 14110, pp. 162–176. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37123-3_14

12. Capodiferro, M., et al.: "University equity": students' facilities in major tourism destination towns. In: Gervasi, O. (ed.) Computational Science and Its Applications - ICCSA 2023 (2023)
13. Florio, E., et al.: SuperABLE: matera accessible for all. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol. 14110, pp. 152–161. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37123-3_13
14. Loscavo, B.E., et al.: Innovation ecosystem: the added value in a unique UNESCO city. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol. 14110, pp. 129–137. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37123-3_11
15. Casas, G.L., Scorza, F.: Sustainable planning: a methodological toolkit. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2016. ICCSA 2016. Lecture Notes in Computer Science, vol. 9786, pp. 627–635. Springer, Cham (2016). https://doi.org/10.1007/978-3-319-42085-1_53
16. Gatto, R.V., Corrado, S., Scorza, F.: Taxonomy for specialized tourism ecosystems : new geographies for sustainable territorial planning. Habitat Int. (2025)
17. Murgante, B., Borruso, G., Lapucci, A.: Sustainable development: concepts and methods for its application in urban and environmental planning. Stud. Comput. Intell. **348**, 1–15 (2011). https://doi.org/10.1007/978-3-642-19733-8_1/COVER
18. Santopietro, L., Scorza, F.: Voluntary Planning and city networks: a systematic bibliometric review addressing current issues for sustainable and climate-responsive planning. Sustainability **16** (2024). https://doi.org/10.3390/su16198655
19. Sica, F., Tajani, F., Cerullo, G.: An evaluation model for an optimal decarbonisation process in the built environment. Built Environ. Proj. Asset Manage. **15**, 51–66 (2024). https://doi.org/10.1108/BEPAM-05-2024-0126
20. Tajani, F., Bologna, A., Cerullo, G., Doko, E., Sica, F.: Upcycling strategies for resilience reconstruction goals: a case study of an Italian public building. Buildings **15** (2025). https://doi.org/10.3390/buildings15203683
21. Pilogallo, A., Scorza, F.: Mapping regulation ecosystem services specialization in Italy. J. Urban Plan. Dev. **148** (2022). https://doi.org/10.1061/(ASCE)UP.1943-5444.0000801
22. Scorza, F., Santopietro, L., Giuzio, B., Amato, F., Murgante, B., Casas, G.L.: Conflicts between environmental protection and energy regeneration of the historic heritage in the case of the city of matera: tools for assessing and dimensioning of sustainable energy action plans (SEAP). In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2017. ICCSA 2017. Lecture Notes in Computer Science, vol. 10409, pp. 527–539. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-62407-5_37
23. Santopietro, L., Solimene, S., Lucchese, M., Di Carlo, F., Scorza, F.: An economic appraisal of the SE(C)AP public interventions towards the EU 2050 target: the case study of Basilicata region. Cities **149** (2024). https://doi.org/10.1016/j.cities.2024.104957
24. Gatto, R.V., Scorza, F.: "Anti-gravity tourism planning": an analytical approach to manage tourism congestion, seasonality and overtourism. Urban Sci. **9** (2025). https://doi.org/10.3390/urbansci9120524
25. Gatto, R., Santopietro, L., Scorza, F.: Roghudi: developing knowledge of the places in an abandoned inland municipality. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds.) Computational Science and Its Applications – ICCSA 2022 Workshops. ICCSA 2022. Lecture Notes in Computer Science, vol. 13382, pp. 48–53. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-10592-0_5
26. Del P. Pablo-Romero, M., Molina, J.A.: Tourism and economic growth: a review of empirical literature. Tour. Manag. Perspect. **8**, 28–41 (2013). https://doi.org/10.1016/j.tmp.2013.05.006
27. Gatto, R.V., Scorza, F.: "Anti-gravity tourism planning": an analytical approach to manage tourism congestion, seasonality and overtourism (2025)

28. Gatto, R.V., Scorza, F.: Sustainable tourism ecosystem balancing territorial values: a place-based perspective. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2023 Workshops. ICCSA 2023. Lecture Notes in Computer Science, vol. 14110, pp. 90–103. Springer, Cham (2023). https://doi.org/10.1007/978-3-031-37123-3_8
29. Gatto, R.V., Corrado, S., Scorza, F.: A taxonomy of specialized tourism ecosystems (STESY): toward new geographies for sustainable territorial planning. Int. J. E-Plann. Res. (2025)
30. Anselin, L., Syabri, I., Kho, Y.: GeoDa: an introduction to spatial data analysis. Geogr. Anal. **38**, 5–22 (2006). https://doi.org/10.1111/j.0016-7363.2005.00671.x
31. Humaira, H., Rasyidah, R.: Determining the appropiate cluster number using elbow method for K-means algorithm. Presented at the March 3 (2020). https://doi.org/10.4108/eai.24-1-2018.2292388
32. Lagonigro, D., Cazzati, V., Viggiano, N., Andrulli, G., Gatto, R.V., Mininni, M., Scorza, F.: Downscaling NUA: matera new urban structure (2023)
33. UNhabitat: The new urban agenda (2016). https://doi.org/10.18356/4665f6fb-en
34. Gatto, R.V., Perrone, F., Scorza, F.: Planning for sustainable tourism in protected areas. A policy-oriented spatial evaluation framework. . TeMA – J. Land Use Mobility Environ. **19**, 171–188 (2026)
35. Scorza, F., Fortunato, G., Carbone, R., Murgante, B., Pontrandolfi, P.: Increasing urban walkability through citizens' participation processes. Sustainability (Switz.) **13** (2021). https://doi.org/10.3390/su13115835
36. Manganelli, B., Murgante, B., Saganeiti, L.: The social cost of urban sprinkling. Sustainability (Switz.) **12** (2020). https://doi.org/10.3390/su12062236
37. Molaei Qelichi, M., Murgante, B., Yousefi Feshki, M., Zarghamfard, M.: Urbanization patterns in Iran visualized through spatial auto-correlation analysis. Spat. Inf. Res. **25**, 627–633 (2017). https://doi.org/10.1007/s41324-017-0128-0
38. Hendawy, E., et al.: The prediction and assessment of the impacts of soil sealing on agricultural land in the North Nile Delta (Egypt) using satellite data and GIS modeling. Sustainability (Switz.) **11** (2019). https://doi.org/10.3390/su11174662
39. Murgante, B., Borruso, G.: Cities and smartness: a critical analysis of opportunities and risks. In: Murgante, B., et al. Computational Science and Its Applications – ICCSA 2013. ICCSA 2013. Lecture Notes in Computer Science, vol. 7973, pp. 630–642. Springer, Heidelberg (2013). https://doi.org/10.1007/978-3-642-39646-5_46
40. Murgante, B., Tilio, L., Lanza, V., Scorza, F.: Using participative GIS and e-tools for involving citizens of Marmo Platano-Melandro area in European programming activities. J. Balkan Near East Stud. **13**, 97–115 (2011). https://doi.org/10.1080/19448953.2011.550809
41. Murgante, B., Borruso, G., Balletto, G., Castiglia, P., Dettori, M.: Why Italy first? Health, geographical and planning aspects of the COVID-19 outbreak. Sustainability (Switz.) **12** (2020). https://doi.org/10.3390/su12125064
42. Gatto, R.V., Corrado, S., Scorza, F.: Specialized Tourism Ecosystem Workshop Report. University of Basilicata (2026). https://doi.org/10.5281/zenodo.18347608
43. Annunziata, A., et al.: Climate actions handbook supporting decision making for regional adaptation strategies in Basilicata, Italy. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 304–320. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_22
44. Gatto, R.V., Dale, M.M., Noennig, J.R.: Exploration of a disaster risk management method for tourism destinations: the case of guatemala. Procedia Comput. Sci., 2047–2056 (2025). Elsevier B.V. https://doi.org/10.1016/j.procs.2025.09.325
45. Tullipani, E.M.P., Gatto, R.V., Scorza, F.: "Croatia 365": a STESY based strategy for tourism destagionalization. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA

2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 212–222. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_15
46. Cascione, F., et al.: "NATURE as the way mobility and well-being": STESY based sustainable tourism development strategy in Belgium. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 234–244. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_17
47. Gatto, R.V., Andrulli, G., Perrone, F., Corrado, S., Cerra, E., Scorza, F.: Enhancing vulture's territorial assets through tourism ecosystems for spatial development. In: Gervasi, O., Murgante, B., Garau, C., Taniar, D., C. Rocha, A.M.A., Faginas Lago, M.N. (eds.) Computational Science and Its Applications – ICCSA 2024 Workshops. ICCSA 2024. Lecture Notes in Computer Science, vol. 14822, pp. 285–292. Springer, Cham (2024). https://doi.org/10.1007/978-3-031-65318-6_19
48. Randò, L., Scavone, M., Tarantino, S., Gatto, R.V., Scorza, F.: "A journey between sky and sea": investigating tourism ecosystem in Madeira. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 223–233. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_16
49. Elhabchi, I., Piliero, A., Gatto, R.V., Scorza, F.: "Sherry triangle", investigating tourism ecosystem in Andalusia (ES). In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15887, pp. 16–26. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97589-9_2
50. Pappalardi, V., Nolè, R., Gatto, R.V., Scorza, F.: A dismissed train line as a new pillar for sustainable tourism development in Corsica: "the maquis way" strategy. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15887, pp. 40–49. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97589-9_4
51. Scorza, F., et al.: Training for territorial sustainable development design in Basilicata remote areas: GEODESIGN workshop. In: Gervasi, O., Murgante, B., Misra, S., Rocha, A.M.A.C., Garau, C. (eds.) Computational Science and Its Applications – ICCSA 2022 Workshops. ICCSA 2022. Lecture Notes in Computer Science, vol. 13379, pp. 242–252. Springer, Cham (2022). https://doi.org/10.1007/978-3-031-10545-6_17
52. Rizzi, F., et al.: Development of an impact model for climate adaptation strategy design: the case study of Basilicata Region, Italy. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 260–277. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_19
53. Iula, G., et al.: Paving the way to basilicata climate adaptation strategy: a geodesign workshop. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 289–303. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_21

# Comparing User Preference for AI-Assisted Search bar, AI+VR Search-Interaction, Gamified Quiz-Driven Product Bundling: Towards Cross-Disciplinary Intelligence and Sustainability

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**Abstract.** There are interests in chat-based (and voice-based) search, without filters. But it is not clear which may be preferred. This study aims to compare perceived ease of use, perceived usefulness and perceived acceptance for gamified quiz-based bundling recommendation, AI-assisted search recommendation and AI+VR interactive visualization in a Figma MUJI mobile application. Framed within the circular economy, the International Requirements Engineering Board's Requirements Engineering and Madani frameworks, analyses, design and development are guided by strategic group map, PESTLE, Sustainability Awareness Framework, TAM 1, 2, 3. Alpha beta testing findings are positive. The averages for all three are almost similar but gamified bundling edges first. Data from a survey of 70 active MUJI customers reveal ease of use and usefulness as significant predictors shaping engagement. Cluster means for AI search recommendations and AI + VR differ from 2.2 to 4.9/5. Age and gender are not significant. Highly accurate/useful product-preference matching/ bundling, and AI + VR highly correlate with and significantly predict intention to adopt the technology, confirming Venkatesh, Speier-Pero and Schuetz's drivers for online shopping. Some circular economy-values-based personalization examples conclude.

**Keywords:** search · shopping experiences · MUJI mobile app · gamified quiz-based bundling interactions · AI-driven search recommendation · AI+VR immersive interaction · cluster analysis · correlation · linear regression · design thinking

## 1 Introduction

In today's evolving retail landscape, personalization has become a key element of digital success, as consumers expect intelligent, intuitive, and visually engaging/ emotionally connected/enjoyable shopping experiences. [1] have suggested that conjunctive aggregation forms a triangle (a t-norm) in rule-based systems. There are possibilities of t-conorm

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refactoring with t-norms and h-norms. Hence, identifying the t-conorm may provide rich probabilistic mixtures, if upper/lower bounds are known.

For the circular economy, [2] highlight cross-disciplinary intelligence and redesign. [3] suggest extending beyond ease of maintenance/upgradability and repair, durability and (dis)assembly to attachment and trust. Such possibilities have provided building blocks to the Learning Sciences' seeds for a more creative society vision and corresponding emphasis on imagination, [4]'s creative analogy and [1]'s cross-selling/ market basket analysis. Subsequently, [5] has proposed simplifying design through design thinking, identifying significant influencing variables and relationships, and how users would like to interact visually and dynamically with the system. Furthermore, with technological advancements, there are interests in voice-based and chat-based search, i.e., without filters. This has motivated our research into comparing gamified quiz-based bundling (the most direct requirements elicitation method) with AI-assisted search recommendation (de facto) and AI + VR interactive visualization (emerging).

MUJI Malaysia is chosen for this case study, as MUJI Malaysia is relatively new to both Malaysian F&B and retail sectors, having less than 20 years of presence in both. Second, it has always focused on minimalist design, functionality, and lifestyle coherence. This presents a valuable opportunity for us to explore how MUJI Malaysia can enhance engagement through digital strategy and innovation.

Our hypotheses are: first, users may prefer the AI-assisted search recommendation, more than the leaner quiz-based recommendation. As such, we gamified the latter to investigate the efficacy of gamification. Gamification is included because in Malaysia, many aspects of life (not only online shopping), are gamified via loyalty points. Second, users may be attracted to AI + VR but only if it remains useful, easy to use, affordable.

Our research questions are:

RQ1: To what extent do age and gender among our sampled respondents influence adoption intentions of AI-assisted recommendation and AI+VR visualization?

RQ2: How will respondents perceive gamified quiz-based bundling compared to AI-driven search recommendations and AI+VR recommendations?

RQ3: To what extent can AI + VR become more localized in terms of circular economy frameworks and values?

We next present related work, which ground our requirements elicitations, validation and refinement.

## 2 Related Work

### 2.1 Frameworks

The International Requirements Engineering Board's (IREB) Requirements Engineering (RE) framework (Fig. 1) elicits requirements corresponding to the system, and development contexts. System context includes subject facet (users' characteristics), usage facet (how users use the system) and IT systems facet (the IT capacity/capability environment). These are analyzed and negotiated in terms of goals, corresponding scenarios and solution-oriented (non)functional requirements. Validation is via user testing.

To guide sustainable design, [6]'s Sustainability Awareness Framework (SusAF) (Fig. 2) covers five dimensions, i.e., individual, social, economic, technical and environmental. Each has immediate, enabling and structural/architectural impacts.

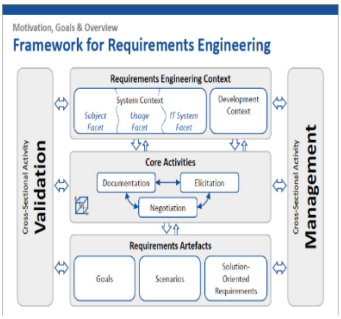


**Fig. 1.** IREB's RE framework

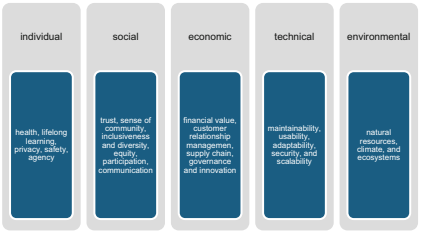


**Fig. 2.** [6]'s SusAF

## 2.2 Technology Acceptance Models 1, 2 and 3 and Online Shopping Drivers

The Technology Acceptance Model (TAM) first started with system usability in terms of perceived usefulness and perceived ease of use [7]. Then, [8] extend it to TAM 2 on social factors and [9] further extend it to TAM 3, to include intrinsic human factors. TAM 1, 2 and 3 are illustrated in Fig. 3a. Subsequently, [10] abstract findings to a model illustrating drivers for online shopping (Fig. 3b). These models are chosen as they are globally-established and accepted.

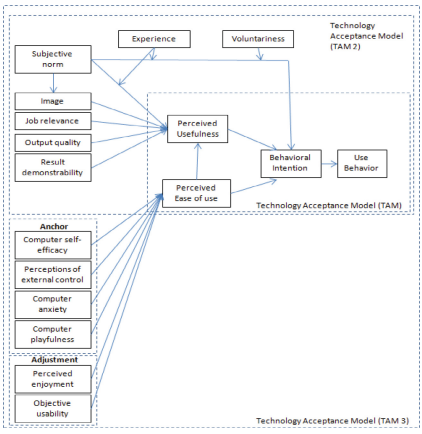


**Fig. 3a.** [7–9]'s TAM 1, 2 and 3

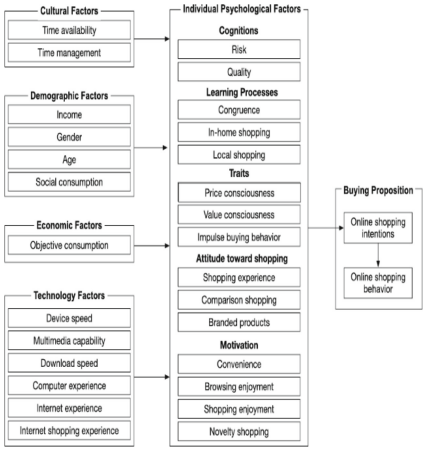


**Fig. 3b.** [10]'s online shopping drivers

**Table 1.** [12]'s Integrated TAM-Madani framework.

| **TAM 1** [7] | **TAM 2** [8] | | | | | | Likely to recommend to others |
|---|---|---|---|---|---|---|---|
| Perceived usefulness | Experience | Voluntariness | Subjective norm | Image | Job relevance | Output quality | Result demonstrability |
| | **TAM 3** [9] | | | | | | |
| Perceived ease of use | **Anchor** | | | | **Adjustment** | | |
| | Computer self-efficacy | Perception of external control | Computer anxiety | Computer playfulness | Perceived enjoyment | Objective consumption | |
| Customer satisfaction | Product/ service Q | Customer service | Price/ **value** | Brand image | Conve-nience | Overall experience | |
| **Madani** [11] | | | | | | | |
| Values | Respect | Innovation | Trust | Compassion | Prosperity | Sustainability | |

### 2.3 Malaysia's Madani Framework

The Malaysian Madani [11] framework (Table 1) is a values-based framework proposed by the Malaysian government. The TAM-Madani framework is proposed by [12] to investigate perceptions towards the design of some additional services for Sunway University's SuperApp. Perception outcomes are promising. A SuperApp transfer of findings is relevant, as a SuperApp hosts multiple subsystems, leading to possible cross-disciplinary intelligence/ecosystems.

## 3 Methodology

As part of Information Systems Analysis and Design, and in line with design thinking and the Software Development Lifecycle (SDLC), we have carried out the following (Table 2). Each strategy in Table 2 ideates according to the IREB RE's goals, scenarios and (non)functional requirements.

**Table 2.** Information Systems Analysis and Design to extend MUJI Passport/mobile app

| Analysis | | | Design | Mining |
|---|---|---|---|---|
| Pre-proposal (competitor analyses) [iteration 1] | Proposal [iteration 2] | Impact/feasibility [iteration 3] | Figma [iteration 4] | Clustering, Regression |
| • The strategic group map highlights the two most important factors (x- y axes) for market positioning<br>• [13]'s Politics, Economics, Social, Technology, Law, Environment (PESTLE) assess feasibility/ viability, competitor analyses [14] | Propose strategies/ value propositions based on market basket analysis [1] | • [6]'s SusAF<br>• [15]'s weighted criteria analysis to prioritize strategies | Alpha-beta user testing (TAM 1, 2, 3) [7–9] | |

Five strategies are first proposed based on strategic group map analyses. To assess feasibility of the proposed five MUJI strategies, weighted criteria analyses is carried out to choose the top three. Subsequently, a pilot survey is carried out via Google form, to

assess/confirm the sampled customers' preferences towards these five strategies. Likert scale is 1 to 5. The survey questionnaire consists of 15 questions. Each strategy is assessed by three questions: Perceptions to the Digital Flywheel strategy (Q1–3), Online Lifestyle Quiz (Q4–6), AR Product Try-On (Q7–9), Subscription Box (Q10–12) and Smart Home Integration (Q13–15). Next, SusAF impact analysis is carried out.

With these feasibility/impact analysis outcomes, a Figma prototype is designed/developed, and alpha and beta user testing carried out. The questions for the pilot, Figma alpha-beta user testing are based on Technology Acceptance Models 1, 2 and 3.

For the next round of research via data mining, data originates from a structured survey of 101 respondents, targeting active online shoppers and MUJI customers, distributed via social media. The survey explores demographic variables (Q1–Q2) and user perceptions of AI and VR-based features (Q3–Q8). Since 31 forms contain missing data, we have 70 valid observations. Gender, AI search, and AI + VR are coded as binary. Age group is coded using an ordinal scale, e.g. 1 for respondents aged $< 18$ and $5 > 45$. To test our hypotheses, we use SAS analytical tools such as clustering, correlation and regression, to evaluate/predict users' perceptions.

### 3.1 Pre-design Analyses

**Competitor/Value Analysis: Strategic Group Map.** MUJI stands out among its competitors, in terms of perceived quality and product variety (Fig. 4a). Perceived quality measures the customer's overall impression in terms of emotional and practical value. Product variety reflects the range, functionality, and innovation/differentiation, critical in a saturated market.

**Competitor/Feasibility Analysis: PESTLE.** This subsection extends from the product variety-perceived quality strategic group map analysis to macro-micro influencing factors, via [13]'s Political, Economic, Social, Technological, Legal and Environmental (PESTLE) dimensions (Fig. 4b).

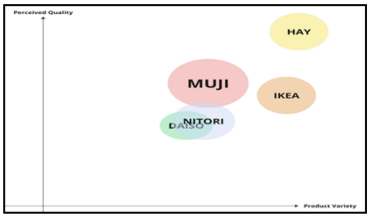


**Fig. 4a.** Strategic group map (variety vs. quality)

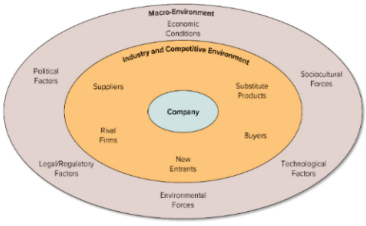


**Fig. 4b.** [13]'s PESTLE and [14]'s Five Forces (inner circle)

**Political:** *MUJI* operates primarily in politically stable countries such as Japan, the European Union, and Southeast Asia. This allows *MUJI* to focus on long-term retail and lifestyle expansion strategies. However, the company faces trade-related risks due to its reliance on global sourcing and cross-border manufacturing. Geopolitical tensions

especially between Japan and China can impact its operations, especially when China remains one of *MUJI's* largest overseas markets [16]. Despite these risks, *MUJI* maintains a neutral brand stance, steering clear of political controversy through its minimalist, "No-Brand" philosophy.

**Economics:** *MUJI* has benefited from the rise of the middle class and growing disposable income in Asian markets, especially in Malaysia and Singapore. In 2021, the company had global revenue of approximately 451 billion yen (about US$4.2 billion), accounting for approximately 10% of the Japanese home furnishings market and approximately 5% of the China market [17]. *MUJI'S* products are generally considered more expensive than some of the local competitors' such as *Daiso* and *Miniso*. This is challenging in the price-sensitive market.

**Social:** *MUJI's* "no brand" minimalist design concept resonates with consumers who are seeking simple, authentic, and environmentally-friendly living. *MUJI* has expanded its business beyond the retail sector, increasing its brand influence by opening concept cafes, galleries, and even its hotel in Ginza, Tokyo [16]. However, with the growing trend of "consumption downgrade" in China cities and consumers paying more attention to cost-effectiveness, *MUJI*'s high-end positioning and Japanese aesthetics sometimes fail to cater to the preferences of the mass market.

**Technology:** *MUJI* has been actively expanding its digital footprint, launching e-commerce platforms and digital membership systems. However, in the application of modern technologies such as artificial intelligence, augmented reality and personalization tools, *MUJI* still lags behind major competitors such as IKEA and *UNIQLO*. Although its Ginza flagship store provides an immersive offline experience through in-store workshops and curated exhibitions, *MUJI* has not yet fully integrated interactive technology into its UX [18].

**Legal:** Setbacks related to intellectual property (IP) rights, e.g. brand name [19], highlight the need for proactive adherence to IP in global markets.

**Environmental:** Environmental sustainability is a core element of *MUJI's* business model. *MUJI* actively promotes the circular economy through the "ReMUJI" project, e.g. recycling and launching a clothing line made of recycled PET materials.

### 3.2 Proposed Strategies

Based on the strategic group map and PESTLE's analysis, we propose 5 strategies that allows *MUJI* to further expand their business. *MUJI's* current mobile application lacks functional digital experience as its current version only showcases what products they are selling. Despite having a variety of products for customers to purchase, they could only view it in their mobile devices and are required to buy the products in MUJI's physical stores. Therefore, the proposed strategies include:

**Digital online shopping enhancement: Mobile first, online lifestyle quizzes leading to personalized product bundles and real-time update/refinement of customer preferences.** *MUJI* should advance its digital shopping experience by enabling mobile

first access so that users can explore product variability/availability, make purchases from anywhere and top up balance directly via an in-app wallet. Top-up promotions e.g. bonus credits can encourage repeat purchases and deepen customer engagement. Furthermore, analysis of customer data e.g. browsing behaviour, purchase history, customer needs and preferences, can lead to real-time personalized deals, future purchase forecast, customer re-segments, and targeted marketing/ automate follow-ups/reminders for abandoned carts optimization.

To refine recommendations, *MUJI's* image as a lifestyle brand can be enhanced by introducing interactive quizzes that generate personalized product bundles across categories such as beauty, fashion, food and beverage. Each quiz response is mapped to corresponding product attributes such as skin type, scent preference, or dietary needs, to form a foundation for personalized bundling. This data is then processed through Salesforce's Einstein Analytics, which scores potential combinations and recommends optimal bundles in real-time. Einstein's AI models assess the likelihood of conversion and suggest product pairings based on current trends, user behaviours, and past purchases. This ensures that bundles are relevant and effective.

New data from each quiz, creates a feedback loop that improves future recommendations especially cross-selling across product categories and smarter inventory decisions across demographics. A cloud-based Customer Relationship Management 360 platform e.g. Salesforce Cloud, can aid scalability, flexibility, and real-time syncing across all channels.

**Digital online shopping enhancement: AR try-on for beauty and furniture via the *MUJI* app.** *MUJI* can implement an Augmented Reality (AR) feature within its mobile application that enables users to virtually try products before purchasing. This strategy will also enhance the user's buying confidence and reduce product return rates. The AR system can be supported by 2 technologies. First, Einstein's AI-powered Knowledge Graph can create a contextual understanding of user behaviour by mapping out customer preferences, interaction history, and product characteristics into a structured data graph. This can enhance cross-category discovery. Recommendations can also be sent if users subscribe to the App. Second, Salesforce Service Cloud can offer real-time chat or assistance for styling tips or product alternatives during a virtual try-on, insitu.

**Smart home integration via the *MUJI* App.** This initiative follows the development of smart furniture and home accessories that merge design with functionality. For instance, aromatherapy diffusers that adjust to user-defined schedules and posture-monitoring furniture that provides wellness feedback. Hence, *MUJI* should take the opportunity to launch Internet of Things (IoT)-enabled furniture [20], in partnership with companies e.g. OGAWA and other lifestyle companies e.g. holographs, with optional habit-based reminders via Salesforce IoT Cloud. The incorporation of smart home technology can enhance *MUJI's* product offerings and consolidate the company's standing in the expanding lifestyle-tech sector, adding competitive advantage in innovation and well-being.

**Table 3.** Weighted criteria analysis of the proposed *MUJI* enhancements

| Criteria | | Digital Flywheel | | Lifestyle Quizzes | | Subscription Boxes | | AR to Try On Products | | Smart Home Integration | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Requirement | Weight | Rating | Weighted score | Rating | Weighted score | Rating | Weighted score | Rating | Weighted score | Rating | Weighted score |
| Customer engagement | 20 | 5 | 100 | 4 | 80 | 3 | 60 | 3 | 60 | 2 | 40 |
| Return on investment | 20 | 5 | 100 | 4 | 80 | 3 | 60 | 3 | 60 | 2 | 40 |
| Differentiation | 10 | 4 | 40 | 4 | 40 | 3 | 30 | 5 | 50 | 4 | 40 |
| | | | **240** | | **200** | | **150** | | **170** | | **120** |
| **Constraints** | | | | | | | | | | | |
| Software cost | 15 | 3 | 45 | 2 | 30 | 2 | 30 | 2 | 30 | 1 | 15 |
| Operating, maintenance cost | 15 | 3 | 45 | 2 | 30 | 2 | 30 | 2 | 30 | 1 | 15 |
| Ease of staffing, training | 10 | 4 | 40 | 5 | 50 | 2 | 20 | 3 | 30 | 2 | 20 |
| Operational complexity | 10 | 4 | 40 | 3 | 30 | 2 | 20 | 3 | 30 | 1 | 10 |
| | | | **170** | | **140** | | **100** | | **120** | | **60** |
| | **Total Mark** | | **410** | | **340** | | **250** | | **290** | | **180** |
| | **Rank** | | **1** | | **2** | | **4** | | **3** | | **5** |

### 3.3 Feasibility Assessment via Weighted Criteria Analysis (WCA)

Based on the above initial analyses and proposals, weighted criteria analysis (Table 3) is carried out, in order to prioritize the design, development and evaluation of the proposed *MUJI* app via Figma. There are different ways to carry out the analysis (depending on the project manager's degree of experience). This study follows [15]'s weighted criteria analysis, which promotes 50%-50% requirements-constraints.

Based on Table 3, the Digital Flywheel strategy has the highest total weighted score of 410, placing it at rank 1. Next are the Online Lifestyle Quizzes with 340 points (ranked second), while AR Product Try-On scores 290 (third). The Subscription Box strategy earns 250 points (fourth), and Smart Home Integration 180 (fifth).

**Confirmation of WCA assessment via pilot testing.** The weighted criteria analysis in Table 3 reflects our internal perspective and may not fully capture customer expectations. Thirty respondents' answers are complete. Based on the results, the Digital Flywheel strategy has the highest overall average of 4.8 (ranking first). This is followed by the Online Lifestyle Quiz with an overall average of 4.46 (second), the AR Product Try-On strategy with an overall average of 4.2 (third), Subscription Box an overall average of 2.62 (fourth) and Smart Home Integration an overall average of 2.27 (fifth). As a rule of thumb, averages above 4.5 indicate high interest, between 4.00–4.49 moderate interest and less than 4.0, may need further refinement to better meet customer expectations. These findings concur with our weighted criteria analysis, where Digital Flywheel ranks highest in terms of strategic value, followed by Online Lifestyle Quiz and AR Product Try-On.

### 3.4 Feasibility Assessment/impact Analysis of WCA Outcomes Based on SusAF

Based on the WCA and customer feedback above, the top three strategies are digital flywheel strategy, online lifestyle quizzes with personalised product bundles and augmented reality (AR). These strategies demonstrate strong alignment with *MUJI*'S brand values of simplicity, sustainability, and personalization. Next, we venture into impact analysis via [6]'s SusAF. Due to space constraint, we present only the individual and economic dimensions and their immediate, enabling and structural effects/impacts.

**Individual dimension.** *Immediate Effect:* When the three strategies are implemented into *MUJI* mobile app, the users are immediately being placed in a guided experience. This is because they are asked to respond to quizzes that assess their lifestyle, needs and preferences, and in return, they receive curated product suggestions. These can complement data from their past purchasing behaviours and interactions and enable suggestions to be refined over time, especially when it comes to personalised product bundles.

*Enabling Effect:* When customers continue to engage with these personalised tools, they might rely more on machine-curated suggestions rather than their own discovery or comparison. Hence, customers might stop developing independent product knowledge or awareness or their own evaluative criteria, because they feel that the system already knows their preferences. Consequently, customers' preferences may be shaped by similar data patterns and predictive logic. Over time, this may reduce critical engagement, limit

exposure to diverse products or ideas, and narrow the scope of what users consider "relevant."

*Structural Effect:* As customer choices converge, more structural partnerships are necessary to attract, acquire and retain customers. Furthermore, *MUJI* would need scalable microservices, cloud-native APIs and real-time databases across *MUJI's* omnichannel collaborative/ competitive business model.

**Economic dimension.** *Immediate Effect:* The immediate economic impact of the implementation of the top three strategies are enhanced value creation, customer engagement, and transaction efficiency. Launching AR strengthens *MUJI'S* market image as an innovative and forward-looking brand. As customers feel that *MUJI* is trying to "understand" them and they are personally addressed, it can strengthen a sense of trust/emotional connection between customers and *MUJI*. This increases sustainable competitiveness in a fast-evolving retail landscape.

*Enabling Effect:* Continuous interaction with customers will allow *MUJI* to refine its pricing strategies, promotional offers, and product bundles based on their actual purchasing behaviour. *MUJI* can gain deeper value through data-driven decision-making, business and system partnerships. Additionally, governance processes can be improved, as all the digital workflows embedded compliance with data protection laws e.g. PDPA and GDPR.

*Structural Effect:* In the long run, fostering a shared sense of identity and belonging within the *MUJI* community by transforming the role of the customer from passive buyer to active participant in *MUJI'S* development, will shift *MUJI's* value creation from product-based to experience-based ecosystems. As *MUJI'S* ability to test, iterate, and deploy new ideas becomes a part of its core economic engine, it can expand across regional markets. Moreover, features such as multilingual interfaces and simplified navigation can allow customers from diverse backgrounds and ages to easily interact with *MUJI'S* services.

## 4 Design: Use Case Diagram

The use case diagram (Fig. 5) illustrates the key interactions between stakeholders. Sample goal-scenario-(non)functional requirements/requirements structure is on the right. Scenario 1 presents sample system logic.

### 4.1 Figma Prototype

Having confirmed the potential and feasibility of the top three strategies, we proceed to design the Figma prototype. It is based on [9]'s research agenda, involving TAM 1, 2, and 3 and possibilities of findings, which may concur with [10]'s model. There are several components to the Figma prototype: Signup/login, virtual try-on for beauty products and furniture, floating hints (so that newcomers will not get lost) and capture look; search pages, cart pages, chatbot pages, quiz pages, member/reward pages. We present some screenshots in Figs. 6a–b below.




**Goal**: View product categories

*Scenario1*: Chat with chatbot to search

*Functional requirement*:

a. Upon login, chatbot will greet the user by name.
b. Then the chatbot will present a menu of options for the user to choose from.

*Scenario 2: Browse catalogue*

*Functional requirement*:
a. Upon login, the user will be able to browse the catalogue based on past purchases and preferences.

**Fig. 5.** Overall use case diagram of enhanced *MUJI* App, sample functional requirements

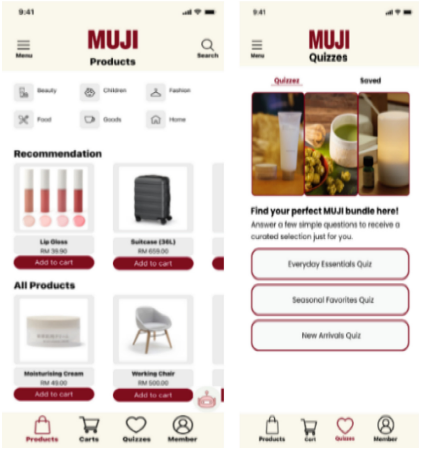


**Fig. 6a.** Main page

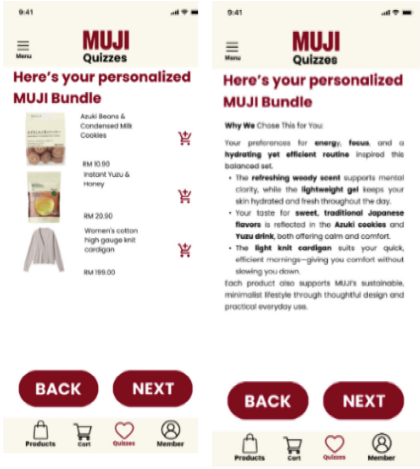


**Fig. 6b.** Personalized bundle

## 4.2 Alpha-Beta User Testing Results and Discussion

*RQ1: To what extent will perception towards gamified quiz-based bundling compare with AI-driven search recommendations and AI + VR recommendations?*

To observe if the proposed enhanced MUJI app meets expectations, we have carried out alpha and beta user testing with a group of 30 respondents using a Google Form. For both alpha and beta user testing, after interacting with the prototype, they answer questions assessing usability, layout clarity, satisfaction, ease of navigation, and feature usefulness on a 5-point Likert-scale (1 Strongly Disagree, 5 Strongly Agree).

The questions test several sections, i.e., Search pages, AR product pages, Quiz pages, Cart pages. The final question is an optional open-ended section, where users can provide their suggestions on improvements. The average for each question and for each section are then calculated and compared. The difference between the alpha and beta user testing survey questions are the *profile information page* in alpha. The question is not included in the beta questionnaire, as it has an average of 4.54/5 in alpha.

**Alpha testing (Figma prototype + survey questionnaire).** Overall, the acceptance towards the proposed enhancements obtained an average of 3.85. The most positive acceptance arises from the profile pages with transaction history and member page, reflecting the importance of identity associated with branding (category's average of 4.54), followed by the rewards page arising from the transaction history, bundled recommended products and referral (category's average of 4.03), the AR pages (category's average of 3.84), cart checkout pages (category's average of 3.46), and the search pages (category's average of 3.14). Areas to be improved on (in bold) are the search efficiency and relevance, the need for an AR tutorial, the cart checkout experience especially with regards to applying discounts/vouchers (Table 4).

**Table 4.** Category, questions, averages per question and per section, ranking per section (alpha testing)

| Category | Question | Avg. | Avg. | Rank |
|---|---|---|---|---|
| Search | **The search bar helped me find products efficiently.** | **3.07** | 3.32 | 5 |
| | **The search results and suggestions were relevant.** | **3.20** | | |
| | The "History" section was clear and useful. | 3.70 | | |
| AR | The AR feature made it easier to understand the product. | 4.60 | 3.84 | 3 |
| | **I was able to use the AR feature without any tutorial.** | **3.07** | | |
| Reward page + history, **bundled products,** referral | The purpose of the Reward Page was clear. | 3.73 | 4.11 | 2 |
| | Bundled products on the Reward Page were easy to view. | 4.37 | | |
| | I could interact with the reward system without confusion. | 3.87 | | |

(*continued*)

**Table 4.** (*continued*)

| Category | Question | Avg. | Avg. | Rank |
|---|---|---|---|---|
| | The process to refer a friend was clear and functional | 4.47 | | |
| Cart checkout | I was able to review and manage the items in my cart easily. | 4.40 | 3.46 | 4 |
| | **The process of applying discount or voucher codes was direct.** | **2.83** | | |
| | I could clearly view the total amount, item breakdown before checkout. | 3.70 | | |
| | **The cart checkout experience felt smooth and simple overall.** | **2.90** | | |
| Profile info. With history, member page | I was able to easily edit my profile information. | 4.60 | 4.54 | 1 |
| | I could access my transaction history without issues. | 4.50 | | |
| | Overall, the Member Page was well-organised and user-friendly. | 4.53 | | |
| | **Overall average** | **3.85** | | |

**Beta testing (Figma prototype + survey questionnaire).** The enhancements are the inclusion of an AI-driven search (Scenario 1 in Fig. 6a), a wizard-like tutorial for the AR, and quiz-based product bundling. Overall, there is an improvement of 0.68 (Table 5). There are improvements in all four categories (delta). The quiz-based product bundling ranked the highest, followed by the AI-driven search with recommendations, and AR with wizard-like tutorials. The findings confirm that the improved *MUJI* prototype app has met user expectations in terms of aesthetic appeal, intuitive navigation, and engagement.

**Table 5.** Feature, questions, AB average differences, averages per feature (beta testing)

| Feature | Question | Avg. (delta) | Avg |
|---|---|---|---|
| Search | The search bar helped me find products efficiently | 4.87 (+1.80) | 4.84 (+1.52) |
| | The search results and suggestions were relevant | 4.81 (+1.81) | |
| AR | The AR feature made it easier to understand the product | 4.90 (+0.30) | 4.84 (+1.00) |
| | I was able to use the AR feature without any tutorial | 4.77 (+1.70) | |

(*continued*)

**Table 5.** (*continued*)

| Feature | Question | Avg. (delta) | Avg |
|---|---|---|---|
| Reward page w history, **quiz/ bundled products** | The quiz page was easy to navigate | 4.87 | 4.86 (+0.75) |
| | The recommended bundle match my personal preferences, needs | 4.87 | |
| | I enjoyed the experience of discovering products through the quiz | 4.94 | |
| | I am more likely to purchase products after using the quiz feature | 4.84 | |
| | Applying MUJI points via the toggle switch is convenient, easy | 4.81 | |
| | The app automatically suggested the most suitable vouchers | 4.84 | |
| Cart checkout | I was able to review and manage the items in my cart easily | 4.40 (+0.00) | 4.06 (+0.6) |
| | The process of applying discount/voucher codes is straightforward | 2.83 (+0.00) | |
| | I could view the total amount/item breakdown before checkout | 3.70 (+0.00) | |
| | I find the Contact Seller option helpful when I had questions/issues | 4.87 | |
| | The cart shows my shipping details, so I can cancel/modify anytime | 4.94 | |
| | I appreciate the confirmation message before completing payment | 4.81 | |
| | The cart checkout experience feels smooth and simple overall | 2.90 (+0.00) | |
| | **Overall average** | **4.53** | |

## 5 Mining Results and Discussion

*RQ1: To what extent do age and gender among our sampled respondents influence adoption intentions of AI-powered recommendation and AI+VR visualization?*

*RQ1: How will respondents perceive gamified quiz-based bundling compared to AI-driven search recommendations and AI+VR recommendations?*

Having determined the feasibility/possible adoption of the proposed strategies/*MUJI* app enhancements, we proceed to the clustering and subsequently, linear regression. Questions are:

1. What is your gender?
2. What is your age?
3. Would you find an AI-powered recommendation/search bar useful when shopping online?
4. On a scale of 1 to 5, how likely are you to use an AI recommendation/search bar when shopping?
5. On a scale of 1 to 5, how satisfied would you be if the AI could suggest products that match your preferences?
6. Would you be interested in using a feature where you snap a picture and AI recommends related items?
7. On a scale of 1 to 5, how likely are you to try the AI + VR feature if available?
8. On a scale of 1 to 5, how helpful do you think this feature would be in improving your shopping experience?

### 5.1 Age/Gender Demographics

Out of the 101 respondents, there are more females (58.42%) than males (41.58%). Furthermore, most (77.23%) are from the 18–24 age group, followed by 13.8% from the $<$ 18 age group, and the 25–34 age group (5.94%) and 45 + age group (2.97%).

### 5.2 Cluster Analyses on Preference for AI Search Recommendation and AI + VR

The survey has explored demographic variables (Q1–Q2) and user perceptions of AI and VR-based features (Q3–Q8). Cluster analysis reveals the existence of 4 clusters (Fig. 7a). The cluster means (Fig. 7a) indicate a range from 2.2 to 4.9. Cluster 1 with cluster mean 4.92–4.98, comprise of respondents who are very positive and highly supportive of both AI-driven features. This is followed by Cluster 4 with cluster means from 3.8–4.46). These respondents are generally positive but less enthusiastic compared to Cluster 1. Cluster 2 demonstrates moderate interest (3.3–4.65). Cluster 3 records the lowest means (2.2–3.2) reflecting users who are less interested/indifferent towards these technologies. Overall, the results suggest that user preferences are segmented into distinct groups ranging from strong supporters to low-interest users of AI and VR.

### 5.3 Correlation Analyses

We do not measure causal improvement, because the study is short term. Evidence of causal improvements are usually possible only for long-term studies. Hence, we depend more on correlation for this preliminary study. With a chi square (effect size) of 13.78 (Fig. 7b), age is positively correlated with the 2 technologies but does not explain the

other variable to much extent. It hints at other variables as more important/significant. The probability of 0.13 indicates that they are not significantly interested and DF of 9 implies that they are open to persuasion given sufficient reasons/incentives. This may apply especially for respondents < 18 years old (13.8%) and 19–24 years old (77.23%).

Cluster Means

| Cluster | Q4 | Q5 | Q7 | Q8 |
|---|---|---|---|---|
| 1 | 4.923076923 | 4.980769231 | 4.865384615 | 4.923076923 |
| 2 | 4.400000000 | 4.650000000 | 3.300000000 | 3.350000000 |
| 3 | 3.200000000 | 3.200000000 | 2.200000000 | 2.400000000 |
| 4 | 3.833333333 | 3.750000000 | 4.458333333 | 4.458333333 |

**Fig. 7a.** Means across clusters

Statistics for Table of CLUSTER by age_group_encoded

| Statistic | DF | Value | Prob |
|---|---|---|---|
| Chi-Square | 9 | 13.7771 | 0.1305 |
| Likelihood Ratio Chi-Square | 9 | 11.7903 | 0.2254 |
| Mantel-Haenszel Chi-Square | 1 | 0.2237 | 0.6363 |
| Phi Coefficient | | 0.3693 | |
| Contingency Coefficient | | 0.3465 | |
| Cramer's V | | 0.2132 | |

**Fig. 7b.** Chi-square, DF, age probability

As for gender, a chi square of 1.9846 (Fig. 7c), and a probability of 0.58, implies there is not much difference between gender. The degree of freedom of 3 further implies that respondents can be persuaded slightly, given usefulness/value. Value in [10]'s online shopping drivers (an abstraction of longitudinal studies), is congruence.

Building on [10, 21]'s findings on an almost similar demographic concur. Hence, new business models, and cooperative value chains should persuade/build on individual/social psychological factors e.g., congruence, value consciousness, trust, enjoyment and adapt strategies to each cluster's attracting and sustaining factors.

Statistics for Table of CLUSTER by gender_encoded

| Statistic | DF | Value | Prob |
|---|---|---|---|
| Chi-Square | 3 | 1.9846 | 0.5756 |
| Likelihood Ratio Chi-Square | 3 | 1.9798 | 0.5766 |
| Mantel-Haenszel Chi-Square | 1 | 0.1555 | 0.6933 |
| Phi Coefficient | | 0.1402 | |
| Contingency Coefficient | | 0.1388 | |
| Cramer's V | | 0.1402 | |

**Fig. 7c.** Chi-square, DF, gender probability

### 5.4 Regression

Figure 8 indicates that likelihood to use an AI recommendation/search bar when shopping (Q4) and intention to use are strongly correlated (chi square of 0.73). However, its dependent mean is 4.63. At $p$ 0.22, the AI search bar is thus not significant. However, respondents would certainly be (DF1) satisfied if the AI could suggest products that match their preferences (Q5). With a $p < 0.001$, highly successful matching significantly predicts the likelihood of using the AI search bar.

The REG Procedure
Model: MODEL1
Dependent Variable: Q4

| | |
|---|---|
| Number of Observations Read | 101 |
| Number of Observations Used | 70 |
| Number of Observations with Missing Values | 31 |

Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 2 | 19.35350 | 9.67675 | 92.76 | <.0001 |
| Error | 67 | 6.98936 | 0.10432 | | |
| Corrected Total | 69 | 26.34286 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 0.32298 | R-Square | 0.7347 |
| Dependent Mean | 4.62857 | Adj R-Sq | 0.7268 |
| Coeff Var | 6.97805 | | |

Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| Intercept | 1 | 0.62234 | 0.30758 | 2.02 | 0.0470 |
| ai_search | 1 | 0.32447 | 0.25965 | 1.25 | 0.2158 |
| Q5 | 1 | 0.79255 | 0.06868 | 11.54 | <.0001 |

**Fig. 8.** Likelihood of customers using the AI search bar

To predict AI + VR adoption, the multiple linear regression analysis in Fig. 9 informs us that age and gender are not significant at $p$ 0.0640 and $p$ 0.0191 respectively. This indicates that, demographic factors do not significantly predict attitudes toward the proposed technology adoption. However, correlation between AI + VR and intention to adopt AI + VR is strong at 0.69 and dependent mean of 0.89. This is supported by likelihood to try's (Q7) and likelihood of improving shopping experience's (Q8) $p <$ 0.05, with a variability of 13–15% respectively. It is not conclusive at this stage, whether findings for AI-assisted recommendations will be similar for AI + VR, i.e., ease of use, and highly accurate/useful recommendations, sustain.

The REG Procedure
Model: MODEL1
Dependent Variable: ai_vr

| | |
|---|---|
| Number of Observations Read | 101 |
| Number of Observations Used | 66 |
| Number of Observations with Missing Values | 35 |

Analysis of Variance

| Source | DF | Sum of Squares | Mean Square | F Value | Pr > F |
|---|---|---|---|---|---|
| Model | 4 | 4.34672 | 1.08668 | 34.69 | <.0001 |
| Error | 61 | 1.91085 | 0.03133 | | |
| Corrected Total | 65 | 6.25758 | | | |

| | | | |
|---|---|---|---|
| Root MSE | 0.17699 | R-Square | 0.6946 |
| Dependent Mean | 0.89394 | Adj R-Sq | 0.6746 |
| Coeff Var | 19.79889 | | |

Parameter Estimates

| Variable | DF | Parameter Estimate | Standard Error | t Value | Pr > \|t\| |
|---|---|---|---|---|---|
| Intercept | 1 | -0.20869 | 0.14986 | -1.39 | 0.1688 |
| gender | 1 | -0.10941 | 0.04545 | -2.41 | 0.0191 |
| age_group | 1 | -0.06439 | 0.03414 | -1.89 | 0.0640 |
| Q7 | 1 | 0.13584 | 0.04392 | 3.09 | 0.0030 |
| Q8 | 1 | 0.15023 | 0.04496 | 3.34 | 0.0014 |

**Fig. 9.** Likelihood of customers adopting the AI + VR

### 5.5 Limitations of the Study

The first limitation of this study is that the sample size is small, as the data is collected at the end of the school semester, as part of the course requirements. Hence, findings cannot be generalized. Second, the perception study is based on a Figma prototype. We do not know how users will perceive an actual system.

## 6 Circular Economy, SusAF, TAM, IREB RE Frameworks, Design Thinking

*RQ3: To what extent can our AI + VR become more localized in terms of circular economy frameworks and values?*

The design of strategies in the methodology section, indicates positive mapping between system functions/value. User testing findings have also indicated high averages, implying technology acceptance towards all three search/visualization methods, i.e., gamified quiz bundling, AI recommendations and AI + VR, though respondents prefer gamified quiz bundling most.

Furthermore, ontology in its diverse representations, e.g. XML, RDF and OWL are part of the Semantic Web. Finding suitable t- and h-conorms [1], and [22]'s aspect/ feature learning e.g. via [23]'s *apriori* can simplify design across SDGs [5]. Contextualizing these within frameworks and respective metrics in Table 2, e.g. SusAF [6], PESTEL [13], drivers for online shopping [10] and designing/developing based on the IREB's RE would provide more holistic guidelines/assessments.

Aggregation and optimization e.g. [24]'s global-local ontological matching and [25]'s imperfect-information games based on exponential counterfactual regret minimization, can balance/optimize tradeoffs to enhance unsupervised learning, agility. However, these are beyond our ability.

Furthermore, [2]'s emphasis on cross-disciplinary intelligence and redesign leads us creative analogies. Exemplary enablers are *Lazada* and *Shopee's* successful aggregation via cross-brand filters and *Starbucks' Ideastorm's* idea-generation/voting/shaping gamified community respectively. [3]'s attachment points us to gamification, critical in sustaining traffic and sales in Asia's *Lazada* and *Shopee* and to propose opt in/out quiz-based AI-personalized AR/VR extending externally from live streaming; simplified from Meta's Google Glass vision, for developing economies. Trust via serious security/privacy and fulfilling terms and conditions of sales/use.

In terms of localization, from Fig. 7a, cluster 3 has the lowest mean across Q4 to Q8, especially Q7 on possibility of trying the AI + VR feature. This indicates that we need to tap into TAM 3's adjustment, i.e., perceived enjoyment and objective consumption (Table 3). Considering that they are mostly young, cost is primary. Hence, AI + VR search may be improved if they can gain points to redeem items related to their studies/hobbies. This emulates Lazada/Shopee, where points are given for any task across brands/ products (objective consumption) the user chooses to carry out in the system at the point collection page. These points can be applied upon checkout. Community service (Madani's compassion) or tasks reducing climate change (Madani's sustainability) can be factored in among these tasks.

Moreover, the promotion of objective consumption can also apply to Cluster 2. However, Cluster 2's means for Questions 4 and 5 are very high at 4.40 and 4.65 respectively. Hence, the game/point system can include the number of likes/shares and consequent likes/shares to update the AI model and to refine AI recommendations.

## 7 Conclusion

MUJI operates across multiple product categories with a focus on cohesive design and usability. This captures a vital aspect of its market identity. It has partnered with Salesforce, SAP, Microsoft to improve data integration, customer engagement, analytics and scalability. Through diverse design frameworks, e.g. the IREB's RE framework, strategic group map, PESTLE, Sustainability Awareness Framework, TAM 1, 2, 3 and Venkatesh, Speier-Pero, and Schuetz's online shopping model, analyses, design and development are guided, validated and managed. Our gamified quiz-based real-time bundling is ranked highest compared to AI solutions, mainly because gamifying sales and services (loyalty points) is expected in Malaysia, as a means to increase inclusion/affordability. Since congruence and enjoyment are key deciders, depending on regions and respective cultures, prioritizing individual/societal values-based design (design thinking) may increase relevance/congruence and thus sustainability; bridging across all 5 SusAF dimensions.

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## References

1. Rudas, I.J., Pap, E., Fodor, J.: Information aggregation in intelligent systems: an application-oriented approach. Knowl.-Based Syst. **38**, 3–13 (2013)
2. Medkova, K., Fifield, B.: Circular Design – Design for Circular Economy. Lahti University of Applied Sciences (2016)
3. TU Delft: Circular Product Design, The Netherlands (2016). https://www.ellenmacarthurfoundation.org/circular-economy/buildingblocks
4. Goel, A.K.: Analogy, design and creativity. IEEE Expert **12**(3), 62–70 (1997). https://doi.org/10.1109/64.590078
5. Lee, C.S.: Simplifying strategic frugal innovation and sustainability formulation and evaluation: an SDG-maslowian approach: a review and proposed framework. In: Gervasi, O., et al. Computational Science and Its Applications – ICCSA 2025 Workshops. ICCSA 2025. Lecture Notes in Computer Science, vol. 15895, pp. 157–174. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97651-3_11

6. Penzenstadler, B., et al.: The SusA Workshop - improving sustainability awareness to inform future business process and systems design. Zenodo (2020)
7. Davis, F.D., Bagozzi, R.P., Warshaw, P.R.: User acceptance of computer technology: a comparison of two theoretical models. Manage. Sci. **35**(8), 982–1003 (1989). https://doi.org/10.1287/mnsc.35.8.982
8. Davis, F.D., Venkatesh, V.: A critical assessment of potential measurement biases in the technology acceptance model: three experiments. Int. J. Hum. Comput. Stud. **45**(1), 19–45 (1996). https://doi.org/10.1006/ijhc.1996.0040
9. Venkatesh, V., Bala, H.: Technology acceptance model 3 and a research agenda on interventions. Decis. Sci. **39**(2), 273–312 (2008). https://doi.org/10.1111/j.1540-5915.2008.00192.x
10. Venkatesh, V., Speier-Pero, C., Schuetz, S.: Why do people shop online? A comprehensive framework of consumers' online shopping intentions and behaviours. Inf. Technol. People **35**(5), 1590–1620 (2022). https://doi.org/10.1108/ITP-12-2020-0867
11. Malaysia Madani. https://malaysiamadani.gov.my/
12. Tan, T.H., Lee**,** C. S.: Investigating the effectiveness of a customer satisfaction - technology acceptance models - madani approach to personalization in a SuperApp. IEEE TEMSCON ASPAC, Thailand, 14–16 September 2025
13. Gamble, J.E., Peteraf, M.A., Thompson, A.A.: Essentials of Strategic Management: The Quest for Competitive Advantage. McGraw-Hill (2023)
14. Porter, M. E.: Competitive Strategy: Techniques for Analysing Industries and Competitors. Free Press, NY (1980)
15. Valacich, J.S., George, J., Hoffer, J.F.: Essentials of Systems Analysis and Design. Wiley & Sons (2015)
16. Han, S.: Analysis of MUJI's development strategy in China under the background of consumption downgrade. J. Appl. Econ. Policy Stud. **12**(1), 36–39 (2024). https://doi.org/10.54254/2977-5701/12/2024119
17. Liu, C.: Research on marketing strategy and business operation mode of FMCG brands: a case study of MUJI. Adv. Econ. Manage. Polit. Sci. **148**(1), 74–81 (2025). https://doi.org/10.54254/2754-1169/2024.LD19171
18. Lewis, L.: The ultimate MUJI experience – across seven floors. Financial Times (2025). https://www.ft.com/content/671c21a1-700d-47fa-81de-e2a1670b973b
19. Beltrán - Urvina, L.I., Acosta - Andino, B.F., Gallegos - Varela, M.C., Vallejos - Orbe, H.M.: Intellectual property as a strategy for business development. Laws **14**(18) (2025). https://doi.org/10.3390/laws14020018
20. Zhao, Y.: Internet of things technology in smart furniture: an overview. J. Electrotechnol. Electr. Eng. Manage. **7**(10), 107–112 (2024). https://doi.org/10.23977/jeeem.2024.070114
21. Lee, C.S., Lee, J.Y.: E-commerce factors that motivate consumers' purchasing decisions: a cross-regional study and local attractors and sustainers for personalization. In: IEEE International Conference on Information & Communication Technology, Melaka, Malaysia, 23–24 August 2023
22. Burnap, A., et al.: Improving design preference prediction accuracy using feature learning. ASME J. Mech. Des. **138**(7), 071404 (2016)
23. Lim, A.H.L., Lee, C.S.: Processing online analytics with classification and association rule mining. Knowl.-Based Syst. **23**(3), 248–255 (2010)
24. Xue, X., Ye, M.: Interactive complex ontology matching with local and global similarity deviations. Electron. Res. Archive **31**(9), 5732–5748 (2020)
25. Li, H., Wang, X., Qi, J., Zhang, Y., Liu, Y., Wu, Jia, F.: Solving imperfect-information games via exponential counterfactual regret minimization. J. IEEE Intell. Syst., 1–10 (2020)

# From Mega-Event to Measurable Legacy: Localising the SDGs Through the UEFA EURO 2032 Sustainability Concept and Strategy

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**Abstract.** Sports mega-events are increasingly required to leave a measurable and lasting legacy in the cities and territories that host them, thus moving beyond the mere rhetoric of sustainability.

In this regard, the Sustainability Concept and Strategy developed by Politecnico di Milano for the Italian Football Federation (FIGC) as part of the UEFA EURO 2032 bid integrates environmental, social, and governance (ESG) principles throughout the entire lifecycle of the sporting event, from its conception to its post-event legacy, and positions the FIGC UEFA EURO 2032 mega-event as a catalyst for transformational change aligned with the United Nations 2030 Agenda and the UEFA Sustainability Strategy 2030.

Specifically, the framework foresees stakeholder engagement from the early stages of proposal development and action monitoring based on Key Performance Indicators (KPIs), in turn aligned with the Sustainable Development Goals (SDGs). The proposed Sustainability Concept and Strategy aims to achieve and localise key sustainability objectives such as carbon neutrality, zero waste, biodiversity protection, sustainable mobility, renewable energy communities, smart energy monitoring, and water reuse systems, generating long-term territorial environmental benefits while ensuring full respect for human rights.

As a key innovation aimed at ensuring long-term territorial benefits across the host cities and promoting a shared culture of environmental sustainability, the Sustainability Concept and Strategy introduces "Sustainable Living Labs" in each host city as participatory governance arenas for the co-design of local actions.

This contribution provides insights into the key elements of the Sustainability Concept and Strategy and discusses how this framework, and sports mega-events more broadly, can evolve from short-term spectacles into measurable sustainability transitions, localising the SDGs throughout the event lifecycle and generating tangible and lasting territorial impact. Finally, the paper offers an interdisciplinary and replicable model for future international sporting events.

**Keywords:** SDG Localisation · Territorial Sustainability · Sustainable Legacy

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## 1 Introduction

Sports mega-events such as the Olympic Games, FIFA World Cup, and UEFA European Championships, have long been recognized as, and proved to be, instruments of territorial development and urban transformation, with both positive and negative impacts on hosting cities and their inhabitants (Antyufeev et al., 2018; Roult and Lefebvre, 2013; Wolfe et al., 2022). However, despite their potential to generate economic benefits and international visibility (Andersson et al., 2008; Boto-García and Santana-Gallego, 2026; Siegfried and Zimbalist, 2006), these events have also been largely criticised since, if not sustainably and adequately planned, can ultimately generate significant environmental impacts (Cerezo-Esteve et al., 2022; Collins et al., 2009) considering e.g. the infrastructure and construction, transportation, and waste management domains (Pourpakdelfekr and Oboudi, 2022); social inequalities such as the creation of disturbances affecting quality of life, including traffic, noise, and urban congestion, gentrification driven by the construction of new infrastructure supporting the event, and the exclusion of citizens from decision-making and planning processes (Mair et al., 2023; Silvestre, 2009); finally, researchers suggest that short-term urban investments often lack a long-term legacy, particularly regarding the post-event conversion and use of infrastructure specifically built for mega-events, which often remain underutilized 'white elephants' (Cornelissen et al., 2011; Reis et al., 2023).

Building on this context and evidence, in recent years international institutions, as well as governing bodies, have progressively integrated sustainability objectives into the planning and management of sport mega-events (Meza Talavera et al., 2019; Moon et al., 2022). The United Nations 2030 Agenda for Sustainable Development, particularly its 17 Sustainable Development Goals (SDGs), have provided a global framework encouraging public institutions and private organisations to incorporate sustainability into decision-making processes (UN Desa, 2016). In parallel, UEFA has introduced its Sustainability Strategy 2030 – "Strength Through Unity", aimed at embedding sustainability principles across European football governance (UEFA, 2021). Within this evolving context, sports mega-events are expected to function not only as entertainment events but also as opportunities for advancing sustainability, considering all its elements, i.e. sustainable urban development, social inclusion, and environmental responsibility (Mair et al., 2023; Moon et al., 2022).

The Italian bid for UEFA EURO 2032 represents a significant case study in this regard. The Sustainability Concept and Strategy developed by Politecnico di Milano to support the Italian Football Federation (FIGC) bid to UEFA 2032 aims to integrate environmental, social, and governance (ESG) principles throughout the entire lifecycle of the event, from the early stages of planning to the post-event legacy. The framework proposes a structured and replicable approach to localising the SDGs within host cities, combining sustainability governance, stakeholder engagement, environmental planning, and monitoring tools based on Key Performance Indicators (KPIs).

The present contribution aims to present the conceptual structure of the Sustainability Concept and Strategy developed for the Italian candidature and discusses how this framework, and sports mega-events more broadly, can evolve from short-term spectacles into measurable sustainability transitions, localising the SDGs throughout the event lifecycle and generating tangible and lasting territorial impact.

### 1.1 Sustainability and Sports Mega-Events: Theoretical Background

Recent scientific research has focused on demonstrating and discussing the importance of integrating sustainability principles, particularly referring to the Triple Bottom Line (Mair et al., 2023), into the planning and management of sport mega-events and their long-term legacies. In this perspective, sustainability in mega-events can be understood as a multidimensional concept involving three main dimensions: environmental sustainability, social sustainability and economic and governance sustainability.

The localisation of the SDGs represents an emerging approach within sustainability governance (Jones and Comfort, 2020; Reddy, 2016; Tan et al., 2019). More specifically, SDG localisation, within the framework of the 2030 Agenda, refers to the process of translating global sustainability goals into actions implemented at the local level (UN, 2024). In this regard, sport mega-events, if adequately conceived and planned, could play a key role in this process by engaging stakeholders, public institutions, and civil society actors around shared sustainability objectives. In addition, the combination of SDG localization with monitoring and evaluation tools, such as sustainability frameworks (Ma et al., 2011; Reis et al., 2023), international standards and guidelines, such as ISO 20121 (Hall, 2012) and the Global Reporting Initiatives (Moon et al., 2022), as well as socio-economic and environmental indicators and KPIs (Leonardsen, 2007; Ma et al., 2011; Mair et al., 2023), can effectively assess the real impact of sustainability strategies and their concrete implementation, thereby ensuring transparency and accountability.

## 2 Methodological Approach

The integrated methodological approach, at the basis of the Sustainability Concept and Strategy developed with FIGC for the candidature to UEFA EURO 2032, is based on three main elements:

- Strategic alignment with international sustainability frameworks
- Multi-level governance and stakeholder engagement
- Monitoring and assessment through sustainability indicators

The framework is aligned with both the UEFA Sustainability Strategy 2030 and the UN SDGs, ensuring coherence with international sustainability standards and aims to create a unique and sustainable experience including all aspects of accessibility, healthy lifestyle, sustainable event management and human rights. An innovative aspect of the methodological approach is the localisation of SDGs through concrete actions implemented in host cities and stadiums, supported by a structured monitoring system based on KPIs.

Stakeholder engagement, through Sustainable Living Labs (De Toni and Morello, 2025; Paskaleva and Cooper, 2021), is considered a central and unique element of the governance model. The framework foresees the creation of a Sustainability Working Group composed of a permanent FIGC Sustainability Task Force, Host Cities. Stadiums and fan representatives, and constantly in contact with UEFA to report on sustainability policy and ongoing activities, will improve stakeholders' relations and the sustainability of the event. This participatory governance structure ensures continuous dialogue among actors involved in the planning and implementation of sustainability initiatives.

### 2.1 The Sustainability Concept and Strategy for UEFA 2032

The Sustainability Concept and Strategy is based on a robust workflow scheme, considering the entire Tournament lifecycle, from planning to post-event legacy.

More specifically, the workflow (Fig. 1) first identifies the main challenges that the Tournament is expected to address during the design and implementation phases. These include, among others, ensuring the climate neutrality of the event; promoting sustainable mobility for all participants, including spectators; fostering circular economy practices aimed at achieving a zero-waste scenario; enhancing infrastructure sustainability by prioritising the use of existing facilities and improving their energy performance; as well as ensuring full respect for human rights and social inclusion. The formulation of the goals must therefore be aligned with the challenges to be addressed, and in turn, for each goal, specific targets, actions, and KPIs are defined, the latter aimed at quantifying the impact of each action implemented. The KPIs are aligned with and must contribute to the SDGs and their related goals and targets, as well as to UEFA's sustainability strategy, thereby ensuring the sustainability of the entire process. One of the key objectives of the Sustainability Concept was to achieve comprehensive coverage of all the SDGs through targeted actions and dedicated budget allocations (see Figs. 1 and 2). This approach supported the ongoing validation of alignment with the 2030 Agenda and facilitated stakeholder discussions whenever gaps or missing aspects were identified.




**Fig. 1.** Summary of the work scheme. The scheme has been simplified to make reading and understanding easier. Different "Goals" and "Targets" may correspond to each "Challenge/Macro-theme", according to an integrated approach. The Localization of UEFA Sustainability Strategy 2030 and SDGs will guide the entire process, from the definition to the monitoring of actions, finally focusing on KPIs.

The Strategy is structured around three components: the Good Governance Plan, the Environmental Plan, and the Human Rights Plan. For each of these, based on the inputs and proposals provided by stakeholders throughout the participatory process, a set of specific sustainability objectives was defined, along with corresponding actions and related KPIs. These objectives were then mapped against the SDGs. Figures 1, 2 and 3 illustrate this relationship graphically, showing the contribution of each objective to the SDGs and clarifying their relative weight within the overall sustainability framework.

The Sustainability Concept and Strategy and the roadmap to the Tournament will increase public awareness on the role of football and its impacts ranging from the local to the global level. Thus, the Sustainability Concept and Strategy must also take into account the three dimensions in which it operates: from the most local dimension, namely the stadium as an infrastructure, to the meso-scale, which positions the stadium within

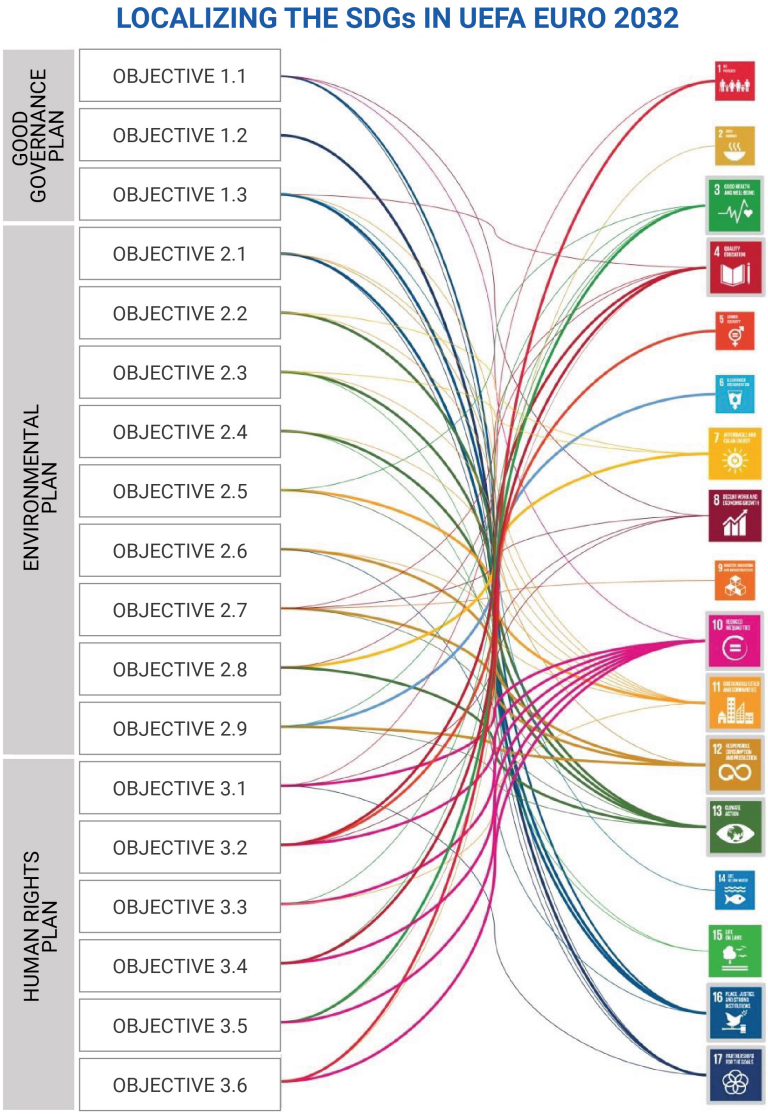


**Fig. 2.** Localizing the SDGs in the UEFA EURO 2032 Tournament, from alignment with UEFA requirements to the verification of full coverage of the 17 SDGs.

the community and city in which it is located, and finally to the global dimension, where the actions implemented to host UEFA EURO 2032 will have an impact on the entire society participating in or following the event, beyond the boundaries of the host city (Fig. 4).

While significant attention has traditionally been devoted to the very local scale of sports infrastructure and facilities, as well as to the broader sustainability values that sport can convey, comparatively limited focus has been placed on the meso-scale of host

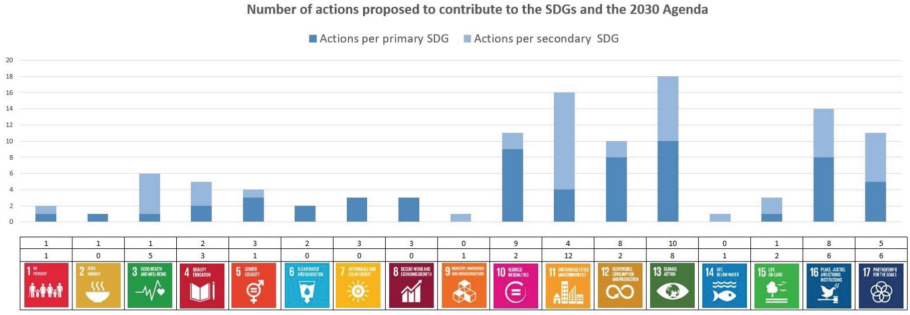


**Fig. 3.** Number of actions proposed within the Sustainability Concept to ensure comprehensive coverage of the 2030 Agenda SDGs in the Tournament.

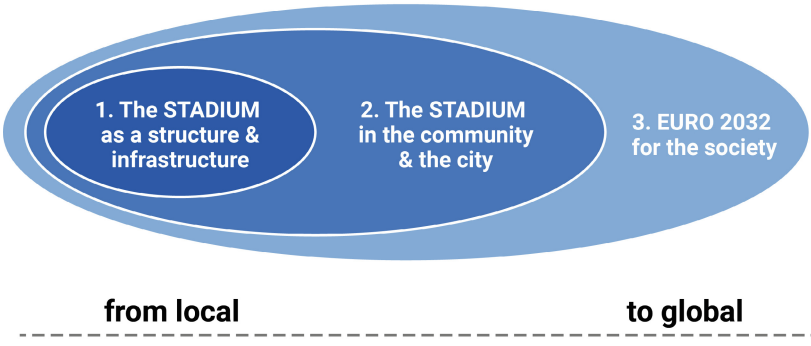


**Fig. 4.** The three dimensions in which EURO 2032 operates: from the local scale (stadium), through the meso-scale (city and community), up to the global dimension (society as a whole that participates in or follows the event).

communities. This gap has contributed to many shortcomings in the long-term legacy of mega sporting events (Meza Talavera et al., 2019; Sobko et al., 2025; Wang et al., 2025). In response, the proposed trans-scalar framework underpinning the Sustainability Concept addresses impacts across multiple scales. Each scale involves distinct stakeholders and relates to different SDGs; therefore, it is essential to map and acknowledge this geography of responsibilities and capacities in order to make each stakeholder's contribution visible and effective.

Grounded in participatory principles, Politecnico adopted a strongly collaborative approach that, based on a guiding framework, prioritized the co-production of the Strategy's contents among all involved stakeholders. The core of the work consisted of two collaborative workshops facilitated by Politecnico, which brought together UEFA and FIGC staff, a professional consulting firm, and technical and political representatives from all the host cities and stadiums involved in the Tournament planning process. This approach followed a solid body of research on participatory methods for sustainability (Moallemi et al., 2021) as well as specific strands of studies on SDG achievement (Messerli et al., 2019).

### 2.2 Good Governance Plan and Stakeholder Engagement

The Good Governance Plan is defined and aligned with the relevant international standards, i.e. relevant UN strategies and guiding principles, deploying a compliance management system according to the risk assessment on relevant issues. Moreover, the Good Governance Plan will follow the guiding principles of a participatory approach, involving relevant stakeholders to identify the main sustainability issues related to the Tournament, in line with the Sustainability Concept and Strategy.

The proposed Good Governance Plan is based on a governance model that includes the establishment of a FIGC Sustainability Task Force, which will coordinate sustainability policies and actions while monitoring progress throughout the entire lifecycle of the event. The Sustainability Task Force will also work closely with both, host cities and stadium authorities, and international and national stakeholders (fan, business, NGOs, public institutions, etc.) (Fig. 5).

Stakeholder engagement plays a key role in ensuring transparency and accountability. The framework promotes continuous dialogue among actors involved in the planning and implementation of sustainability initiatives. Participatory governance mechanisms are particularly important in the context of urban sustainability transitions, as they enable the co-production of knowledge and policies among different actors.

### 2.3 Environmental Strategy

The environmental strategy for UEFA EURO 2032 addresses several key sustainability challenges, including climate action, sustainable mobility, circular economy, and resource efficiency.

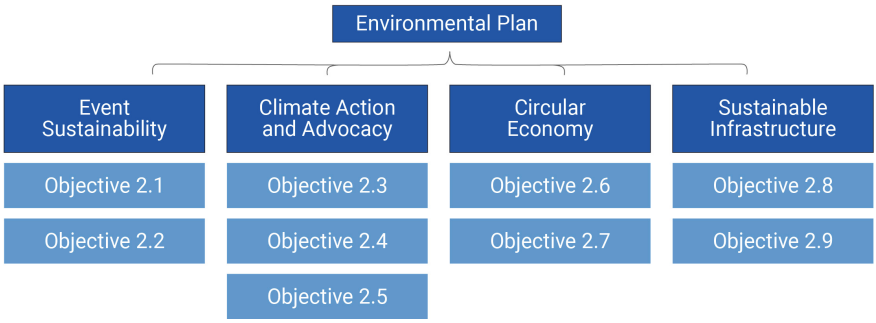


**Fig. 5.** Environmental Plan at a glance.

The Environmental Plan is organized around 4 areas of Actions and 9 Objectives, established merging SDGs with policy and proposals from all the stakeholders involved (UEFA, FIGC, host cities and host stadiums). Based on this structure, all the actions to be implemented were organized into a sustainability matrix, indicating for each of them: Objective, Indicators, Status quo and target to achieve, Time frame (start-end), Actors (leader and partners), Budget and allocation per actor (with co-financing), and SDGs (primary and secondary in terms of impact).

In this way, alignment with the SDGs went beyond a merely indicative or referential exercise, becoming instead a structuring element in the definition of actions. This approach was intended to ensure that the project, as a whole, contributed as broadly and evenly as possible across the SDG framework. In doing so, it seeks to move beyond a conception of the SDGs as discrete, sector-specific targets to be considered primarily at the stage of impact monitoring, and instead frames them as an integrated and generative mosaic to be embedded within the design and planning phases of the event (Brockwell et al., 2024).

**Climate Neutrality**

The framework aims to achieve carbon neutrality by estimating and measuring greenhouse gas emissions (GHG) generated by the event and implementing mitigation and compensation measures. A plan for the reduction and compensation for all the unavoidable GHG emissions of the event will be defined aiming for a carbon neutral event according to EU and national policies. The compensation measures can be guaranteed through afforestation projects which have to take place in the metropolitan areas hosting the event. In each venue, new Green Areas will be created to promote environmental awareness and compensate GHG emissions of the Tournament.

**Sustainable Mobility**

The mobility strategy, with the overall aim of achieving 80% of spectators using public transport to reach the Tournament, will be defined based on three mobility scales:

- **Local mobility to reach the stadium**: primarily targeting spectators attending the Tournament, it includes promoting the use of local public transport through dedicated offers for ticket holders, alongside limiting parking to electric and low-emission vehicles, and encouraging shared mobility and micro-mobility;
- **Transfers between venues**: for teams and staff, most travel between venues will take place by train, thanks to the high-speed rail network connecting the host cities;
- **Arrival in Italy**: discounts will be provided for ticket holders entering Italy by train or other sustainable modes of transport, alongside the implementation of compensation schemes for those travelling by air.

Finally, the mobility strategy will promote healthy spaces and well-being through:

- The implementation of safe and comfortable pathways to reach the venues, encouraging walkability and the use of public transport.

**Circular Economy**

Based on the quantification of current values of waste produced and recycling levels achieved during normal operation, FIGC will implement a Zero Waste scenario per Host City and Stadium, particularly addressing:

- Selling of paper or biodegradable packaging and products in the stadium (services and vending machines): tetra pack for drinks;
- Plastic-free event (both services and vending machines);
- Collection of organic waste and agreements with local waste management utilities;

- Green public procurement for cleaning and toilets.

Moreover, the environmental impact of waste treatment will also be optimized. A dedicated programme on Circular Economy will be developed in schools in all venues before the Tournament as part of the roadmap to the event. Finally, 10 Circular Labs (circular economy city-based projects) will be created, enhancing consultation, collaboration with local organisations, schools and stakeholders on circularity practices within the local urban living labs activated in each city.

**Sustainable Infrastructure**

The Tournament will represent an opportunity to improve environmental standards and achieve excellence across all Host Cities and venues, with priority given to the use of existing or already planned infrastructure.

Infrastructure-related activities will mainly focus on the areas of energy and water.

**Energy:** the implementation of a harmonised smart metering system and data analytics across all 10 stadiums, aimed at quantifying energy consumption and related sources, will be one of the main objectives. Investing in the communication of sustainability values and data to the public will be another key goal, including energy consumption, clean energy production, and the overall ecological footprint of the event. The purchase of 100% green electricity for all sports facilities and stadiums will ensure environmental protection while maximising the use of renewable energy sources.

Ten Citizen Energy Communities (CECs), one per city, will be established by leveraging all suitable surfaces around sports facilities (stadiums, parking areas, and open spaces) for photovoltaic installations, while actively involving local stakeholders in the energy transition based on local needs.

**Water:** starting from the essential preliminary activity of measuring water use and subsequently optimising it, the main objectives related to water management include promoting a sustainable water supply, providing one drinking water fountain for every 1,000 spectators, and encouraging the use and sale of reusable water bottles. Additional actions include the separation of white, grey, and black water with reuse for flushing systems; the collection and reuse of rainwater across all venues; the reuse of collected rainwater for evaporation systems and irrigation; and, finally, the implementation of Sustainable Urban Drainage Systems (SUDS) around the 10 stadiums (following the "sponge city" approach), strengthening ecological infrastructure and drainage systems.

### 2.4 Human Rights and Social Inclusion

Beyond environmental sustainability, the strategy includes a comprehensive Human Rights Plan, a due diligence plan and risk analysis related to human rights will be defined and implemented, also including an effective grievance mechanism.

Particularly, policies focus on:

- equality and inclusion
- anti-racism and anti-discrimination initiatives
- inclusion and Football For All Abilities

- child and youth safeguarding
- refugee support and inclusion programmes
- health and well-being promotion

Educational programmes and awareness campaigns will be implemented in schools, football academies, and fan communities to promote social inclusion and human rights.

### 2.5 Sustainable Living Labs and SDGs Localisation

Drawing on the Politecnico di Milano's longstanding expertise, two of the most innovative elements of the Sustainability Concept and Strategy are, on the one hand, the introduction of Sustainable Living Labs in each host city, on the other hand, the SDGs localisation.

Living Labs spaces are conceived and designed to reach a common goal by co-designing solutions and deploying technology and innovation (De Toni and Morello, 2025; Mukama et al., 2022). In this specific case, they function as participatory arenas where local stakeholders collaborate to design and implement sustainability initiatives linked to the Tournament. Indeed, the overall goal is to promote the culture of diversity and sustainable practices, increasing stakeholders' awareness of stadium and event sustainability actions and activities the FIGC, Host Cities, Stadiums, Airports and other mobility hubs will implement. By fostering collaboration between public institutions, local communities, and event organisers, Living Labs can contribute to building long-term sustainability capacities within host cities.

The localisation of SDGs is a recent issue described as "the process of defining, implementing and monitoring strategies at the local level for achieving global, national, and sub-national sustainable development goals and targets" (Open Working Group of the General Assembly on Sustainable Goals, 2014). The 2030 Agenda (and its update) will be translated into local measures and impacts, highlighting how the challenges will be addressed and exceeded by implementing actions that are as cross-cutting as possible across the key sustainability themes.

### 2.6 Monitoring and Sustainability Performance Assessment

The evaluation of sustainability outcomes represents a critical challenge for mega-events. The proposed framework includes a monitoring system based on Key Performance Indicators (KPIs) aligned with the SDGs and UEFA sustainability targets, to be implemented during and after the Tournament.

According to the Environmental Strategy and the Human Rights Plan, indicators will measure:

- greenhouse gas emissions
- waste production and recycling rates
- mobility patterns
- energy consumption
- social inclusion indicators

Since monitoring will occur throughout the event lifecycle, it will enable continuous assessment of sustainability performance and provide valuable data for future events.

Table 1 provides an illustrative set of KPIs for each thematic area addressed by the framework:

**Table 1.** Illustrative KPIs by thematic area, with baseline values and sustainability targets defined within the UEFA EURO 2032 Sustainability Concept and Strategy.

| Macro-theme | KPI (example) | Baseline | Target |
|---|---|---|---|
| Mobility | Share of spectators using public transport to reach venues | Previous similar event data per each Host City | 80% |
| Climate | Total GHG emissions of the Tournament ($tCO_2eq$) | Estimated carbon impacts of similar event per each Host City | Carbon neutrality (100% offset) |
| Energy | Share of electricity from renewable sources across all stadiums | Current % of renewable energy per Stadium (to be inventoried) | 100% renewable energy used |
| Waste | Separate waste collection rate at stadiums | Kg/year estimation per type of waste per each Stadium involved | Zero-waste scenario |
| Water | Drinking water fountains per 1,000 spectators | Existing drinking water fountains per Stadium (to be inventoried) | $\geq$ 1 per 1,000 spectators |
| Social inclusion | Number of anti-discrimination programmes activated | Existing programmes per host city (to be inventoried) | $\geq$ 1 per host city |
| Sustainable Living Labs | Number of stakeholder organisations engaged per host city (Living Labs) | Not yet established | $\geq$ 15 organisations per city |

## 3 Discussion: From Mega-Events to Sustainability Transition

The Sustainability Concept and Strategy developed for UEFA EURO 2032 contributes to a growing body of scientific literature that seeks to orient sport mega-events towards sustainability principles by quantifying and reporting their impacts.

Compared to previous strategies, the proposed Sustainability Concept and Strategy addresses several critical issues highlighted in the literature and past experiences, as outlined below.

**Apparent Sustainability vs Embedded Sustainability**

In contrast to past strategies, in which sustainability has often been integrated during or

after the event through event-greening initiatives or, in some cases, forms of greenwashing (Meza Talavera et al., 2019), UEFA EURO 2032 embeds sustainability objectives directly into the design of actions and structurally aligns them with the SDGs, making sustainability a true driver of both the planning and management of the event. Furthermore, integrating a structured KPI system aligned with the SDGs enhances the measurability of outcomes.

**Event Footprint vs Territorial and Trans-scalar Perspective**
While the present Sustainability Concept and Strategy builds on previous studies that focus on the environmental footprint of mega-events (Ma et al., 2011; Meza Talavera et al., 2019; Pourpakdelfekr and Oboudi, 2022), it goes a step further by adopting a territorial and trans-scalar perspective. It explicitly links stadium-level interventions with broader territorial, urban, and regional dynamics, thereby raising the likelihood that the proposed actions and interventions will generate sustainable outcomes in the medium to long term.

**Consultation vs Participatory Governance and Co-design**
Stakeholder engagement is not, in itself, an innovation, either in the scientific literature or in practice. However, participation in the planning and management of mega-events has often taken the form of top-down communication of decisions or superficial opinion surveys (Ma et al., 2011; Silvestre, 2009), rather than genuine co-production processes. By contrast, the present Sustainability Concept and Strategy is grounded in participatory design from its earliest stages and is intended to be implemented through dedicated Sustainable Living Labs, which will actively involve a wide range of stakeholders in co-design processes.

**Limitations and Implementation Challenges**
The proposed framework is characterized by certain limitations, which are less conceptual in nature than practical, relating to its implementation within real-world contexts. In practice, the actions to be implemented are contingent upon: i) the complexity of multi-level governance, which entails a medium-to-high risk of decisional fragmentation; ii) the intrinsic characteristics of the host cities, including significant heterogeneity in the availability and quality of baseline data across venues and cities and the local political decisions that each city will be required to make in accordance with the shared sustainability objectives; and iii) potentially divergent interests between host cities and long-term legacy goals. These factors introduce variables that fall outside the direct control of the framework, and which will be collectively addressed and discussed within the Sustainable Living Labs, specifically established as participatory arenas designed to mitigate the mentioned risks. Furthermore, the design of a detailed work plan for the Sustainable Living Labs, specifying both the activities and the participants to be involved, will be essential to ensure that the participatory process functions as a genuine arena for collaborative problem-solving, rather than a mere instrument for building consensus around pre-determined decisions. Finally, the sustained fulfilment of post-tournament commitments, including the achievement of agreed KPI targets, remains heavily dependent on political will beyond the event itself.

**Future Pathways**
Ultimately, the present contribution is primarily prospective in nature, since the Sustainability Concept and Strategy was developed in the context of a candidature, and its empirical validation will necessarily depend on the actual hosting of UEFA EURO 2032. Suggestions for future research should include the assessment of KPI achievement as ex-post evaluation, the effectiveness of Living Labs and the transferability of the framework to other mega-event contexts.

## 4 Conclusion

The UEFA EURO 2032 Sustainability Concept and Strategy aims to reposition sports mega-events from short-term spectacles into drivers of long-term sustainability transitions. The proposed framework emphasizes two key dimensions in order to address the inherent complexity of such events. First, it adopts a trans-scalar perspective, considering the spatial dimensions of action from the micro to the meso and macro scales, each involving different stakeholders and contributing to distinct SDGs. Second, it incorporates a long-term temporal perspective, grounded in a life-cycle approach that requires early-stage planning and governance design to enable effective collaboration. This approach fosters the meaningful involvement of host cities and local communities in processes of co-design, co-production, and, ultimately, co-management and co-monitoring of the infrastructures and solutions implemented beyond the duration of the event.

We argue that only an integrated spatial and temporal vision can ensure both the success of the event and the durability of its legacy. The engagement and empowerment of local territories, alongside the development of transformative capacities through participation in projects and deliberative processes, require robust, open, and long-term sustainability governance. In this sense, the clear definition of spatial and temporal boundaries represents a fundamental step toward establishing a shared vision and advancing sustainability as a pathway for broader societal transition.

**Disclaimer.**

The views expressed are purely those of the writers and may not in any circumstances be regarded as stating an official position of the FIGC.

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## References

Andersson, T.D., Armbrecht, J., Lundberg, E.: Impact of mega-events on the economy. Asian Bus. Manag. **7**, 163–179 (2008). https://doi.org/10.1057/abm.2008.4

Antyufeev, A.V., Ptichnikova, G.A., Antyufeeva, O.A.: City and mega event: transformation of urban structure. In: IOP Conference Series: Materials Science and Engineering, p. 12146. IOP Publishing (2018)

Boto-García, D., Santana-Gallego, M.: Old questions, new methods: revisiting the economic effects of hosting mega-sport events. Tour. Manag. **113**, 105324 (2026). https://doi.org/10.1016/j.tourman.2025.105324

Brockwell, A.J., Mochizuki, Y., Sprague, T.: Designing indicators and assessment tools for SDG Target 4.7: a critique of the current approach and a proposal for an'Inside-Out'strategy. Comp. A J. Comp. Int. Educ. **54**, 731–749 (2024). https://doi.org/10.1080/03057925.2022.2129957

Cerezo-Esteve, S., Inglés, E., Segui-Urbaneja, J., Solanellas, F.: The environmental impact of major sport events (Giga, MEGA and major): a systematic review from 2000 to 2021. Sustainability **14**, 13581 (2022). https://doi.org/10.3390/su142013581

Collins, A., Jones, C., Munday, M.: Assessing the environmental impacts of mega sporting events: two options? Tour. Manag. **30**, 828–837 (2009). https://doi.org/10.1016/j.tourman.2008.12.006

Cornelissen, S., Bob, U., Swart, K.: Towards redefining the concept of legacy in relation to sport mega-events: insights from the 2010 FIFA World Cup. Dev. South. Afr. **28**, 307–318 (2011). https://doi.org/10.1080/0376835X.2011.595990

De Toni, A., Morello, E.: Sustainable regeneration of industrial areas through enterprise engagement in collaborative design. J. Clean. Prod., 144936 (2025). https://doi.org/10.1016/j.jclepro.2025.144936

Hall, C.M.: Sustainable mega-events: beyond the myth of balanced approaches to mega-event sustainability. Event Manag. **16**, 119–131 (2012). https://doi.org/10.3727/152599512X13343565268294

Jones, P., Comfort, D.: A commentary on the localisation of the sustainable development goals. J. Public Aff. **20**, e1943 (2020). https://doi.org/10.1002/pa.1943

Leonardsen, D.: Planning of mega events: experiences and lessons. Plan. Theory Pract. **8**, 11–30 (2007). https://doi.org/10.1080/14649350601158105

Ma, S.-C., Egan, D., Rotherham, I., Ma, S.-M.: A framework for monitoring during the planning stage for a sports mega-event. J. Sustain. Tour. **19**, 79–96 (2011). https://doi.org/10.1080/09669582.2010.502576

Mair, J., Chien, P.M., Kelly, S.J., Derrington, S.: Social impacts of mega-events: a systematic narrative review and research agenda. Methodol. Adv. Soc. impacts Tour. Res., 140–162 (2023). https://doi.org/10.1080/09669582.2020.1870989

Messerli, P., et al.: Expansion of sustainability science needed for the SDGs. Nat. Sustain. **2**, 892–894 (2019). https://doi.org/10.1038/s41893-019-0394-z

Meza Talavera, A., Al-Ghamdi, S.G., Koç, M.: Sustainability in mega-events: beyond Qatar 2022. Sustainability **11**, 6407 (2019). https://doi.org/10.3390/su11226407

Moallemi, E.A., et al.: Evaluating participatory modeling methods for co-creating pathways to sustainability. Earth's Futur. **9**, e2020EF001843 (2021). https://doi.org/10.1029/2020EF001843

Moon, P., Bayle, E., François, A.: Assessing international sport federations' sustainability practices: toward integrating sustainability in their main sports events. Front. Sport. Act. Living **3**, 752085 (2022). https://doi.org/10.3389/fspor.2021.752085

Mukama, M., Musango, J.K., Smit, S., Ceschin, F., Petrulaityte, A.: Development of living labs to support gendered energy technology innovation in poor urban environments. Technol. Soc. **68** (2022). https://doi.org/10.1016/j.techsoc.2021.101850

Paskaleva, K., Cooper, I.: Are living labs effective? Exploring the evidence. Technovation **106** (2021). https://doi.org/10.1016/j.technovation.2021.102311

Pourpakdelfekr, T., Oboudi, B.: Overview of sustainable solutions to improve the environmental impacts of mega sporting events. Athens J. Sport **9**, 1–16 (2022). https://doi.org/10.30958/ajspo.9-4-2

Reddy, P.S.: Localising the sustainable development goals (SDGs): the role of local government in context (2016). https://www.local2030.org/library/307/Localising-the-SDGs-The-role-of-Local-Government-in-context.pdf

Reis, R., Telles, S., Teixeira, M.C.: Measuring the legacies of sports mega events: a systematic review. J. Phys. Educ. Sport (2023). https://doi.org/10.7752/jpes.2023.04125

Roult, R., Lefebvre, S.: Stadiums, public spaces and mega-events: cultural and sports facilities as catalysts for urban regeneration and development, in: the Routledge companion to urban regeneration, pp. 548–557. Routledge (2013)

Siegfried, J., Zimbalist, A.: The economic impact of sports facilities, teams and mega-events. Aust. Econ. Rev. **39**, 420–427 (2006). https://doi.org/10.1111/j.1467-8462.2006.00431.x

Silvestre, G.: The social impacts of mega-events: towards a framework. Esporte e Soc. **4**, 1–26 (2009)

Sobko, I., Adamchuk, V., Hrynchenko, I., Bursala, T.: Current status and prospects for the development of Ukraine's sports infrastructure: an analytical review. Heal. Technol. **3**, 36–44 (2025). https://doi.org/10.58962/HT.2025.3.1.36-44

Tan, D.T., et al.: Systems approaches for localising the SDGs: co-production of place-based case studies. Global. Health **15**, 85 (2019). https://doi.org/10.1186/s12992-019-0527-1

UEFA, U. of E.F.A.: UEFA football sustainability strategy 2030: strength through unity (2021). https://editorial.uefa.com/resources/0270-13f888ffa3e5-931c597968cb-1000/uefa_football_sustainability_strategy.pdf

UN DESA: Transforming our world: the 2030 agenda for sustainable development (2016). https://sdgs.un.org/2030agenda

UN, U.N.: Inter-agency policy brief: accelerating SDG localization to deliver on the promise of the 2030 agenda for sustainable development (2024). https://sdgs.un.org/publications/inter-agency-policy-brief-accelerating-sdg-localization-deliver-promise-2030-agenda

Wang, W., Cai, Y., Xiong, X., Xu, G.: Evaluating accessibility and equity of multi-level urban public sports facilities at the residential neighborhood scale. Buildings **15**, 1640 (2025). https://doi.org/10.3390/buildings15101640

Wolfe, S.D., Gogishvili, D., Chappelet, J.-L., Müller, M.: The urban and economic impacts of mega-events: mechanisms of change in global games. Sport Soc. **25**, 2079–2087 (2022). https://doi.org/10.1080/17430437.2021.1903438

# Specifics of Smart Cities Development in Europe (SPEED 2026)

# Small and Medium-Sized Enterprises as Providers of Regional Environmental Open Data: Connecting LCA Indicators with ESG Reporting and Sustainable Regional Development

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**Abstract.** Small and medium-sized enterprises (SMEs) generate considerable amounts of environmental data in their everyday operations, but much of this information remains unused outside the enterprise. These data could support regional policymaking, especially if they were collected and shared in a structured form. In practice, business-generated data often do not meet the standards required for integration into public databases. This paper examines how SMEs can contribute to regional environmental open data, with a focus on Life Cycle Assessment (LCA), ESG reporting, and sustainable regional development. The study combines preliminary empirical evidence from Slovak SMEs with a systematic review of relevant literature. It investigates whether SMEs monitor environmental indicators more frequently in the earlier stages of the product life cycle, particularly procurement and production, than in the later stages, such as consumption, use, and end-of-life treatment (H1). Five specific indicators are examined: product origin transparency (H2a), energy consumption in production (H2b), fuel consumption (H2c), average product lifespan (H2d), and the proportion of repaired products compared with discarded products (H2e). The findings show that SMEs tend to focus mainly on indicators linked to internal processes. Indicators from downstream life cycle phases are monitored less frequently. The paper contributes to the discussion on how SME-generated environmental data can be transformed into regional open data and used more effectively in sustainability-oriented policy and reporting.

**Keywords:** Life cycle assessment (LCA) · Small and medium-sized enterprises (SMEs) · Open data · ESG reporting · Regional development

## 1 Introduction

Over the past few years, data have taken on a much more significant role as a strategic resource for public institutions, businesses, and society. The rise of digital technologies has reshaped how data are gathered, analysed, and applied. In this context, open data

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are increasingly viewed as a valuable instrument for fostering innovation, enhancing governance, and generating public value. At the same time, enterprises are under growing pressure to incorporate sustainability into their everyday operations, driven largely by environmental challenges, stakeholder expectations, and regulatory requirements within the European Union. Reliable environmental assessment therefore requires evidence-based information that can support both business decisions and regional sustainability policies. In this context, environmental open data can help connect corporate activities with regional decision-making, particularly in relation to SMEs.

Following an analysis of various scholarly sources [5, 8, 9, 15, 16, 23] several frameworks focusing on open data, environmental reporting, ESG, and LCA were identified. However, existing studies provide only minor coverage of SMEs as active providers of environmental open data.

The strategic research gap addressed by this study lies in the absence of an integrated approach that systematically links the environmental data of SMEs with regional open data initiatives within the framework of LCA and ESG reporting. Specifically, there is a lack of identification of administratively manageable environmental data and a deeper understanding of the barriers preventing SMEs from engaging in the open sharing of environmental information.

## 2 Literature Review

Open data consist of information collected and provided by public entities that is made accessible for reuse without restrictions. It is characterized by its multi-dimensionality, reproducibility and real-time dynamics. Typical examples include governmental data, such as postal codes, meteorological data, and survey results [2] which are primarily available in Europe through portals such as data.europa.eu, Eurostat, or the EEA Datahub. Research highlights [11, 20, 22] the increasing significance of open data for the digitalization of the economy and corporate management, where data-driven insights support innovation and the generation of economic value, particularly within the SME environment.

Enterprises are producing increasing amounts of data. Some of these data are slowly entering open data systems, but many enterprises still face a strategic dilemma: whether to keep data for internal use or share selected information through open data channels. Participation in open data ecosystems may create additional value, but the practical conditions for doing so remain unclear, especially for SMEs [9].

This issue is also pointed out by the World Economic Forum [23]. They emphasize that SMEs often face difficulties not only in publishing open data, but also in effectively using their own data. Among the main obstacles are insufficiently developed data governance structures, unclear responsibilities, and ongoing concerns related to data security. Enders et al. [9] similarly identify privacy and security risks as important obstacles to data sharing. In addition, many SMEs have limited IT infrastructure and analytical capacity. This reduces their ability to extract value from the data they already collect. The relevance of open data becomes especially clear in the context of sustainability and environmental management. Enterprises are increasingly expected to reduce their environmental impact and provide more transparent information about their activities [3]. For

SMEs, however, the implementation of sustainability practices is often limited by financial and human resources, technical expertise, and awareness of environmental impacts [4, 18]. These limitations are reinforced by low perceived benefits of environmental data sharing, time and cost constraints, missing reporting standards, and restricted access to information from supply chain stakeholders [23].

SMEs are central to the European economy. They represent more than 99% of all business entities in Europe and are responsible for a significant share of environmental pollution, estimated at 60–70% [19]. They also contribute to regional development and employment [1]. Although SMEs possess a wide range of potentially useful data, several barriers still prevent these data from being shared as open data [5, 15]. The academic literature has paid only limited attention to SMEs in the role of data publishers.

From an operational perspective, SMEs regularly generate environmental, ESG, and LCA-related information. This includes data on energy and water consumption, material inputs, emissions, waste, and logistics [5]. De la Puente et al. [8] also point out that routine environmental practices, such as recycling, energy saving, and waste reduction, produce information that could be used as environmental open data.

Other frameworks extend this view beyond internal operations. The OECD framework [21], for example, assesses SME environmental engagement through publicly available sources such as company websites. This approach includes elements of communication and transparency (environmental certifications, environmentally friendly processes, responsible sourcing, and emissions). Fortier et al. [12] also propose ESG indicators suitable for measuring SME environmental performance. These could be for example energy and water use, waste generation, recycling, carbon footprint, and product lifetime. These approaches suggest that SMEs already own relevant environmental data. What varies is the way these data are utilized. In some cases, they serve internal management purposes or support daily operations, while in others they have the potential to be applied in external communication, ESG reporting, or even integrated into standardized open data frameworks.

LCA is particularly relevant in this context. It enables environmental impacts to be assessed across the whole product life cycle. Its importance is reinforced by the CSRD Directive (EU) 2022/2464, which introduces sustainability reporting requirements for large enterprises and gradually affects SMEs through value chains [17]. Niemann et al. [16] show that SMEs are increasingly aware of the need for environmental reporting, but they often face numerous barriers.

At the regional level, environmental data remain relatively underdeveloped and are still concentrated mainly among large enterprises. If SMEs were able to collect and share selected LCA-related information, regions could gain a more complete picture of cumulative environmental impacts. Such a perspective cannot be achieved through large-enterprise reporting alone [6, 13]. Local and regional authorities could therefore play a more active role in supporting the collection, aggregation, and use of environmental indicators generated by SMEs.

Open data are an important part of this ecosystem. According to the European Union [10], making environmental data openly available helps to strengthen environmental protection by improving access for public institutions, businesses, and the research community. From this perspective, environmental data generated by SMEs have the potential

to go beyond transparency alone. They can also support innovation, more effective decision-making, and contribute to sustainable development at the regional level. Connecting open data practices with tools such as LCA and ESG reporting creates value not only for individual enterprises, but also for the development of public policies [7, 14].

## 3 Methodology and Hypotheses

The primary objective of this research is to determine whether SMEs measure indicators associated with becoming active providers of regional open data within the context of LCA and ESG reporting, and to identify which specific indicators are being measured. The paper applies a two-phase research approach. Primary research is based on a questionnaire survey and combined with qualitative research (a systematic literature review). Based on the findings, recommendations are formulated for SMEs, aimed at overcoming the obstacles that limit their participation as active providers of environmental open data.

**Phase 1.** The preliminary quantitative research, conducted between October 2025 and February 2026, focused on assessing the readiness of SMEs to implement the LCA method. The objectives were to determine whether they measure environmental indicators relevant to LCA and ESG reporting, identify which specific indicators are monitored, and explore the overall level of preparedness for engaging in corporate environmental data practices.

**Phase 2.** The second phase was based on a systematic literature review methodology to synthesize existing knowledge on SMEs as providers of environmental open data, with a particular focus on the connection of LCA, ESG reporting, and sustainable regional development. A structured search strategy was applied across selected academic databases. The databases systematically searched included Scopus (1996–2025), Web of Science Core Collection (1996–2025), and Google Scholar, which was used to identify supplementary sources. The search strategy employed Boolean operators with the following terms: (“open data” OR “environmental open data” OR “open data for sustainable region”) AND (“LCA” OR “ESG reporting”) AND (“SMEs”). Backward citation tracking was conducted on all included studies to identify additional relevant sources not captured in the initial database search. The study included publications meeting the following criteria: peer-reviewed journal articles and conference proceedings published in English, thematically focused on open data, LCA, and SMEs, covering theoretical frameworks or practical applications, published between 2017 and 2025, and available in full text. The final sample consists of 23 articles.

Artificial intelligence tools were used to assist in improving the clarity and formulation of the presented results.

**Sample**

The preliminary research focused on SMEs operating in Slovakia. The representativeness of the sample was verified using a chi-square test, considering a margin of error of 5% and a proportion of $p = 0.5$ for an unknown population parameter. The overall test of representativeness yielded a p-value of 0.778, exceeding the significance level of $\alpha = 0.05$. The minimum required sample size was set at 100 SMEs.

**Data Analysis**

To evaluate the hypotheses, IBM SPSS Statistics 29 was used. Methods of inductive and correlational statistics were applied. The Friedman test was used to identify statistically significant differences among the measured environmental indicators. The Wilcoxon signed-rank test was used to determine which indicators are most frequently measured by SMEs in Slovakia.

**Hypotheses**

Based on the literature review and empirical evidence, four hypotheses were formulated to be tested in the context of Slovak SMEs:

**H1:** It is assumed that SMEs measure environmental indicators related to the production and procurement phase more frequently than indicators associated with the consumption, use, and end-of-life disposal phase.

The types of environmental data routinely generated by SMEs are primarily linked to internal operations such as production processes, material inputs, and energy consumption, indicating a stronger measurement focus on upstream life cycle phases [5]. SMEs face limited access to data from customers and downstream processes, which limits their ability to measure environmental indicators related to the use and end-of-life phases [23]. The structure of ESG indicators in SMEs is largely concentrated toward production related metrics, while indicators associated with product use, lifespan, and end-of-life management are less frequently emphasized [12].

By formulating hypotheses H2a-H2e, the study aims to examine patterns in the measurement of environmental indicators across different phases of the product life cycle and to identify which indicators are most frequently monitored by SMEs.

**H2a:** It is assumed that, in the procurement phase, SMEs most frequently measure the indicator of product origin transparency.

Indicators related to procurement, such as material inputs and responsible sourcing practices, are commonly observed in SMEs, suggesting an increasing emphasis on supply chain transparency, including aspects related to product origin [5, 21].

**H2b:** It is assumed that, in the production phase, SMEs most frequently measure the indicator of energy consumption in production.

Among environmental indicators, energy consumption represents one of the most routinely collected metrics within SME production processes, as it is directly linked to internal activities and does not require complex data acquisition [5, 12].

**H2c:** It is assumed that, in the transport and distribution phase, SMEs most frequently measure the indicator of fuel consumption.

Although logistical processes are recognized as part of SME environmental data, specific indicators such as fuel consumption are not consistently emphasized, indicating a less systematic measurement approach in the transport and distribution phase [5, 12].

**H2d:** It is assumed that, in the consumption and use phase, SMEs most frequently measure the indicator of average product lifespan.

Indicators related to the use phase, such as product lifespan, reusability, and repairability, are identified in SME ESG frameworks, however, their measurement is

less directly embedded in routine operations compared to production related indicators [12].

**H2e:** It is assumed that, in the end-of-life phase, SMEs most frequently measure the indicator of the proportion of repaired products versus discarded products.

End-of-life indicators in SMEs are reflected through waste generation or recycling activities, however, more detailed metrics, such as the proportion of repaired versus discarded products, are not systematically captured [8, 12].

## 4 Results and Discussion

This section presents the main empirical findings and interprets them in relation to the literature. Hypothesis 1 was tested using the Wilcoxon signed-rank test, which compared the number of environmental indicators measured across selected life cycle phases. The results show that SMEs measure more indicators in the production and procurement phases than in the consumption, use, and end-of-life phases. The difference was statistically significant ($p < 0.001$). In the questionnaire, questions 28 and 29 focused on procurement and production. Questions 36 and 37 addressed transport and distribution, consumption, and use (Fig. 1).

**Wilcoxon Signed Ranks Test**

**Ranks**

| | | N | Mean Rank | Sum of Ranks |
|---|---|---|---|---|
| o36_37 - o28_29 | Negative Ranks | 44[a] | 26,07 | 1147,00 |
| | Positive Ranks | 5[b] | 15,60 | 78,00 |
| | Ties | 51[c] | | |
| | Total | 100 | | |

a. o36_37 < o28_29
b. o36_37 > o28_29
c. o36_37 = o28_29

**Test Statistics[a,c]**

| | | | o36_37 - o28_29 |
|---|---|---|---|
| Z | | | -5,376[b] |
| Asymp. Sig. (2-tailed) | | | 0,000 |
| Monte Carlo Sig. (2-tailed) | Sig. | | 0,000 |
| | 99% Confidence Interval | Lower Bound | 0,000 |
| | | Upper Bound | 0,000 |
| Monte Carlo Sig. (1-tailed) | Sig. | | 0,000 |
| | 99% Confidence Interval | Lower Bound | 0,000 |
| | | Upper Bound | 0,000 |

a. Wilcoxon Signed Ranks Test
b. Based on positive ranks.
c. Based on 10000 sampled tables with starting seed 2000000.

**Fig. 1.** Wilcoxon Signed Ranks Test for H1

Since the p-value is below the 0.05 significance threshold, the null hypothesis is rejected, and Hypothesis 1 is confirmed. The results indicate that SMEs monitor environmental indicators mainly in the earlier stages of the product life cycle. Indicators linked to product use and end-of-life disposal receive less attention.

This pattern can be understood in terms of how data are available, who has control over them, and the limits SMEs face in terms of resources. In practice, most environmental data is generated and handled in internal processes. In areas such as production and procurement, collecting data is already part of routine operations [5]. These activities are directly linked to energy use, material consumption, and relationships with suppliers. This makes it easier to track and monitor. In contrast, downstream phases such as consumption, use, and end-of-life are less visible to SMEs. They often depend on customers, users, or post-sale processes. This makes systematic measurement beyond the production more difficult [23].

Our findings are consistent with the theoretical frameworks of LCA [5, 12, 17, 23], which emphasize the importance of assessing environmental impacts across all phases of the life cycle. However, empirical evidence suggests that SMEs only partially apply this perspective. Their attention is mainly paid to indicators in upstream phases, while end-of-life indicators remain less developed. This suggests a gap between the theoretical framework and its practical implementation in SMEs.

Hypothesis H2a was tested using the Friedman test to compare the frequency of measurement among procurement-related environmental indicators (Fig. 2).

**Friedman Test**

**Ranks**

| | Mean Rank |
|---|---|
| o28a | 2,94 |
| o28b | 2,96 |
| o28c | 3,15 |
| o28d | 2,94 |
| o28e | 3,02 |

Test Statistics[a]

| | |
|---|---|
| N | 100 |
| Chi-Square | 3,644 |
| df | 4 |
| Asymp. Sig. | 0,456 |

a. Friedman Test

28a Share of certified suppliers among all suppliers
28b Share of purchases of environmentally certified products
28c Share of materials from recyclable sources among all raw materials
28d Transparency of product origin
28e Share of local suppliers among all suppliers

**Fig. 2.** Friedman Test for H2a

The analysis did not identify statistically significant differences between the indicators ($p = 0.456$). The mean ranks were very similar, indicating that SMEs measure procurement indicators with approximately the same intensity. Product origin transparency did not stand out as a clearly dominant indicator. Since the p-value is above

0.05, Hypothesis H2a is not supported. The results suggest that SMEs do not prioritize one procurement indicator, but rather apply a balanced measurement approach.

The procurement phase plays a key role. It represents the stage where SMEs engage directly with suppliers and obtain inputs. Existing research [12, 21] highlights that responsible sourcing and transparency regarding product origin are becoming increasingly important in the context of ESG reporting. In reality SMEs often struggle to obtain reliable data from their suppliers [23]. This barrier is further worsened by the absence of standardized frameworks and defined data governance, resulting in fragmented approaches to measuring environmental performance.

Hypothesis H2b was assessed using the Friedman test, which examined differences in measurement frequency among production-related indicators. The test showed statistically significant differences between the analysed indicators ($p < 0.001$), meaning that SMEs do not monitor all production indicators with the same intensity.

**Friedman Test**

**Ranks**

| | Mean Rank |
|---|---|
| o29a | 6,52 |
| o29b | 6,03 |
| o29c | 5,92 |
| o29d | 5,16 |
| o29e | 5,27 |
| o29f | 5,01 |
| o29g | 5,37 |
| o29h | 5,14 |
| o29i | 5,02 |
| o29j | 5,58 |

**Test Statistics[a]**

| | |
|---|---|
| N | 100 |
| Chi-Square | 60,552 |
| df | 9 |
| Asymp. Sig. | 0,000 |

a. Friedman Test

29a Energy consumption in production
29b Water consumption in production
29c Heat consumption in production
29d Volume of polluted wastewater discharged into the environment
29e Energy consumption in warehouse facilities
29f Heat consumption in warehouse facilities
29g Rate of use of recycled or recyclable packaging
29h Amount of packaging material per unit of product
29i Share of environmentally labeled products
29j Amount of waste generated from production

**Fig. 3.** Friedman Test for H2b

Energy consumption in production reached the highest mean rank in Fig. 3 and was therefore the most frequently measured indicator in this phase. The Wilcoxon signed-rank test further confirmed that energy consumption was statistically more significant than the other production-related indicators.

A second group of indicators included water consumption in production, heat consumption in production, and the volume of wastewater discharged into the environment. These indicators are also monitored, but not as consistently as energy consumption.

Hypothesis H2b is confirmed. SMEs appear to focus primarily on energy consumption in production, most likely because it is directly linked to operating costs, regulatory expectations, and environmental impact.

Production is the most data-intensive stage of the product life cycle for many SMEs. The indicators measured in this phase are usually connected with internal processes, where data collection is already embedded in daily operations [5].

Energy consumption is especially important because it relates to production efficiency, cost management, and environmental performance. Fortier et al. [12] note that SMEs tend to focus on indicators that are easy to measure and economically relevant. Energy consumption meets both conditions and is also central to ESG reporting and LCA assessment.

From an ESG reporting perspective, SMEs tend to prefer metrics that are easy for them to measure and directly relate to their economic performance. These indicators are often also necessary for ESG reporting, which is consistent with our theoretical frameworks.

**Friedman Test**

**Ranks**

| | Mean Rank |
|---|---|
| o35a | 4,38 |
| o35b | 4,47 |
| o35c | 5,38 |
| o35d | 4,53 |
| o35e | 4,30 |
| o35f | 3,95 |
| o35g | 4,30 |
| o35h | 4,71 |

**Test Statistics[a]**

| | |
|---|---|
| N | 100 |
| Chi-Square | 44,703 |
| df | 7 |
| Asymp. Sig. | 0,000 |

a. Friedman Test

35a Share of deliveries carried out by environmentally certified transport providers
35b Share of consolidated shipments
35c Fuel consumption in vehicles
35d Average vehicle capacity utilization
35e Share of low-emission vehicles in the fleet
35f Number of driver trainings on eco-driving
35g Share of empty runs
35h Vehicle maintenance rate

**Fig. 4.** Friedman Test for H2c

Hypothesis H2c was tested using the Friedman test for transport and distribution indicators (Fig. 4). The results showed statistically significant differences between the analysed indicators ($p < 0.001$). This confirms that SMEs do not measure all transport-related indicators equally.

Fuel consumption achieved the highest mean rank. Meaning that it is the most frequently measured indicator in this phase. This result was also supported by the Wilcoxon signed-rank test, which showed that fuel consumption was statistically more significant than the other transport-related indicators.

Other indicators, such as the share of consolidated shipments, average vehicle capacity utilization, and the share of low-emission vehicles in the fleet, formed a second tier. They are monitored, but less frequently than fuel consumption.

Since the p-value is below 0.05, Hypothesis H2c is confirmed. SMEs mainly monitor fuel consumption in transport and distribution because it is closely related to logistics costs, operational efficiency, and environmental impact.

Transport and distribution are important life cycle phases because they influence energy use, emissions, and logistics performance. SMEs generate operational data in this area, especially on fuel consumption, which is directly connected with transport activity and cost structures [5]. Fuel consumption is also one of the most quantifiable transport indicators.

Its relevance is strengthened by its connection to greenhouse gas emissions and environmental performance, both of which are important elements of ESG reporting [12]. Under growing sustainability and regulatory pressure, SMEs are more likely to monitor indicators that provide information about both economic performance and environmental footprint. Fuel consumption fulfils this role well.

More complex logistics indicators are more difficult to measure. SMEs may lack integrated information systems or the analytical capacity needed to track indirect indicators such as logistics optimization metrics [23]. Enders et al. [9] also show that enterprises tend to prioritize data that are readily available and strategically useful.

For regional open data systems, transport-related environmental data could provide valuable information on environmental impacts [6, 13]. Its measurability and practical relevance make it a suitable indicator for both enterprise monitoring and regional sustainability analysis.

Hypothesis H2d was evaluated using the Friedman test for indicators in the consumption and use phase (Fig. 5). The test showed statistically significant differences between the analysed indicators ($p = 0.023$), suggesting that SMEs do not measure all use-phase indicators with the same intensity.

Average product lifespan reached the highest mean rank in the sample. However, the Wilcoxon signed-rank test did not confirm statistically significant differences between individual indicators.

This means that, although differences were observed at the group level, no single indicator can be identified as statistically dominant across all SMEs.

Hypothesis H2d is therefore neither confirmed nor rejected. The results point to a possible tendency to prioritize product lifespan. Larger sample would be needed to verify whether this pattern also applies to the broader SME population.

**Friedman Test**

**Ranks**

| | Mean Rank |
|---|---|
| o36a | 3,25 |
| o36b | 2,83 |
| o36c | 2,96 |
| o36d | 3,02 |
| o36e | 2,95 |

**Test Statistics[a]**

| | |
|---|---|
| N | 100 |
| Chi-Square | 11,357 |
| df | 4 |
| Asymp. Sig. | 0,023 |

a. Friedman Test

36a Average product lifespan

36b Share of environmentally labeled products

36c Approximate water consumption during the use of your main product

36d Approximate electricity consumption during the use of your main product

36e Approximate heat consumption during the use of your main product

**Fig. 5.** Friedman Test for H2d

The consumption and use phase is important because long-term environmental impacts depend on product durability, efficiency, and user behaviour. Average product lifespan is especially relevant, as it reflects both resource efficiency and the sustainability of product design [12].

The LCA perspective stresses that environmental impacts should be assessed across the whole life cycle, including product use. Extending product lifespan can reduce environmental burdens by lowering the need for new inputs and reducing waste generation [6].

At the same time, SMEs often have limited control over how products are used after sale. They may also lack access to user-related data, which makes the measurement of these indicators difficult [23]. This explains why such indicators are less embedded in everyday monitoring than production-related indicators [9].

Despite these limitations, ESG reporting and regulatory developments are gradually broadening environmental monitoring toward downstream phases [16, 17]. In this context, product lifespan is a useful indicator because it links environmental, economic, and functional aspects of sustainability.

Hypothesis H2e was also tested in a similar way, using the Friedman test to compare end-of-life indicators. The results showed statistically significant differences between the analysed indicators ($p = 0.045$). Suggesting that SMEs do not measure all end-of-life indicators equally (Fig. 6).

The proportion of repaired products compared with discarded products achieved the highest mean rank. This suggests that the indicator may be relatively important for the analysed SMEs. However, the Wilcoxon signed-rank test did not confirm statistically

**Friedman Test**

**Ranks**

| | Mean Rank |
|---|---|
| o37a | 2,43 |
| o37b | 2,49 |
| o37c | 2,44 |
| o37d | 2,65 |

**Test Statistics**[a]

| | |
|---|---|
| N | 100 |
| Chi-Square | 8,067 |
| df | 3 |
| Asymp. Sig. | 0,045 |

a. Friedman Test

37a Share of products involved in take-back schemes

37b Amount of waste sent to landfill

37c Share of products designed for disassembly or recycling

37d Share of repaired products versus discarded products

**Fig. 6.** Friedman Test for H2e

significant differences between individual indicators. As a result, it is not possible to identify a clearly dominant end-of-life indicator for the broader SME population.

Hypothesis H2e is therefore neither confirmed nor rejected. The findings suggest a tendency to monitor the proportion of repaired versus discarded products, but further research with a larger sample is needed to confirm this relationship.

The end-of-life phase is increasingly important for sustainable product management. The ratio of repaired to discarded products can show how effectively enterprises extend product life cycles and reduce waste [12]. Previous research [13] emphasizes that environmental impacts continue after production, especially through decisions related to repair, reuse, recovery, and disposal. A higher share of repaired products can reduce raw material demand and environmental pressure, while also supporting regional sustainability goals.

In practice, however, SMEs face difficulties in collecting reliable end-of-life data. These difficulties are mainly related to limited contact with consumers and insufficient data infrastructure [23]. Still, current policy developments and sustainability frameworks increasingly support circular practices, including repair and reuse, as part of ESG and LCA integration [3, 17]. Waste handling and product recovery are also reflected in broader measures of environmental engagement [21].

For this reason, the proportion of repaired versus discarded products can be considered a meaningful end-of-life indicator. It captures both environmental performance and the degree to which SMEs move toward circular economy practices.

From an open data perspective, this imbalance in data availability at different LCA phases has important implications. It suggests that SMEs' contribution to regional open data using environmental indicators is currently limited to internally generated data.

These findings also confirm our theoretical assumptions [13, 21, 23] that SMEs find it difficult to collect and evaluate indicators in the consumption and disposal phases, as they often need information from customers or other stakeholders that is not available to them.

## 5 Conclusion

The research findings confirm that environmental data practices in SMEs are unevenly distributed across the product life cycle, with clear differences in the intensity of indicator measurement between individual phases. The production and procurement phases appeared as the most intensively monitored stages. In contrast, downstream phases, such as consumption, use, and end-of-life, were found to be significantly less systematically measured.

At the level of specific indicators, energy consumption in production and fuel consumption in transport and distribution were identified as the most frequently measured indicators, confirming their key role in SME environmental monitoring. No dominant indicator was identified in the procurement phase. For the consumption and end-of-life phases, although differences in measurement intensity were observed, the results did not provide sufficient statistical support to establish a clear hierarchy of indicators. This indicates that these phases remain underdeveloped in terms of systematic environmental data collection.

The results further demonstrate that SMEs already generate a large volume of environmental data which could be utilized at the regional level. This potential is not fully utilized due to organizational, technological, and knowledge-related barriers. The findings suggest that the key limitation is not the absence of data, but rather the lack of structured approaches to its standardization, integration, and sharing within regional open data.

Our findings provide a basis for the design of a governance-oriented framework for open data generated by SMEs. The findings suggest that initially regions should start creating open data systems primarily based on indicators that are routinely monitored in SMEs. These are, for example, energy or fuel consumption. We also identified barriers and limitations to tracking end-of-life data. This requires the need for supportive policies for SMEs, which would gradually expand data collection across all phases of LCA (the support is especially needed in the end-of-life indicators). To bridge this gap, a governance-oriented framework should be developed that enables the systematic collection, standardization, and aggregation of SME generated environmental data at the regional level. This framework could be based on the definition of a “minimum regional dataset”. It would be composed of key indicators such as energy and fuel consumption, waste generation, and material use, which are already routinely measured by SMEs. Regional authorities should play an active facilitating role by providing methodological guidelines, unified data templates, and digital platforms. This approach would enable simpler and more secure data submission. At the same time, cooperation among stakeholders can help reduce the barriers of data availability.

SMEs should prioritize the systematic monitoring of environmental indicators that are already incorporated in their operations, while gradually expanding measurement

practices toward downstream life cycle phases. Strengthening internal data governance, including clear responsibilities and standardized data collection procedures is essential. At the same time, enterprises should begin to perceive environmental data not only as a reporting obligation but as a strategic resource that can enhance their position within the market.

While this preliminary analysis focused on Slovak SMEs, the findings can be extended to other European countries. This applies for countries with a similar composition of SMES, comparable regulatory frameworks, and a similar level of digital development. Research from other EU member states points to many of the same challenges, particularly in areas such as data management, limited resources, and restricted access to downstream data. That said, these conclusions do not necessarily hold in settings with a different institutional context. For instance, in non-EU countries or in economies where sustainability reporting is subject to less regulatory pressure.

The limitations of the preliminary research are primarily related to the sample size and its focus on Slovak SMEs. This affected the generalizability of some findings, particularly in downstream phases where results were inconclusive. While the quantitative analysis provides valuable statistical insights, future research should incorporate qualitative methods to better understand the underlying reasons behind SME data practices and barriers. Further studies should also focus on testing the proposed framework in real regional contexts and on the development of tools that enable the automated transfer of SME data into open data platforms.

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## References

1. Artin P.: Critical sustainability factors of regional SMEs; A case study of regional Australia. Curr. Res. Environ. Sustain. **4** (2022)
2. Ayre, L., Craner, J.: Open data: what it is and why you should care. Pub. Libr. Q. **36**, 173–184 (2017)
3. Bálint, L., Várallyai, L., Botos, S.: Evaluation of data-driven sustainability potential at SMEs using an altered ecocanvas model. Economies **13** (2025)
4. Bianchi, G., Testa, F.: How can SMEs effectively embed environmental sustainability? Evidence on the relationships between cognitive frames, life cycle management and organizational learning process. Bus. Ethics Environ. Responsib. **31**, 634–648 (2022)
5. Bianchini, M., Michalkova, V.: Data analytics in SMEs. OECD SME and Entrepreneurship Papers (2019)
6. Daddi, T., Nucci, B., Iraldo, F.: Using life cycle assessment (LCA) to measure the environmental benefits of industrial symbiosis in an industrial cluster of SMEs. J. Clean. Prod. **147**, 157–164 (2017)

7. Deeksha, Mukherji, R.K., Uniyal, A.: Breaking barriers: the role of open data in advancing global sustainability innovation. In: Open Access as a Knowledge Platform for Implementing the United Nations Sustainable Development Goals. World Sustainability Series, pp. 283–312 (2025)
8. De La Puente, M., Torres, J., Guzman, H.: Environmental practices and ecosystem impact of SMEs: a comparative sectoral analysis in Venezuelan and Colombian coastal regions. Cogent Soc. Sci. **11** (2024)
9. Enders, T., Satzger, G., Fassnacht, M., Wolff, C.: Why should i share? Exploring benefits of open data for private sector organizations. In: Proceedings of the 29th Pacific Asia Conference on Information Systems (PACIS 2022) (2022)
10. European Union: Nurturing an economy for all: the role of SMEs and open data (2024)
11. European Union: Open data driving sustainability: towards sustainable development and innovation (2024)
12. Fortier, J., Gamache, S., Fonrouge, C.: Measuring environmental performance in digital transformation within SMEs. IFAC-PapersOnLine **19**, 842–847 (2024)
13. Gómez-Garza, R., Güereca, P.L., Padilla-Rivera, A., Ibarra, A.A.: Barriers and enablers of life cycle assessment in small and medium enterprises: a systematic review. Environ. Dev. Sustain. (2024)
14. Lnenička, M., Nikiforova, A., Clarinval, A., et al.: Sustainable open data ecosystems in smart cities: a platform theory based analysis of 19 European cities. Cities (2024)
15. Moghadasi, A.: Do SMEs consider open data as a vital intellectual asset? A systematic literature review. J. Knowl. Econ. **15**, 11784–11818 (2023)
16. Niemann, L., Morssinkhof, S., van der Linden, M.J., De Vries, K.: Data requests in value chains: the effects of corporate sustainability reporting on SMEs in The Netherlands. Sustainability **17** (2025)
17. Pantazi T.: The introduction of mandatory corporate sustainability reporting in the EU and the question of enforcement. Eur. Bus. Organ. Law Rev. (2024)
18. Seidel Sterzik, H., McLaren, S., Garnevska, E.: Effective life cycle management in SMEs: use of a sector based approach. Sustainability **10** (2018)
19. Tritto, N., Dias, J.G., Bassi, F.: SMEs circular economy practices in the European union: multilevel implications for sustainability. Soc. Indic. Res. **175**, 965–988 (2024)
20. Wainwright, T., Huber, F., Stöckmann, C., Kraus, S.: Open data platforms for transformational entrepreneurship: inclusion and exclusion mechanisms. Int. J. Inf. Manage. **72** (2023)
21. Wildnerova, L., Menon, C., Dehghan, R., Kinne, J., Lenz, D.: Which SMEs are greening? Cross-country evidence from one million websites (2019)
22. Wirtz, B.W., Weyer, C.J., Becker, M., Müller, M.W.: Open government data: a systematic literature review of empirical research. Electron. Mark. **32**, 2381–2404 (2022)
23. World Economic Forum: Data unleashed: empowering small and medium enterprises (SMEs) for innovation and success (2023)

# Smart Governance and Data-Driven Employment Policies in Less Developed Regions: A Regional Governance Model from the Banská Bystrica Case

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**Abstract.** This paper explores how smart governance and data-driven approaches are relevant to labour market issues in less developed regions. Over the last few years, the definition of smart cities has progressed from a purely technology-based lens to an evolving model of smart cities centered on governance, institutional cooperation, and data-infused decision-making. However, empirical evidence remains sparse regarding these techniques in structurally underprivileged and peripheral contexts. The study concentrates on the Banská Bystrica Region in Slovakia, a typical example of a less developed European region experiencing a period of long-term unemployment, demographic decline, and regional differences. Based on a qualitative case study methodology, the study reviews employment support measures by the Regional Development Agency in a time span ranging from 2018 to 2024. The analysis is informed by institutional data, program evidence, as well as theoretical principles on smart governance and data-driven policymaking. The study examines policies targeting young people in NEET situations. Our research confirms that data-driven, coordination, and context-dependent governance interventions can, to a certain extent, produce better design and delivery of employment policy. Personalised services, geographical reach and close monitoring appeared to be more important factors for effective policies. This study adds to the literature by applying the concept of smart governance beyond urbanization, and by examining the phenomenon empirically from a less developed context. Further, it offers a theoretical framework of Smart Regional Employment Governance that could be useful for a further study in policy making on the issue. Together, it can be maintained that effective employment policy does not rest solely on technological instruments, but is also contingent upon governance capacity and institutional learning.

**Keywords:** Smart Governance · Smart Regions · Employment Policy · NEET · Data-driven Governance · Regional Development

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# 1 Introduction

The European Union has long resisted significant regional differences. Some areas are not as advanced as others and have problems that have been going on for a long time, not enough jobs, not enough people living there and not enough new ideas. In Central and Eastern Europe you see these issues especially where there is difficulty getting people to work and where the population is shrinking [11]. This makes it difficult for these areas to catch up with the EU, with its many regional economies and its diverse, but all-weather regions [5].

Smart governance represents a promising approach in this regard. Instead of addressing only technological solutions, it also emphasizes inter-agency coordination, data-driven governance, and adaptive policy mechanisms [1, 6, 10].

In our research aims to understand what smart governance will mean for regional employment policies. Secondly, it considers real cases of job creation programs in the Banská Bystrica Region to understand what works. Third, it devises a plan for other similar regions to enhance their policies relating to employment.

# 2 Theoretical Background

## 2.1 From Smart Cities to Smart Governance

Over the past 10 years, the concept of smart cities has undergone major changes [2]. Initially it was about technology and computers for cities to become smart [4]. They believed data platforms, sensors and digital networks were the secret to smarter cities.

But some people feel that just thinking about the technology doesn't cut it. These are officials who say it does not take into account how governments operate and the social aspect. Others have suggested that focusing solely on the technology side overlooks how messy things get in public administration and the role that good institutional arrangements play in public administration.

So some of the more recent research is starting to look at smart development as a wider scope, and governance is vital to that. That requires an inquiry into how governments and institutions work together to move smart development forward – rather than simply relying on technology to "do" everything.

## 2.2 Data-Driven Governance

Data-driven governance has become a key element of modern public administration, referring to the systematic use of data across the policy cycle, including problem identification, policy design [14, 15, 19], implementation, and evaluation. Our research shows that access to real-time data, analytical tools, and monitoring systems enables policymakers to better understand socio-economic dynamics and allocate resources more effectively. This is particularly relevant in employment policy, where granular data allows for the identification of target groups and the design of tailored interventions.

At the same time, our findings highlight that effective data use depends on data quality, system interoperability, and responsible data governance. Strong institutional frameworks and regulatory mechanisms are essential to ensure trust, accountability, and the ethical use of data.

### 2.3 Employment Policy and NEET Concept

The NEET category is made up of young people not being in school, who do not have employment, and who do not receive any kind of training [8, 9]. In our research we found that leveraging data and smart governance let us make smart decisions on how to support them to shape policies that work.

NEET is very heterogeneous in terms of diversity, composed of a diverse population of learners from various levels of education, competences and social status. Some may be confronted with institutional obstacles, for example, lack of educational qualifications, some may be deprived of socialisation or few are excluded or not as fortunate to have the opportunity to get a job. Given this heterogeneity, standardised policy solutions may not reflect the heterogeneity. Personalised and flexible solutions, adapted to individual needs, are important to effective interventions. This encompasses individual counselling, training programmes, and support services to address labour market integration.

These features strongly remind us of the concepts behind smart governance. The more you use data, the better idea you can achieve about who you are trying to reach audience. And together, when different organisations collaborate, they can make a difference and support more people.

### 2.4 Smart Governance in Regional Contexts

The vast majority of knowledge about smart governance in local context is focused on urban settings, although it also become a fact that governance innovation is as important in regional and rural contexts. Less developed areas often struggle with structural disadvantages, such as reduced institutional capacity, slower economic diversification, and restricted access to facilities.

Smart governance in a regional context can therefore be comprehended as a local-level, place-specific and location-focused solution. Knowledge of local conditions – economic architecture, demographic patterns, institutional configurations – is crucial. Territorial accessibility-wise, it is equally important that one is mindful of access to services is a significant challenge in regions with dispersed populations and fragile infrastructure. Decentralised service delivery and local engagement are thus necessary elements of good governance [12, 13].

Its practical, therefore, broadening of smart governance into regional settings has brought a major conceptual and practical departure between theory and practice on a new wave of smart governance to both theory and, in some ways, actual application. It underlines the fact that governance innovation is not unique to technologically advanced cities, but it is as important to the challenges faced in frontier developing areas of governance.

### 2.5 Governance, Digitalisation and Labour Market Transformation

Governance and digital transformation are reshaping labour market policies and require a more forward-looking and dynamic approach. Conventional policy instruments often respond to problems only after they emerge, which is insufficient in the context of rapid

technological change. Our research suggests that public institutions must anticipate labour market developments, identify emerging risks, and respond more flexibly.

In this context, smart governance plays a crucial role by integrating digital tools, coordinating institutional actors, and supporting evidence-based decision-making. Policymakers [7, 22] can develop more effective interventions by using employment data, monitoring systems, and analytical tools, particularly in regions where labour market challenges are linked to skills mismatches and weak cooperation between public institutions and industry.

Our findings also highlight that digital transformation is not only a technical process but a governance challenge. Its success depends on the ability of institutions to coordinate actors, manage data responsibly, and ensure that digital tools reduce rather than reinforce inequalities. At the same time, labour market changes driven by automation and digitalisation increase the demand for adaptable, analytically skilled workers.

Recent developments associated with Industry 4.0 and artificial intelligence further intensify the transformation of labour markets and governance systems. Automation, predictive analytics, machine learning, and digital platforms increasingly influence both employment structures and public policy implementation. In this context, smart governance requires not only digital infrastructure, but also institutional capacities capable of integrating AI-supported decision-making, labour market forecasting, and adaptive policy coordination. These developments are particularly relevant for less developed regions, where technological transformation may simultaneously generate new opportunities and deepen existing socio-economic inequalities if governance systems remain insufficiently adaptive [3, 20].

Overall, these trends reinforce the need for governance systems that can effectively use data, coordinate across policy domains, and adapt interventions to changing conditions, thereby extending the concept of smart governance beyond technological solutions.

## 3 Methodology

This study employs a qualitative case study approach to examine the implementation of smart governance principles in regional employment policy. The objective is not to test causal relationships, but to understand institutional processes, governance dynamics, and policy implementation mechanisms.

The Banská Bystrica Region was selected as a case study because it is a less developed area in Europe which in a way still presents challenges in the labour market, yet also tries ways to prove a novel and creative form of governing within it. The region represents a particularly relevant case due to its long-term structural unemployment, demographic decline, territorial disparities, and relatively weak economic performance within the Slovak and EU context. At the same time, the region has implemented innovative governance initiatives focused on employment support and institutional coordination, making it suitable for examining the application of smart governance principles in less developed regions. We can understand all of the complexity within the interaction of institutions, policies and governance processes between them when studying this region so we can comprehend their implication towards regional growth.

Three questions shape the research:

1. How are smart governance principles applied in regional employment policy?
2. What role does data-driven governance play in shaping employment interventions?
3. Which governance mechanisms contribute to improved labour market outcomes in less developed regions?

This means that these questions contribute to the research by representing both theoretical and practical dimensions and offer insights into the governance process in the context of the broader findings of the study.

### 3.1 Research Design

The research is exploratory qualitative by nature. This is particularly useful in the study of complex governance systems, where multiple actors, institutions, and policy domains co-mingle. This study is concerned with governance structures rather than causal relationships.

The case study approach will allow an in-depth analysis of a specific regional context. It allows the scholar to analyse not just policy outcomes, but also the means for achieving them. I.e., the way in which institutions coordinate, how decisions are made, how policy interventions are implemented (e.g., in case of a pandemic or crisis).

The Banská Bystrica Region is a good example of a city where there are big problems, but they are using new and innovative solutions. Long-running unemployment, a declining population and some areas that aren't doing as well as others are taking a toll in this region. But the principals of an institution like this have put in immense effort to devise original solutions, relying on data and banding together to implement them. The Regional Development Agency (RABBSK) has been a leading player in this direction, trying innovative methods to grow and flourish the region.

The study's guiding research questions are as follows:

RQ1: How are smart governance principles operationalised in regional employment policy?

RQ2: What role does data-driven governance play in shaping employment interventions?

RQ3: Which governance mechanisms contribute to improved labour market outcomes in less developed regions?

As a result this balance of elements makes the region an excellent setting in which to examine how smart governance may operate in less-developed settings.

### 3.2 Data Sources and Analytical Approach

The study draws on multiple data sources to ensure analytical depth and contextual understanding. The following sources of data support such research:

- institutional reports and programme documentation,
- administrative data related to employment interventions,
- secondary statistical data,
- implementation insights derived from RABBSK activities (2018–2024) [18].

Our analysis confirms that this triangulation increases reliability. The empirical material was analysed using qualitative thematic analysis and institutional policy analysis. The analytical process focused on identifying governance mechanisms, patterns of institutional coordination, and the role of data-driven decision-making in employment interventions. The analysis also examined how governance structures influenced programme implementation and labour market outcomes. By comparing different types of evidence, the research reduces the risk that a single data source will bias findings. Methodological triangulation was used to improve the validity and reliability of the findings. Combining institutional reports, administrative data, secondary statistical sources, and implementation evidence enabled a more comprehensive interpretation of governance processes and policy outcomes.

In addition, the methods for data analysis are both objective and interpretative as well. First, the study examines the outcomes of these programs and those who have taken part in them to try and understand how large they are and what they do. Then it looks at how the programs are managed – how data is organized, how different people collaborate, how services are provided – to study how everything plays out in actual day-to-day life.

The analysis does not seek to prove one thing is directly a driver of another. Rather, it searches for links and attempts to understand what's at the core. This method was similar to how qualitative research does what it does. It is more about having a better understanding of complex stuff that needs to take place than coming up with figures which can be used to study much of the different situations.

A special emphasis is placed on the intersection of data-driven processes with governing institutions. This includes looking at how data is employed in decision-making, how institutions organize their activities, or the kinds of services they offer to a certain group of people.

### 3.3 Limitations of the Research Design

Though the research design is strong in some ways, there also exist some limitations that need to be mentioned for it to be considered. This study refers to information that already exists, such as reports from organisations. This data could be incredibly useful, but is probably not an exhaustive picture of the whole. The organisations that provide such information may not have similar means to gather and report it, which can lead to biases. If a project runs in the organisation, in its own interests, there can be influencing data that is obtained from program participants; and these can affect the results.

There is also a lack of original data collection for a second effect. The same study does not collect information with participants or other members of government or organisations engaged in providing services. Such qualitative information may facilitate better understanding of user experiences, challenges and perceived effectiveness of interventions.

Drawbacks to the case study method include the limitations in their ability to generalize the findings to other contexts. Since Banská Bystrica Region has unique socioeconomic and institutional conditions, the results are really specific to the context of the Banská Bystrica Region. This isn't trying to make sweeping statistical generalizations,

but to identify trends that might also play out in comparable areas, which is useful by its own standards.

Then there is the one problem of counterfactual analysis. It is not possible to ascertain with certainty if the observed results are directly due to the interventions assessed in this study or due to other exogenous factors. In addition, the absence of systematic longitudinal tracking limits the ability to evaluate the long-term sustainability of employment and educational outcomes among programme participants. Accordingly, the discovery should not be assumed to be definite.

Even if the study took place between 2018 and 2024, its scope is likely too brief to indicate the full reach of policy impacts. That's especially the case for things like employment outcomes, that can take an amount of time to manifest – particularly for the already vulnerable, people who are not in education, employment or training at all.

The more research there is that follows those trends over a longer time frame, the better to understand what is happening. Long-term monitoring would provide a better understanding of which interventions are effective and sustainable over time. Despite these limitations, the qualitative case study approach provides valuable contextual insights into governance dynamics that would be difficult to capture through purely quantitative methods.

### 3.4 Methodological Reflection

Given the broader context the approach we take to this challenge shows how complex governance research can be. Smart governance is not some kind of easy simple thing we can measure - it is all more or less a complex concept involving a lot of different parts and parts, institutions, processes, and how they all interact with each other.

Using this complexity in qualitative case study approach, the complexity can be captured by our qualitative case study research approach through use of real practices and institutional dynamics. It offers insight into how governance systems work, how policies are enacted, and how various players communicate.

But there's a reason how we do this should be scrutinized. It is not so much about providing some easy-to-follow answers as it is making us understand what is going on, so that we can act on what we know, so we make the right decisions.

It is because the methodology has implications for the overall aim of the paper as an exercise not to analyse one case and at the same time contribute to a new conceptualisation of smart governance in regional contexts.

## 4 Empirical Analysis

### 4.1 RABBSK as a Smart Governance Actor

RABBSK is part of various institutions working in the region, and acts as a central intermediary between regional governments across the spectrum of employment policy interventions. Instead of a conventional form of administrative authority, RABBSK is a hybrid governance actor which integrates both policy coordination, service integration, and data-driven decision-making. From this standpoint, the role played by RABBSK

has been interpreted along three interrelated dimensions. It enables multi-level governance by linking regional authorities, municipalities, national institutions, and local stakeholders. This coordination role is most important in less developed regions since the fragmentation of institutions sometimes limits the successful implementation of policy measures.

The organisation is now using data to inform its decisions. It's pulling information from a lot of different sources, such as administrative data, oversight and monitoring systems, and using that to assess its programs. This provides the organisation with the right information to make decisions, and adapt the decisions accordingly. It's a departure from tried-and-true, one-size-fits-all policies to a flexible, evidence-based method of governance. Utilizing that kind of data gives the organisation both the tools to adapt more quickly to changing circumstances and to ensure that the responses it's implementing actually make a difference. In addition, this continuous improvement of life-learning and learning enhances what the organisation aims to achieve. In so doing, the organisation is able to be dynamic and flexible and the process of decision is easier in making a better informed and effective decision.

A central role of RABBSK is that of the "boundary spanning" actor. Its interaction with multiple levels of institutions and stakeholders fosters cross-knowledge sharing and promotes teamwork. This is especially important in remote areas where institutional-target relationship gaps inhibit policy efficacy.

### 4.2 Employment Support Programs

RABBSK operates various employment support programmes to address structural labour market problems that impact young people living in NEET contexts. These programs, which move away from policy instruments to tailor-make, integrative, and territorially embedded, focus on personalisation and integrative measures rather than tools of policy.

One of the essential characteristic features of the programme is the focus on person-centred support. Personal counselling sessions offer opportunities to recognize individual barriers that participants, such as skill gaps, lack of work experience, or social limitations, may encounter specifically. From this evaluation, we develop tailored support routes (including training programmes, placement support, job placement and educational reintegration) according to a person's needs.

Territorial access is also an important aspect. To serve the people, services are provided through a range of local contacts and activities to help ensure that care exists for those who live in remote or disadvantaged areas. This decentralised approach reduces spatial inequities and fosters inclusivity of policy intervention.

Also there is some outreach/engagement in the programme. Because many potential recipients of NEET are not registered with employment service, active strategies are often necessary to reach NEET people. The programme engages hard-to-reach groups as it undertakes targeted outreach programmes, working with local organisations and community actors.

Accordingly, the program also is an important avenue for establishing trust between organisations and the communities they serve. By providing readily available services, it promotes awareness of and connection to the needs of people. This is particularly crucial for vulnerable communities who find such assistance difficult to find with institutions.

### 4.3 Results

We found that around 900 people who weren't working or in school were able to get involved, which shows that outreach programs can actually work. Usually, these programs are seen as a big obstacle in employment policies. However, the fact that not many people completed their requalification training suggests that we need to improve the way we help people develop new skills and provide long-term training. This is really important for helping people get back into the workforce. By strengthening these training pathways, we can make a bigger impact and help more people achieve their goals.

The facts and figures clearly show how well these interventions are working and the impact they have:

- more than 5400 clients participated
- approximately 900 NEET individuals were engaged
- outcomes include:
- around 100 individuals entering employment
- nearly 20 returning to education
- 16 completing requalification programs [24]

Although long-term monitoring data remain limited, preliminary programme evaluations indicate that participants who completed requalification activities demonstrated improved labour market readiness and stronger engagement with employment support services. Similarly, individuals returning to education showed higher levels of continued participation in educational pathways, suggesting positive effects on social and labour market reintegration.

The findings suggest that programme effectiveness should not be evaluated exclusively through immediate employment outcomes. In the context of vulnerable NEET populations, intermediate outcomes such as educational reintegration, skills acquisition, institutional engagement, and increased employability also represent important indicators of policy success.

### 4.4 Interpretation

Our findings indicate that several key mechanisms explain the effectiveness of the interventions:

1. Personalization – tailored services address individual barriers
2. Territorial accessibility – local centres reduce spatial inequalities
3. Service integration – combining employment, education, and social support
4. Data-driven adaptation – continuous monitoring improves policy effectiveness.

These mechanisms should be understood not just as independent elements. Instead, they are elements from a set of holistic governance mechanisms. Their efficacy relies on their simultaneous enactment and reinforcement. For example, personalised services are far more effective when supported by good data available to us and service delivery structures in the market.

The empirical findings indicate that governance interventions may generate broader social and institutional effects beyond direct labour market integration. Improved engagement with public institutions, increased participation in educational activities, and

strengthened individual employability capacities represent important indirect outcomes, particularly in structurally disadvantaged regions.

### 4.5 Governance Processes and Implementation Dynamics

On a larger scale, it's not only numbers and results. We want to know not only what decisions are created, but how decisions. Our analysis shows us that a good plan isn't enough; it's equally critical to evaluate how effectively that plan is actually executed and how the different aspects connect to each other. It's an essential factor and can make all the difference in why the program actually works.

Inter-institutional coordination represents a critical prerequisite for effective policy implementation. Coordination becomes increasingly complex when multiple actors, including municipalities, employment offices, educational institutions, and non-governmental organisations, are involved in policy implementation. All of them have to coordinate their work so that they're helping each other out rather than duplicating work or stopping in each other's path. That is important because it helps ensure that people receive the services that are needed, so that none of the various services we have out there completely overlap. These groups will put their respective strengths pooling for a more efficient and serviceable system for everyone.

But as you go you have to modify a programme – that is incredibly important. In this way, you are able to tailor the services to address some of the contextual needs of your local area and the persons that you serve. By doing so, your interventions become more likely to be effective.

To achieve this, continuous data collection and feedback mechanisms are essential. If something in the code changes that will be able to guide the programme in a more and better direction, to give the program a direction that will only improve with the passing of time.

Frontline workers and service providers are also key. Their interactions with clients influence the availability and perceived relevance of services. It is equally important we gain the trust and interest of our members so that they want to participate, particularly among our most vulnerable.

It's simple: you have to learn from your experiences. As time passes, knowledge and experience allow programmes to be improved. But this learning process is aided by systems that track progress and make use of data to assess what works and what does not.

These systems provide the data needed to inform changes and enhancements of the interventions. There's data to make decisions based on and improving upon the data over time refining and refining existing programmes. This is vital in this regard and if you are going to demonstrate that what's been done is working.

## 5 Discussion

Our results back the idea that governments are now doing the decision-making with data and good governance. This is a step in a general evolution in the ways in which public administration operates, in which it emphasizes creating strong institutions, coordinating

efforts and developing flexible policies instead of just a technological phenomenon. Doing so helps them formulate more relevant and improved policies for the citizens. What matters is not only technology but also the quality of governance system that matters most for 'smart' governance to work well.

For example in Banská Bystrica Region the benefits of improved employment outcomes are strongly contextualized by the inter-organisational ties, institutions and the level of integration of services – the time taken to adjust policies. It indicates that effective governance is required to achieve digital transformation make effective contributions to the public sector, as many experts have claimed. In short, it is not just the right technology but the system and process must also work well together to do everything in technology effectively. This suggests that governments should establish strong governance frameworks before implementing new digital solutions. In this way they can create an environment of opportunity for digital things really to go a long way and make their way into people's day-to-day lives.

Our results also show the role of territorial embeddedness. This is particularly important for regional peripheral areas. Unlike metropolitan areas, where labour markets and institutional networks are abundant and diversified, less developed areas are weighed down by social and structural constraints that govern access, infrastructure and demographic decline. Decentralised provision of services through local contact points removes massive spatial barriers and policy interventions became even more inclusive. This would suggest that we still need close – in the digital era of politics – nourishing physical proximity and local stake in the process.

It is also important to think about how it affects the potential availability or chance for everyone to have an equal shot at economic advancement, opportunity to growth and labour market participation. By linking jobs, education and social services, we are doing a holistic job of providing help for those who are struggling to get jobs. And yet this is exactly what the OECD found as well, that we have to work together across industries to ensure equal opportunity for all to prosper [16]. But there are still huge regional disparities, suggesting that some regions haven't developed as rapidly as others. This is the result of larger shortcomings in the way in which our systems and institutions work – and this may cause regional differences in opportunity.

However, when we turn our gaze down and zoom out to governance, you can very effectively tell that organisations such as RABBSK play an important part. We identified that serve in the area where the various levels of government and policy are working, organizing things, exchanging knowledge, moving things along. The thing is their ability to cover the gaps between institutions, especially in developing and under-resourced areas. One such means of doing so, however, is to invest in, and strengthen the capacity of these intermediary organisations as they exist in regional development, in order to facilitate more effective regional development projects. Doing so, we can develop a much more unified and effective system where different tiers of government and policy areas interact smoothly with one other as one. This can result in more beneficial outcomes for the people and community. This emphasizes the need for participatory, collaborative forms of governance that have emerged as critical to the development of smart governance systems [17].

It's based on results, which are what it is, evidence that data is key to today's systems of government. By actively monitoring and receiving feedback, policymakers make their plans so that as things change and they are able to operate much more efficiently. And that also brings with it some significant challenges, particularly in terms of whether the data is robust, can be brought into play with other systems, and is used fairly. So, it is extremely important policymakers to ensure that the use of data in decision making is open and responsive and involves everyone. The increasing integration of AI-based analytical systems into public administration also raises new governance challenges related to transparency, accountability, algorithmic bias, and digital inclusion. That means they should be careful about collecting, using and sharing data, too, and how to make sure not only that a few individuals make decisions, but that all voices matter. If done so they can ensure that data-driven governance is equitable, reliable and working for all [23].

What is necessary to consider further is the level of application of the model in different contexts and places. Our results aren't necessarily specific to a given area, but mechanisms by which those systems govern themselves, such as merging things, personalizing them, or using data to adjust, aren't just for that area, and could work in other areas that aren't as developed. However, making these models work involves a lot of factors. The way decision-makers make choices as well as the level of funding, such as how well the region can manage new systems? Not all places will be ready to implement these kind of integrated systems, which could lead to problems for these individuals – some likely won't have the infrastructure and systems in place to enable those systems to work – and people need to be helped in building their capacity and receiving the right support for them in doing so. That's especially true for areas with less effective administrativeness, where implementing new systems can be an uphill battle.

Moreover, a rise in digital technologies raises questions about digital inclusion and accessibility. To make sure that vulnerable members of societies are not excluded from digitalised services has been a major challenge, mainly in rural and disadvantaged contexts of remote areas. Good governance is less about making things better now, better now with plans for the future, and more about making things better after all. That includes systems which can evolve and learn with time. This may involve one method: collect and analyze the data that shows how policies are operating, and adjust as and when necessary. It's like your long-term plan is malleable to newly-created information and problems. This allows governments to make informed decisions, to have a great future. This way, they can construct institutions that withstand whatever comes their way, and confirm that what they try to do can actually function. To do this, the concept of smart governance can be expressed as the dynamic capability of public institutions, to adjust to changing socio-economic conditions. Rather it transforms individual interventions on their own to the institutional level and the adaptability of the system to the new governance context.

Our findings theoretically offer guidance in understanding the historical trajectory of governance paradigms in the emergence of the digital age of transformation. The lessons are that smart governance should be framed not as a technology for public administration but the wider, institution-side transformation of data, coordination and adaptive learning. This view resonates with emergent public governance paradigms that emphasize dynamic capabilities, organisational learning and system-wide adaptability. Smart governance therefore can be seen as a governance methodology that promotes the

functionality and performance of public institutions on a system under instability and complexity.

So what we're seeing here is that it's fundamentally about connecting the smaller, local ways of delivering service with the bigger, overall mechanisms of governance. Developing good employment policies isn't just about top-level plans; they require the people delivering it to get along with the people who need it. This means that we need governance systems both up and down, along the lines and also side to side that work well together to ensure everything is connected and working. This will ensure everyone is on the same page and that the services deliver true services to the intended people. Balancing a system is about finding that balance and whether the lower-level parts of it are working perfectly well with the upper-level parts as a whole.

So, then, what this means for smart governance? These results show that these new ways of governing can indeed be successful, as long as they are made into routine ways of doing things. We must ensure that these new practices are integrated into the formal norms and policy and obtain resources, support, encouragement, skills of people in order for them be effective in the long run. Maintaining it is a matter not only of trying out new ideas, but also making them a living part of our way of governing. The significance of this is that it may inform us to make better decisions and advance the lives of people. But to get there we need leaders who are committed to making it happen and institutions that can support it.

Our results should be treated with caution. They relate to a particular context, and are unlikely to be useful everywhere. Yet they provide us with some very helpful suggestions for how to adapt our style of governing in similar places – particularly where the underlying issues are like ours.

### 5.1 Implications for EU Cohesion Policy

The empirical findings from this study will have a variety of important implications for the EU on cohesion policy design and action. The findings suggest that the place-based approach is crucial, and is a main contribution to the EU's cohesion policy. And smart governance provides that capability for place-based strategies to work, which does this by helping to focus the goals of our efforts with greater detail and tailoring our approaches to our local social and economic context. Not least in these less developed parts of the world, because the one-size-fits-all approach often fails to provide effective solutions as it does not take into account the specific challenges they face.

Smart governance makes it possible to ensure that our policies are personalised to each region's need, but also that we maximise all efforts on resources use. This serves as an instrument to tackle the root causes behind why these regions are stalling ahead of us and create better chances for development. So is it necessary to use data to make decisions? The study goes on to emphasize how data can help inform decisions in policy that promote unity. By putting administrative data, monitoring systems, and evaluation tools together, decisionmakers can then determine how effectively systems are working and in what areas they should spend what. This method is consistent with how the EU is moving towards performance-driven funding and making policies that aim only to deliver specific results.

Our results in reality demonstrate the necessity of coordination across government levels. In this sense, there's plenty of play going on with cohesion policy, with a lot of players, from the EU, to national-level, regional, and local levels. For things to run smoothly, these actors have to work harmoniously. If they do not, you are left with a policy that's all over the place and doesn't really do what it's meant to do. One example of this in practice is RABBSK, which demonstrates how intermediation (for these organisations) can play a real role in that coordination. So it is likely a good idea for EU policy frameworks to recognise and support these organisations more. In doing that, they can do their job more effectively and help make sure cohesion policy functions the way that it's meant to work. As a result of this, we will not be fragmented and will be sure in order to keep everything on the same page.

For tackling difficult social and economic issues – like youth unemployment – we have to work horizontally, across jobs, education and ensuring we are all included. So the policy should continue to favor the fostering of team work and collaboration in various sectors. The outcomes also significantly influence the overall course of EU policies, and most particularly their transformation into digital as well as more sustainable measures [21]. An intelligent way of governing can be a big leap towards making all of this happen by making policy systems more flexible, more empowered and more inclusive.

## 6 Conceptual Model

In order to distil the insights gained from this study, a new idea is being presented: Smart Regional Employment Governance. This idea is essentially an amalgamation of key elements with data-based decision-making; collaboration across various levels of government; and region-specific services. It demonstrates the connections among policy, governance and job market outcomes as seen in the context of learning from experience and continuous feedback loops.

This also builds a system able to evolve and get better; something really important for a good labour market policy and good employment outcomes. The concept of Smart Regional Employment Governance is based on understanding the complex relationships with each of these factors in a multifactorial way and helps build effective employment policy and programs.

Figure 1 summarises the structure and functioning of the proposed model.

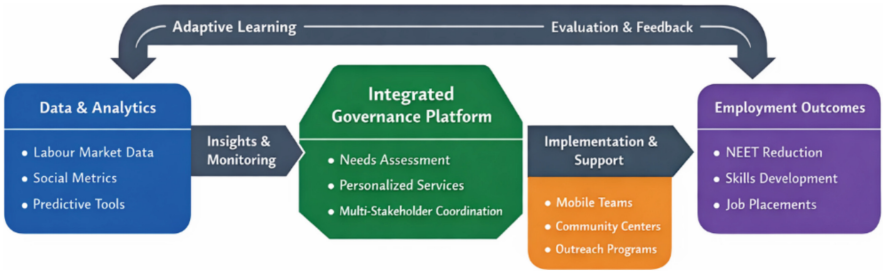


**Fig. 1.** Smart Regional Employment Governance model

Figure 1 presents the Smart Regional Employment Governance Model, which captures the dynamic interplay among data-informed decision-making, governance coordination, and employment drivers in less developed regions. This includes a structured, cyclical governance model in which data, mechanisms for implementation, and policy outcomes are continuously embedded in feedback mechanisms.

It's really important for you to do that when you're making decisions, you use data and analytics. This ranges from the sort of information about the job market, social trends, and the tools that know what it will be looking like as of next decade. With these array of data sources, policymakers can determine who needs help the most, what problems need fixing, and what they should do. The concept here is that by using data to inform decision making, also, being able to make adjustments as required. This is about using data to inform policy and improving over time. A good mix of skillful track-following and analysis would help policymakers craft policies informed by information and flexible to the changing times.

A key component of the model is an Integrated Governance Platform, basically the hub of smart governance. This platform lets you figure out what people need, gives you services that suit each individual and brings together a lot of different groups. It connects government agencies, job centres, schools and community organisations in an organised way, so everybody is ensured to work together to solve the problem at hand. Through this, the platform ensures that everyone's efforts are synchronized, focused on what is right and adapted to the specifics of every single area. This way everyone can more effectively collaborate to respond to the challenges local people face.

The implementation and support layer turns governance decisions into concrete measures. This involves the use of mobile teams, community centres and outreach programmes to increase the availability of territorial services to reaching vulnerable community members. Decentralised and locally embedded delivery mechanisms are of particular interest in peripheral areas, which may be limited by geographical constraints and institutional fragmentation in the provision of public services.

The final element of the model examines what is happening with people's work, looking at how people are doing at work – reducing the number of youth out of work or out of school, helping them build new skills and getting them jobs. These serve to demonstrate not only just how well each program works, but how well the whole system is functioning. This model works by looking back on results to create feedback loops, or feedback loops and learning loops. That helps the system improve over time, ensures policies are working and builds the system to be strong in the long term.

In this way, the model can continue to evolve and adapt to new information, which is crucial for good decisions and finding employment for people. The model also demonstrates the impact of employment policy on less developed regions via data in a context of governance and service delivery integrated into a consistent and adaptive system. It proves that smart governance is not a straight line; rather it is a dynamic cycle, involving the analysis, coordination, implementation and evaluation.

## 7 Conclusion

In this paper, we focus on the smart governance and data-driven policy approach to tackle labour market challenges in a less-developed European region. Based on the qualitative case study of the Banská Bystrica Region, our analysis shows that governance innovation rather than the technical innovation alone plays an important role in enhancing the efficiency of labour policies.

Our results show that using a mix of local support, integrated services and decision-making based on data can be highly useful not only within your educational community but also for young people who are not working or in school today. This is the group that often feels lost and out of a job. Smart governance can help overcome the countless factors keeping people from finding work by offering them individual support, facilitating access and monitoring their progress through providing them with access to services and monitoring where they are, and making sure that once they're taken onboard they aren't getting stuck. This can have a major impact in assisting vulnerable populations, such as the young, get a job and getting out.

Our research highlights insights in smart governance. Most of the time people speak of how it functions in big cities, but this paper demonstrates that it is also critical in smaller, less-developed regions. These are places where you really need good institutions in place, to get everybody to work together and be involved in making decisions. This can matter a great deal in determining what success a policy will have. Examining these factors can tell us how to make smart governance work differently in different places like big cities and smaller, less populated places, like towns and villages. This will ensure we are creating policies that help people and will ultimately benefit people.

Smart Regional Employment Governance is the brand of new management of jobs and employment in region. A framework that can help us better understand how different parts of the system interact to influence the results of policies. Understanding some big picture, such as data, how governments work together, the distribution of services and how accessible and easy it is to transit through a region can give insight into how smart governance operates across regions. That way of thinking can take its form anywhere, so it's a wealth of opportunity for those seeking to impact on jobs and governance in different regions positively.

From a policy perspective, the findings propose that smart governance can greatly advance EU cohesion policy (e.g. better designed and adjusted policies). The authors claim, we might consider its role for government departments, organisations within the EU as an additional factor or area of expertise. Yet unlocking the potential for this approach requires continued investment not merely in digital technologies but also in the infrastructure, governance, and workforce of institutions of these technologies.

There are some constraints to this study we have to consider. Firstly, we look at one case, and we are often basing our judgments on information that has been made available by the institution. This may complicate extrapolating our results to other domains. Also, we're having a qualitative study so we don't know quite with certainty what causes what. Future studies are urged, in order to consolidate our findings, to study different regions and apply a variety of methods of research. This will enable us to understand why it isn't good. We should be careful how our findings transfer to other places, and we should also

put together ways of testing our ideas more consistently. In doing these we might make our own research more reliable and helpful.

Future lines of research include:

- comparison between EU regions,
- quantitative analysis of the impact of employment policy,
- articulation of advanced data analytics and AI in governance,
- long-term sustainability and scalability of smart governance interventions.

In its own right, smart governance is an attractive and adaptable solution for tackling labour market problems in less developed areas. By integrating governance innovation with data science, it paves the way to a stronger, more inclusive and more productive approach to regional development in the European Union.

The shift to smart governance is also a component of a more systemic shift in how the public sector is operated - and in which the ability to be flexible, able to respond and to collaborate are all significant. On one hand, in the shadow of growing socio-economic uncertainty (especially based on demographic change, technology disruption, labour market change), governance systems have to be more resilient and responsive. Smart governance provides the means of doing this by integrating data, institutions and service within a coherent system.

The growing complexity of socio-economic challenges demands, as well, governance pathways that are capable of managing uncertainty, interdependencies, and rapid change. Smart governance is one way to tackle them and offers a way forward through the integration of data, institutional coordination and service innovation. However, its successful implementation has been shaped and defined by the capacity of public institutions to build and nurture those capacities, to promote collaborative processes, and to ensure they emphasize inclusivity and accessibility.

We need to be cautious about examining these results as they may not apply everywhere.

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## References

1. Almulhim, A.: Smart governance sustainability. Smart Cities. https://doi.org/10.3390/smartcities8040113
2. Anthopoulos, L.: Smart city emergence. Elsevier. Amsterdam. https://doi.org/10.1016/C2015-0-06222-8
3. Brynjolfsson, E., McAfee, A.: The second machine age: Work, progress, and prosperity in a time of brilliant technologies. W.W. Norton & Company, New York (2014). ISBN 978-0-393-24125-9 (e-book)

4. Caragliu, A., Del Bo, C., Nijkamp, P.: Smart cities in Europe. J. Urban Technol. https://doi.org/10.1080/10630732.2011.601117
5. Clark, J.: Uneven innovation: The work of smart cities. Columbia University Press, New York (2019). https://doi.org/10.7312/clar18350
6. Das, D.: ICT governance in smart cities. Int. J. Urban Sci. https://doi.org/10.1080/19463138.2024.2433983
7. El-Sheikh, G.: Human-centric governance in smart cities. Smart Cities. https://doi.org/10.1007/s44327-026-00190-7
8. Eurofound: NEET policies and labour market integration. Publications Office of the European Union, Luxembourg. https://doi.org/10.2806/65376
9. European Commission: Youth employment support: A bridge to jobs for the next generation. Publications Office of the European Union, Luxembourg. https://doi.org/10.2767/17725
10. Grossi, G., et al.: Smart governance frameworks: a systematic perspective. Urban Stud. https://doi.org/10.1177/00420980241227807
11. International Labour Organisation (ILO): Global employment trends. ILO, Geneva. https://doi.org/10.54394/XJZN8595
12. Kummitha, R.: Smart governance and regional development. Reg. Stud. https://doi.org/10.1080/00343404.2024.2399262
13. Meijer, A., Bolívar, M.: Governing the smart city: a review of the literature. Int. J. Public Adm. Rev. https://doi.org/10.1108/IJAR-08-2015-0098
14. OECD: Digital government outlook 2023. OECD Publishing, Paris (2023)
15. OECD: Smart city data governance. OECD Publishing, Paris. https://doi.org/10.1787/e57ce301-en
16. OECD: Smart cities and inclusive growth. OECD Publishing, Paris. https://doi.org/10.1787/8a4ce475-en
17. Palacin, V., et al.: Participatory governance in smart cities. In: Proceedings of the 25th Annual International Conference on Digital Government Research (Dg.O 2024), pp. 1–10. ACM (2024). https://doi.org/10.1145/3635144
18. Regional Development Agency of the Banská Bystrica Region (RABBSK): Annual report 2018–2024. Banská Bystrica (2024)
19. Ruijer, E., et al.: Smart governance toolbox: data-driven public administration. Smart Cities. https://doi.org/10.3390/smartcities6020042
20. Schwab, K.: Schwab, Klaus. The Fourth Industrial Revolution. Ginebra: World Economic Forum, 172 pp. Economía. 41. 194–197 (2016). https://doi.org/10.18800/economia.201801.012.
21. Sharifi, A., et al.: Smart cities and the SDGs. Cities. https://doi.org/10.1016/j.cities.2023.104659
22. Shin, B., et al.: Digital participation in governance. Gov. Inf. Q. https://doi.org/10.1016/j.giq.2024.101954
23. Szpilko, D., et al.: AI in smart cities. Eng. Manag. J. https://doi.org/10.2478/emj-2023-0028
24. Szum, K.: IoT in smart cities. Eng. Manag. J. https://doi.org/10.2478/emj-2021-0017



# Integrating Behavioral Economics and IoT for Energy Efficiency in Smart Cities: A Multi-case Study Approach

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**Abstract.** Urban areas play a vital role in global sustainability, especially regarding energy consumption. While smart city strategies emphasize technological innovation such as Internet of Things (IoT) and big data, behavioral factors also influence energy consumption. This paper aims to explore the integration of behavioral economics (namely nudging), with IoT-enabled systems to support energy efficiency within smart governance in urban areas. Using a qualitative case study methodology, three cases are analyzed: (1) the Renewable Energy Community of Magliano Alpi (Italy), (2) the NUDGE project (5 European Union countries), and (3) an IoT-driven behavioral intervention in municipal housing in Greenwich (United Kingdom). The findings show that combining real-time data with behavioral interventions enhances energy awareness and citizen participation in energy saving, which leads to increased energy efficiency. The paper links behavioral design, IoT infrastructure, and governance mechanisms, contributing to urban and regional planning.

**Keywords:** behavioral economics · nudging · Internet of Things · smart governance · sustainability

## 1 Introduction

The pace of urbanization in the 21st century has significantly increased the pressure on cities to address sustainability, improve energy efficiency, and manage resources more effectively, all while sustaining economic competitiveness and social cohesion. In response, the concept of smart cities has emerged as a notable shift in urban and regional planning, bringing together digital technologies, data-informed governance, and more participatory approaches to improve how cities function [9, 22]. Within this context, concepts such as smart governance and open governance emphasize transparency, active citizen involvement, and the purposeful use of open data and large-scale data infrastructures to support decision-making [15, 29, 49].

From a behavioral economics perspective, the assumption that individuals act as fully rational agents is increasingly subject to scrutiny. Empirical studies indicate that decision-making is frequently influenced by heuristics and cognitive biases, including

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status quo bias, loss aversion, and bounded rationality [23, 46]. In the context of energy consumption, these effects are reflected in a relatively low propensity to switch energy providers, a tendency to underinvest in energy-efficient technologies despite their potential long-term benefits, and the persistence of habitual patterns that may contribute to higher levels of energy use (overconsumption) [3, 4, 10].

To address these behavioral barriers, the concept of nudging, as introduced by Thaler and Sunstein [46], has gained attention as a policy approach that seeks to influence behavior by modifying the context in which decisions are made, without limiting individual choice. Various forms of nudges, including feedback mechanisms, social comparison, default settings, and framing techniques, have been examined in relation to energy consumption. Empirical research shows that such interventions can have measurable, albeit typically modest, effects. For example, social norm feedback has been associated with average reductions in household energy use of approximately 2–5% [2, 3], while real-time feedback appears to support increased awareness and behavioral change [12].

Building on these insights, integrating behavioral interventions with IoT technologies is an important development within smart city ecosystems. IoT devices—such as smart meters, sensors, and connected appliances—enable continuous collection of energy-use data, often at relatively high temporal and spatial resolutions, which, in turn, provides a basis for more data-informed nudging approaches, in which behavioral interventions can be tailored to individual users, promptly, and adapted to specific conditions [24].

In contrast to more traditional, static interventions (e.g., informational campaigns), IoT-enabled nudges can be adjusted dynamically in response to user behavior, environmental conditions, and broader system constraints. For example, real-time notifications can encourage users to change consumption to periods of high renewable energy production, thus aligning individual behavior with system efficiency goals. The above is consistent with emerging perspectives on adaptive and data-driven governance, including concepts such as smart governance, where urban systems are managed through continuous feedback loops and adaptive governance mechanisms [48, 51].

Despite growing interest in both behavioral interventions and smart technologies, there remains a gap in understanding how to systematically integrate these approaches into smart governance and urban planning strategies. In practice, many existing initiatives tend to emphasize either technological capabilities without sufficiently incorporating behavioral insights or, conversely, behavioral approaches without fully leveraging the potential of real-time data and connected infrastructure.

This paper addresses this gap by examining the combined use of behavioral economics (nudges) and IoT technologies in urban energy systems. It emphasizes the role of behavioral interventions in achieving sustainability, participation, and strategic urban development goals. The novelty of the contribution is threefold: (1) prior research has examined behavioral interventions and IoT-enabled energy systems largely in isolation; this paper brings an approach that links behavioral design, real-time data infrastructures, and governance arrangements. (2) The paper advances existing work on digital nudging by comparatively analyzing how different configurations of personalization, feedback, and social embedding influence behavioral outcomes across cases. (3) The paper extends current knowledge by incorporating governance and participation as a core analytical

dimension, thereby highlighting how institutional contexts influence the effectiveness and scalability of IoT-enabled behavioral interventions.

## 2 Theoretical Background

Evidence from CEE countries suggests that the effectiveness of smart energy interventions is strongly conditioned by institutional and market structures, including the role of policy support and innovation systems [20, 26]. The transition toward sustainable urban energy systems also calls for institutional innovation. In this context, smart governance frameworks emphasize participatory approaches, positioning citizens not only as consumers but also as active contributors, often described as "prosumers." The emergence of energy communities responds to this need by facilitating the collective production, sharing, and management of renewable energy resources. This perspective is broadly consistent with Ostrom's [35] theory of collective action, which highlights the roles of trust, shared norms, and institutional arrangements in the governance of common-pool resources.

Similarly, participatory digital platforms, e.g., IoT-based, enhance open governance and participation by providing citizens with access to real-time data and enabling co-creation, which supports both economic competitiveness through innovation and efficiency gains and social cohesion through more inclusive forms of participation [13].

From an urban and regional planning perspective, integrating behavioral economics with IoT technologies supports a complex approach to sustainability. Traditional urban planning, especially in the CEE, often focuses on infrastructure and regulatory frameworks, as well as on barriers to technology diffusion and adoption [27, 43]. In contrast, new approaches emphasize the interplay between physical systems, digital infrastructures, and human behavior [14].

The concept of digital nudging (nudges delivered through digital interfaces) extends behavioral interventions into everyday life, embedding them within urban planning [50]. When combined with IoT, these interventions influence behavior at the point of decision-making, highlighting the potential for interventions that are not only scalable and relatively cost-effective but also capable of addressing both environmental sustainability objectives and, potentially, aspects of social equity. Although recent studies explore IoT-enabled nudging architectures [30] and smart meter feedback interventions [40], these contributions tend to focus primarily on technological performance or behavioral outcomes, with limited attention to cross-case comparison and governance contexts.

The integration of behavioral economics and IoT within smart city governance can be conceptualized as a multi-layered system. In such a system, technological infrastructures enable behavioral interventions, which are, in turn, embedded within broader governance and planning. The framework presented in Table 1 captures the relationships among the technological, behavioral, and institutional dimensions of the system.

The presented framework builds on previous research that combines behavioral economics [11, 46], IoT-enabled systems [21, 54], and smart governance theory [31, 32]. It reflects a socio-technical perspective on urban sustainability [18], where technological infrastructures, behavioral mechanisms, and institutional arrangements interact.

While the above-mentioned studies are from different European contexts, the findings are particularly relevant for Central and Eastern European (CEE) countries, where

**Table 1.** Conceptual framework

| Dimension | Studies | Components | Function | Expected Outcomes |
|---|---|---|---|---|
| Behavioral Design | [1, 11, 41, 45] | Nudges (feedback, social norms, prompts, defaults) | Influence individual decision-making | Reduced energy consumption, habit change |
| IoT & Data Layer | [3, 5, 21, 33, 52, 54] | Smart meters, sensors, platforms, apps | Real-time monitoring and data analytics | Increased awareness, personalization |
| Governance Layer | [8, 25, 32, 42] | Public institutions, policies, participation | Enable coordination and trust | Higher engagement, collective action |
| Urban Planning Context | [18, 29, 37, 39] | Sustainability strategies, infrastructure | Integration into spatial and policy planning | Long-term resilience and efficiency |

Source: own based on the authors

a combination of legacy infrastructure, lower levels of digitalization, and evolving governance capacities shapes energy transitions. In these contexts, cost-effective, scalable approaches such as IoT-enabled behavioral interventions may offer a pragmatic pathway to improving energy efficiency without requiring large-scale infrastructure investments.

## 3 Research Design

This study aims to examine how integrating behavioral economics (nudging) and IoT-based technologies can improve energy efficiency in urban areas, and to assess their role in smart governance through a comparative analysis of selected case studies.

To address this objective, we use a qualitative multiple-case study approach [53], which is well-suited to exploring complex, context-dependent phenomena such as the integration of behavioral interventions and IoT technologies in urban energy systems. The case study design allows for the identification of key patterns and mechanisms, as well as similarities and differences across cases. This approach allows for insights generalization.

Three cases: Renewable Energy Community in Magliano Alpi (Italy), NUDGE Project (interventions in 5 European Union countries) and IoT-driven behavioral intervention in municipal housing in Greenwich (United Kingdom), were selected using purposive sampling based on the following criteria:

- Integration of behavioral and technological interventions (nudges + IoT or digital systems).

- Relevance to smart city and governance frameworks.
- Empirical evidence of implementation and evaluation (i.e., the interventions are already implemented and have yielded some outcomes).
- Diversity of contexts (municipal and cross-national settings).

The cases were selected to ensure variation in (1) level of personalization, (2) governance model, and (3) scale of implementation, enabling theoretically informed comparison rather than just a description.

The analysis is based on secondary data obtained from project documentation, evaluation reports, and related case materials. These sources include information on intervention design and implementation, behavioral mechanisms and tools applied, technological infrastructures (e.g., IoT devices and digital platforms), and monitoring and evaluation results and reported outcomes. A structured template was used to ensure comparability across cases. This template was developed within the STICS (Smart Transformation and Innovation Consortium Slovakia) research project - a standardized coding template covering behavioral mechanisms, technological components, governance arrangements, and reported outcomes.

The cases are analyzed using a comparative framework (based on Table 1) and research questions (RQ):

1. Behavioral Design – focusing on type of nudges used (e.g., feedback, social norms, prompts), and degree of personalization and targeting.
   RQ1: How do behavioral mechanisms such as social norms, feedback, and prompts influence user engagement and energy-related decision-making?
2. Technological Infrastructure – dealing with the role of IoT devices (e.g., smart meters, sensors), data collection and processing capabilities, the design of user interfaces and digital platforms.
   RQ2: How do IoT-based systems (e.g., smart meters, sensors, digital platforms) enable real-time feedback and personalized nudging strategies?
3. Governance and Participation – analyzing the role of public institutions and other stakeholders (including citizen participation), institutional and policy arrangements.
   RQ3: What roles do public institutions, governance structures and citizens play in the adoption of IoT-enabled behavioral interventions?

## 4 Results and Discussion

### 4.1 Renewable Energy Community of Magliano Alpi (Italy)

The Renewable Energy Community (REC) in Magliano Alpi is one of the first community-based energy initiatives in Italy. It is a non-profit entity created in December 2020, based upon the open and voluntary participation of citizens, small and medium enterprises (SMEs) and the City of Magliano Alpi. Its strategic objective is to use energy as the catalyst of local sustainable development.

The intervention aims to transform citizens from passive consumers into active "prosumers," while addressing challenges such as energy dependency, rising costs of energy, and low citizen engagement in local energy systems. In small municipalities such as Magliano Alpi (2,230 inhabitants), these issues can have significant economic

and environmental impacts because local governments often have limited financial and infrastructural capacity to implement large-scale energy solutions independently [38].

The intervention combines physical energy infrastructure with renewable generation and local sharing mechanisms. In particular, solar photovoltaic panels were installed on selected local buildings, including municipal facilities and private rooftops, and an accompanying system was introduced to enable the distribution and sharing of locally generated electricity among community members.

In addition to the physical infrastructure, the REC incorporates behavioral and social design elements to influence how citizens engage with local energy systems. In this case, the collective behavioral approach relies on trust and social norms rather than individualized feedback or targeting. The following behavioral mechanisms were identified:

- Social norms and social proof: The municipality plays an active signaling role, framing participation as both expected and socially beneficial.
- Default-like structures: Citizens are invited to join an already working system, which reduces the complexity of the participation decision.
- Framing and identity cues: Participation is presented as contributing to environmental sustainability and broader community well-being.
- Reduction of participation barriers: Administrative and technical requirements are streamlined through municipal coordination.

Behavioral mechanisms build on status quo bias (by providing an established infrastructure, citizens are more likely to "opt in") and social visibility (shared infrastructure reinforces collective identity and commitment). In this case, behavioral change is driven by collective norms, trust, and institutional leadership.

After the first year, the project produced several results. Locally generated electricity was successfully shared among participating members, thereby increasing local self-consumption of renewable energy. In addition, the initiative was associated with higher participation in renewable energy activities, including a change toward more active prosumer behavior, strengthening the citizen participation and engagement. Average benefits for participants included approximately €94 per person per year from incentives and up to €340 per year when including tax incentives and savings from energy bills.

The estimated investment payback period is about 8.8 years [19]. The project became Italy's first renewable energy community and a model replicated by other municipalities. Overall, the intervention is considered successful, as it demonstrated the feasibility of citizen-led renewable energy systems.

### 4.2 NUDGE - NUDging Consumers Towards EnerGy Efficiency through Behavioral Science

The NUDGE project (2020–2023) was a large-scale EU initiative aimed at systematically testing behavioral interventions to improve energy efficiency across five countries. It combined IoT technologies, digital platforms, and behavioral science to deliver and evaluate multiple nudging strategies in real-world conditions [34].

All five pilots in NUDGE launched summer 2021 and their execution followed an identical three-phase time plan: pre-interventions phase, enabling the establishment

of a benchmark, or baseline, in terms of energy use and consumer behavior for the participating households in each pilot (June–November 2021), testing phase, including the actual testing of the planned interventions in each pilot (between December 2021 and May 2023, so as to provide for the execution of several (consecutive) interventions and their evaluation) and post-interventions phase, running between June and September 2023, the pilots kept on running in the absence of any intervention, to evaluate whether the consumers maintain an improved energy efficient behavior after nudges cease, thus gaining insights into the long-lasting impact of the NUDGE approach.

Interventions included an interdisciplinary project-based education on home energy consumption **for children in Belgium**, where children were educated on and understand the impact of everyday life decisions on home energy consumption, with the support of intergenerational learning among family members and a great replication potential by transferring lessons learned to parents, family and friends. Smart electricity meters were installed at the children's households (N = 55) and schools, with a dashboard to visualize the collected consumption data. The social comparison with the households of classmates was one of the nudging interventions.

**The pilot study in Greece** aimed at improving the efficiency of natural gas boilers used for residential space heating. A total of 102 participants from five Greek cities took part in this study. Each household was equipped with the DOMX (domestic automation) smart heating controller, which allowed for efficient control of legacy gas boilers. This device could modulate heating based on weather conditions and pre-set schedules, potentially leading to energy savings of up to 30% without compromising user comfort. The study tested three types of nudges: NUDGE 1, which provided historical information on gas usage and consumption; NUDGE 2, which facilitated the adoption of energy efficient heating settings (configuration of lower target room temperatures or activation of weather adaptive control) through just in time prompts; and NUDGE 3, which involved the delivery of personalized notifications to encourage the adoption of energy efficient settings.

In **Portugal**, a study involving 101 families with children aimed to reduce electricity consumption while ensuring comfortable and healthy living environments. The study involved a detailed survey of the buildings and the installation of smart meters and indoor air quality (IAQ) sensors in homes. These devices monitored electricity use, carbon dioxide levels, airborne particles, temperature, and humidity. An app was developed to deliver nudging interventions to participants. The first nudging intervention, which provided historical electricity usage data, did not significantly reduce electricity consumption but increased the motivation to save energy. The second intervention, allowing users to view IAQ data, notably increased both the intention to save energy and awareness of households' energy positioning. It also effectively reduced average CO2 levels, with many participants acknowledging the usefulness of the IAQ data in understanding air quality factors and expressing a greater motivation to save energy when IAQ considerations were included.

In **Germany**, 111 households with photovoltaic (PV) systems in the Rhine-Neckar metropolitan area were involved. Among these, 39 had electric vehicle charging stations that could be remotely controlled, forming the EV group. This pilot focused on encouraging energy-saving behaviors and increased self-consumption of energy in households

with electric vehicles (EVs). Two digital platforms were used to deliver nudges: a web portal for all participants to track home energy usage and the HERMINE charging app for the EV group. The nudging strategies included providing feedback, raising awareness about energy efficiency, and offering comparisons, suggestions, and controls. The nudges led to a reduction of household consumption between 4–5%, and they also increased the self-consumption, generally between 3–4%. The EV group showed a more significant response, with self-consumption rising by 10–12%, compared to the average increase of 2–3% among all participants.

**The Croatian Pilot** engaged 82 consumers with PV systems installed in their home and monitored their real-time data on both electricity consumption and production. A user-friendly smartphone app was developed for the pilot to expose participants to nudges, which aimed to cultivate empathy, enhance awareness of energy usage, and encourage energy efficiency goal setting. The outcomes of the pilot suggest that consumers were more susceptible to adapting their energy use in response to external factors, namely limitations imposed by the regulatory framework, and less because of the nudges.

Types of nudges used across these 5 pilots can be summarized as:

- Feedback: Historical and real-time energy consumption data.
- Social comparison: Benchmarking with similar households.
- Prompts and reminders: real-time notifications.
- Goal setting and gamification: Encouraging engagement through targets and challenges.
- Personalized recommendations.

Behavioral Mechanism can be seen in turning energy management into a "challenge" or "game" with social leaderboards. For example, in a German pilot participants received "just-in-time" push notifications on their smartphones when solar production is high (e.g., a sunny afternoon), encouraging them to start energy-intensive tasks like laundry or EV charging. This approach helped residents optimize EV charging specifically during peak solar hours, increasing self-consumption by up to 15%.

Observed behavioral outcomes:

- 4–5% reduction in energy consumption.
- Increased renewable self-consumption.
- Higher engagement with digital tools.

This project systematically tested behavioral nudges across 5 EU countries to increase energy efficiency and renewable self-consumption. Throughout the project, a total of 472 households were directly involved in these pilot trials. Municipalities have used gamification to increase the residents´ awareness of energy usage and/or the share of self-consumption from renewable sources like solar PV.

### 4.3 Greenwich IoT Behavioral Intervention

This behavioral intervention was developed to address increasing energy costs, inefficient household energy use, and low awareness among residents about their energy consumption [36]. Because many residents struggle to understand how energy is used in their homes, they often cannot identify where savings are possible. Inefficient energy

behaviors, such as leaving appliances on standby or running devices unnecessarily or limited knowledge about which devices consume the most electricity means that energy consumption is difficult to track and residents often lack feedback about how their behavior translates into energy costs.

The Greenwich intervention is a municipal pilot project (2022–2023) targeting social housing residents and their energy consumption. By combining the use of IoT with a behavior change approach, centered around nudges and other behavioral interventions, the project sought to aid residents in developing a greater understanding of energy use, associated costs and ways to reduce them, and connecting residents to one another to support shared learning and increase motivation/engagement [28].

Of council social housing residents, 40 participants were recruited. AI-powered Sense monitors were chosen for this project, since the monitors use AI and machine learning to identify different devices within the home, measuring and recording their energy usage in KwH (kilowatthour) and providing estimations for how much the devices cost to run. The device is linked to a smartphone app that is downloaded by residents, where they can:

- view real-time energy consumption,
- track trends over time,
- identify which appliances used the most electricity,
- set energy-saving goals.

In the Greenwich case, several types of nudging interventions were implemented as part of an IoT-enabled behavioral program. These included real-time feedback on energy consumption and associated costs, informational prompts and energy-saving tips, as well as social norm-based mechanisms facilitated through peer interaction and community groups. The goal-setting elements and behavioral challenges were incorporated into the intervention to encourage engagement over time.

From a perspective of behavioral economics, these interventions are based on salience (immediate feedback stresses out the how individual actions are related to the energy outcomes), and on habit disruption (increased awareness can interrupt routine or automatic patterns of energy use).

In terms of observed outcomes, the intervention was associated with an average reduction in electricity consumption of approximately 4%, with reductions reaching up to 20% in some households. Moreover, reported effects included increased awareness of energy use and higher levels of user engagement with the system.

Throughout the pilot project, residents generated a greater understanding of their energy use, specifically around individual devices. The trial continues, following further support from Greenwich Council to continue to work with residents and gather lessons learned. Residents are still taking part in the Energy Community WhatsApp group and receiving support as well as energy-saving tips and advice.

### 4.4 Summary of Main Findings

The following Table 2 summarizes the main findings following the structure of the three research questions.

**Table 2.** Comparative Analysis of Case Studies: Behavioral, Technological, and Governance Dimensions

| Dimension | Key Aspect | Magliano Alpi (Italy) | NUDGE Project (EU) | Greenwich (UK) |
|---|---|---|---|---|
| Behavioral Design (RQ1) | Type of nudges | Social norms, moral framing, default-like participation, reduced friction | Feedback, social comparison, prompts, goal setting, gamification, personalization | Real-time feedback, prompts, social interaction, goal setting |
| | Behavioral mechanisms | Social proof, trust, status quo bias, collective identity | Salience, social comparison, commitment, learning effects | Salience, habit disruption, social norms, peer influence |
| | Personalization level | Low (collective, non-targeted) | High (segmented, data-driven, context-aware) | Moderate–high (household-level feedback, semi-tailored nudges) |
| | Effect on behavior | Increased participation, prosumer behavior, community engagement | 4–5% energy reduction, increased self-consumption, higher engagement | Avg. 4% reduction (up to 20%), increased awareness and engagement |
| Technological Infrastructure (RQ2) | IoT components | Smart meters, PV systems, energy-sharing platform | Smart meters, sensors, heating controllers, apps, dashboards | AI energy monitors, smart plugs, sensors |
| | Data capabilities | Aggregated monitoring of production and consumption | High-resolution, multi-source data (energy, environment, behavior) | Appliance-level, real-time consumption data |
| | User interfaces | Limited user-facing interfaces (system-level focus) | Mobile apps and dashboards with interactive features | Mobile app + messaging platform (WhatsApp) |
| | Role in nudging | Indirect (supports system efficiency, not personalized nudges) | Core enabler of personalized, adaptive nudging | Direct feedback–action loop enabling behavioral change |

(*continued*)

**Table 2.** (*continued*)

| Dimension | Key Aspect | Magliano Alpi (Italy) | NUDGE Project (EU) | Greenwich (UK) |
|---|---|---|---|---|
| Governance & Participation (RQ3) | Governance model | Municipality-led, community-based energy governance | Multi-level, research-driven consortium | Municipality-led with private partners |
| | Stakeholders | Public sector, citizens, businesses, research institutions | EU institutions, research orgs, private companies, households | Public sector, tech providers, residents |
| | Citizen participation | High (active prosumers, co-creation) | Moderate (participants in pilot trials) | Moderate–high (active engagement in community groups) |
| | Policy integration | Strong (aligned with EU and national energy transition policies) | Strong (EU-level policy alignment and recommendations) | Moderate (linked to local sustainability and social policies) |
| | Key governance role | Build trust, enables collective action | Enables experimentation and scalability | Enables targeted intervention and inclusion |
| Overall Contribution | Strengths | Strong social cohesion and collective engagement | High scalability, personalization, and empirical validation | Strong behavioral impact through real-time feedback and engagement |
| | Limitations | Limited personalization and individual feedback | Less community-driven participation | Smaller scale, pilot-based implementation |

The findings indicate that integrating behavioral economics with IoT technologies represents an effective approach for improving energy efficiency in smart city contexts. By combining real-time data with targeted nudges, cities can influence citizen behavior.

A cross-case comparison reveals several insights. First, the effectiveness of behavioral interventions appears strongly dependent on the level of personalization enabled by IoT systems. Cases in larger municipalities (NUDGE, Greenwich) demonstrate measurable reductions in individual energy consumption (individual approach), whereas smaller municipalities (Magliano Alpi) primarily influence participation and social engagement, building on local ties (collective approach). Another insight shows that governance structures shape not only implementation but also behavioral outcomes. Municipality-led and

community-embedded models (Magliano Alpi, Greenwich) show stronger trust-based engagement, while large-scale experimental settings (NUDGE) achieve greater standardization and scalability but somewhat weaker social cohesion. Finally, the interaction between behavioral mechanisms and technological infrastructure indicates that nudges are most effective when embedded in continuous feedback loops.

These findings imply that the effectiveness of IoT-enabled behavioral interventions is not determined solely by individual components, but by their use within broader socio-technical systems.

These findings are mostly consistent with existing research. Across the three cases, behavioral mechanisms—particularly feedback, social norms, and prompts—appear to play an important role in shaping energy consumption behavior, aligning with the behavioral economics literature, which portrays nudges as tools for influencing decision-making without restricting choice. In particular, systematic reviews indicate that real-time feedback can increase user awareness and responsiveness, especially when individuals can directly associate their actions with observable outcomes [40]. The influence of social norms, which is especially evident in the Magliano Alpi case, is also well documented in the literature [2, 7, 17, 47], which supports the finding that community-based interventions, where participation is visible and socially reinforced, may support collective behavioral change even in the absence of personalized feedback.

However, the case studies also show that nudges' effectiveness increases with personalization and contextualization, as demonstrated by the NUDGE project, consistent with recent IoT-based research that finds that personalized feedback, social comparison and goal setting influence actual energy-saving activities [30].

On the other hand, the literature also highlights that nudging alone may not be sufficient to bridge the intention–behavior gap fully [6, 44], which partially explains why interventions relying solely on digital nudges (without strong governance or social embedding) may yield limited or short-term effects.

Across all three cases, IoT technologies emerge as a key enabling layer that translates behavioral concepts into operational, real-time feedback systems [30]. As outlined in the conceptual framework (Table 1), IoT systems do not only function as data collection tools, but also support continuous feedback loops between user behavior, system data, and intervention design. Additionally, IoT and big data enable user segmentation and targeting, thereby further enhancing the precision and effectiveness of behavioral interventions [16].

Finally, the analysis highlights the importance of governance and participatory structures in shaping the effectiveness of IoT-enabled behavioral interventions - a dimension that is scarcely mentioned in technology-centered studies [40]. Overall, the findings support the argument that sustainable energy transitions in smart cities are more likely to be effective when approached through integrated socio-technical frameworks, rather than through isolated technological deployments or standalone behavioral interventions.

## 5 Conclusions

This paper aimed to examine how integrating behavioral economics (nudging) and IoT-based technologies can improve energy efficiency in urban areas, and to assess their role in smart governance through a comparative analysis of selected case studies.

The conceptual framework used in this study provides a basis for future research and policy design, emphasizing the need for interdisciplinary approaches that connect technology (technological dimension), smart governance (institutional dimension), and human behavior (behavioral mechanism dimension).

Based on the analysis, we can conclude several main findings. First, technological and behavioral dimensions must complement each other: IoT systems, on their own, do not necessarily lead to energy savings; rather, their effectiveness depends on how the generated data is translated into actions through behavioral interventions such as nudges. Following this finding, real-time feedback mechanisms appear to enhance salience and learning by making energy consumption more immediately observable and interpretable. Also, social dynamics play an important role in strengthening behavioral effects, as evidenced by the cases of Magliano Alpi and Greenwich, which indicate that community-based approaches can support higher levels of engagement than individually oriented interventions. Moreover, governance arrangements appear to influence implementation outcomes, particularly when municipal involvement and institutional trust support adoption and scalability. Finally, heterogeneity among users points to the potential importance of personalization, as illustrated by the NUDGE project, where tailored interventions are associated with more differentiated behavioral responses.

From an urban planning perspective, these findings support a shift toward integrated socio-technical systems in which infrastructure, data, and human behavior are co-designed.

These insights are especially interesting for CEE countries, where municipalities often face financial and institutional constraints in implementing large-scale smart city solutions. The integration of behavioral mechanisms with relatively low-cost IoT technologies offers a feasible and scalable policy pathway in such conditions.

The study's limitation is that it analyzes only secondary data, which limits the depth of behavioral insights and introduces bias in reporting. Additionally, the heterogeneity of case studies disables direct comparison. While the findings support analytical generalization, they should not be interpreted as statistically generalizable because the study is qualitative and case-based.

Future research could focus on long-term effects of such IoT-behavioral mechanism combined interventions, scalability across different urban contexts, and ethical considerations related to data use and digital nudging.

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## References

1. Abrahamse, W., Steg, L., Vlek, C., Rothengatter, T.: A review of intervention studies aimed at household energy conservation. J. Environ. Psychol. **25**(3), 273–291 (2005)
2. Allcott, H., Mullainathan, S.: Behavior and energy policy. Science **327**(5970), 1204–1205 (2010)
3. Allcott, H.: Social norms and energy conservation. J. Public Econ. **95**(9–10), 1082–1095 (2011)

4. Amadori, M., Votta, M.: SDGs and the engagement of EU citizens: the role of behavioral science in the energy transition. Resour. Environ. Econ. **3**(1), 239–244 (2021)
5. Balta-Ozkan, N., Amerighi, O., Boteler, B.: A comparison of consumer perceptions towards smart homes in the UK, Germany and Italy: reflections for policy and future research. Tech. Anal. Strat. Manag. **26**(10), 1176–1195 (2014)
6. Batalla-Bejerano, J., Trujillo-Baute, E., Villa-Arrieta, M.: Smart meters and consumer behaviour: insights from the empirical literature. Energy Policy **1**(144), 111610 (2020)
7. Bergquist, M., Nilsson, A.: Using social norms in smart meters: the norm distance effect. Energ. Effic. **11**, 2101–2109 (2018). https://doi.org/10.1007/s12053-018-9709-6
8. Bridoux, F., Stoelhorst, J.W.: Stakeholder governance: solving the collective action problems in joint value creation. Acad. Manag. Rev. **47**(2), 214–236 (2022)
9. Caragliu, A., Del Bo, C.F., Nijkamp, P.: "Smart cities in Europe" revisited: a meta-analysis of smart city economic impacts. J. Urban Technol. **30**(4), 51–69 (2023)
10. Claudy, M.C., Peterson, M., O'driscoll, A.: Understanding the attitude-behavior gap for renewable energy systems using behavioral reasoning theory. J. Macromark **33**(4), 273–287 (2013)
11. Dolan, P., Hallsworth, M., Halpern, D., King, D., Vlaev, I.: Influencing behaviour: the MINDSPACE way. J. Econ. Psychol. **33**(1), 264–277 (2012)
12. Fischer, C.: Feedback on household electricity consumption: a tool for saving energy? Energ. Effic. **1**(1), 79–104 (2008)
13. Frederiks, E.R., Stenner, K., Hobman, E.V.: Household energy use: applying behavioural economics to understand consumer decision-making and behaviour. Renew. Sust. Energ. Rev. **1**(41), 1385–1394 (2015)
14. Gabriel, M.F., et al.: Opportunities for promoting healthy homes and long-lasting energy-efficient behaviour among families with children in Portugal. Energies **16**(4), 1872 (2023)
15. Garau, C., Balletto, G., Mundula, L.: A critical reflection on smart governance in Italy: definition and challenges for a sustainable urban regeneration. In: International Conference on Smart and Sustainable Planning for Cities and Regions, pp. 235–250. Springer International Publishing, Cham (2015)
16. Ge, W., Chen, B.: Electricity user behavior analysis and marketing strategy based on internet of things and big data. Energy Inform. **7**(1), 100 (2024)
17. Geelen, D., Mugge, R., Silvester, S., Bulters, A.: The use of apps to promote energy saving: a study of smart meter–related feedback in the Netherlands. Energ. Effic. **12**(6), 1635–1660 (2019)
18. Geels, F.W.: The multi-level perspective on sustainability transitions. Environ Innov Soc Transit. **1**(1), 24–40 (2011)
19. Ghiani, E., Trevisan, R., Rosetti, G.L., Olivero, S., Barbero, L.: Energetic and economic performances of the energy community of Magliano Alpi after one year of piloting. Energies **15**(19), 7439 (2022)
20. Giest, S.: Do nudgers need budging? A comparative analysis of European smart meter implementation. Energy Res. Soc. Sci. **60**, 101325 (2020)
21. Gubbi, J., Buyya, R., Marusic, S., Palaniswami, M.: Internet of things (IoT): a vision, architectural elements, and future directions. Futur. Gener. Comput. Syst. **29**(7), 1645–1660 (2013)
22. Hollands, R.G.: Will the real smart city please stand up?: intelligent, progressive or entrepreneurial? In: The Routledge Companion to Smart Cities, pp. 179–199. Routledge (2020)
23. Kahneman, D.: Thinking, Fast and Slow. Farrar, Straus and Giroux, New York (2011)
24. Karaliopoulos, M., Tsolas, L., Koutsopoulos, I., Halkidi, M., Van Hove, S., Conradie, P.: Beyond clustering: rethinking the segmentation of energy consumers when nudging them towards energy-saving behavior. ACM SIGEnergy Energy Inform. Rev. **2**(4), 28–43 (2023)

25. Kitchin, R.: The real-time city? Big data and smart urbanism. GeoJournal **79**(1), 1–4 (2014)
26. Kochański, B., Korczak, K., Skoczkowski, T.: Enablers and barriers in the market-driven rollout of smart metering: the case of Poland. Energies. **14**(17), 5259 (2021)
27. Kowalska-Pyzalska, A., Byrka, K., Matuszewska-Janica, A., et al.: What makes consumers adopt smart meters? The role of behavioral and socio-demographic factors. Energies. **13**(18), 4737 (2020)
28. Local Government Association, DG Cities. Nudging energy behaviours: Combining Internet of Things and behavioural science. (2023). London: LGA; [cited 2026 Mar 20]. https://www.local.gov.uk/case-studies/nudging-energy-behaviours-combining-internet-things-and-behavioural-science-help
29. March, H., Ribera-Fumaz, R.: Smart contradictions: the politics of making Barcelona a self-sufficient city. Eur. Urban Reg. Stud. **23**(4), 816–830 (2016)
30. Masmali, F.H., Khan, S.M., Hakim, T.: IoT-enabled digital Nudge architecture for sustainable energy behavior: an SEM-PLS approach. Technologies **13**(11), 504 (2025)
31. Meijer, A., Bolívar, M.P.: Governing the smart city: a review of the literature on smart urban governance. Int. Rev. Adm. Sci. **82**(2), 392–408 (2016)
32. Nam, T., Pardo, T.A.: Conceptualizing smart city with dimensions of technology, people, and institutions. In: Proceedings of the 12th Annual International Conference Digital Government Research, pp. 282–291 (2011)
33. Nastjuk, I., Trang, S., Papageorgiou, E.I.: Smart cities and smart governance models for future cities: I. Nastjuk et al. Electron. Mark. **32**(4), 1917–1924 (2022)
34. NUDGE Project: NUDging Consumers towards enerGy Efficiency through Behavioural Science [Internet]. Brussels: Institute for European Energy and Climate Policy, (2020–2023). [cited 2026 Mar 20]. https://ieecp.org/projects/nudge/
35. Ostrom, E.: Governing the Commons: the Evolution of Institutions for Collective Action. Cambridge University Press, Cambridge (1990)
36. Pelka, S., et al.: Self-consumption rises due to energy crises? An evaluation of prosumers' consumption behavior in 2022. In: 2023 19th International Conference on the European Energy Market (EEM), pp. 1–6. IEEE (2023)
37. Ramirez Lopez, L.J., Grijalba Castro, A.I.: Sustainability and resilience in smart city planning: a review. Sustainability **13**(1), 181 (2020)
38. Renewable Energy Community of Magliano Alpi: Project documentation and reports. (2023) [cited 2026 Mar 20]. https://cermaglianoalpi.it/index.php/who-we-are/?lang=en
39. Salas, J., Yepes, V.: Enhancing sustainability and resilience through multi-level infrastructure planning. Int. J. Environ. Res. Public Health **17**(3), 962 (2020)
40. Samancioglu, N., Castano-Rosa, R., Väänänen, K., Komal, M.: The role of smart meter feedback in enhancing inhabitants' energy efficient behaviour in residential buildings. Energ. Buildings **7**, 116689 (2025)
41. Schultz, P.W., Dear-Ferguson, S.D., Hernandez, P.R., Bergquist, M., Hed, A.N.: Changing behavior through normative social influence. In: Research Handbook on Social Influence, pp. 89–103. Edward Elgar Publishing (2025)
42. Sørensen, E., Torfing, J.: Enhancing collaborative innovation in the public sector. Adm. Soc. **43**(8), 842–868 (2011)
43. Spodniak, P., Brisuda, J., Wozniak, J.: Diffusion and drivers of smart meters in central and Eastern Europe. Int. J. Inf. Technol. Manag. **11**(3), 247–262 (2014)
44. Stieglitz, S., Mirbabaie, M., Deubel, A., Braun, L.M., Kissmer, T.: The potential of digital nudging to bridge the gap between environmental attitude and behavior in the usage of smart home applications. Int. J. Inf. Manag. **1**(72), 102665 (2023)
45. Sunstein, C.R.: Nudging: a very short guide. J. Consum. Policy **37**(4), 583–588 (2014)
46. Thaler, R.H., Sunstein, C.R.: Nudge: Improving Decisions about Health, Wealth, and Happiness. Yale University Press, New Haven (2008)

47. Tiberio, L., et al.: Unveiling the power of social norms interventions: investigating energy savings behavior in an Italian energy cooperative. Energy Res. Soc. Sci. **1**(122), 103989 (2025)
48. Tongsubanan, S., Kasemsarn, K.: Developing a design guideline for a user-friendly home energy-saving application that aligns with user-centered design (UCD) principles. Int. J. Hum. Comput. Interact. **41**(12), 7424–7446 (2025)
49. Vitálišová, K., Laco, P., Vaňová, A., Borseková, K., Sýkorová, K., Vavrúšová, M.: Open local governance: the case of district cities in Slovakia. In: International Conference on Computational Science and its Applications, pp. 97–110. Springer Nature Switzerland, Cham (2025)
50. Weinmann, M., Schneider, C., Brocke, J.V.: Digital nudging. Bus. Inf. Syst. Eng. **58**(6), 433–436 (2016)
51. Wendt, C., Kosin, D., Adam, M., Benlian, A.: Sustainable energy consumption behaviour with smart meters: the role of relative performance and evaluative standards. Inf. Syst. J. **34**(6), 1995–2023 (2024)
52. Wilson, C., Hargreaves, T., Hauxwell-Baldwin, R.: Smart homes and their users: a systematic analysis and key challenges. Pers. Ubiquit. Comput. **19**(2), 463–476 (2015)
53. Yin, R.K.: Case Study Research: Design and Methods, 5th edn. Sage Publications, Thousand Oaks (CA) (2014)
54. Zanella, A., Bui, N., Castellani, A., Vangelista, L., Zorzi, M.: Internet of things for smart cities. IEEE Internet Things J. **1**(1), 22–32 (2014)

# Smart Innovations in Biosphere Reserves

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**Abstract.** The paper aims to define the smart innovations in biosphere reserve from the theoretical point of view and subsequently, identify the examples of good practice in their real conditions, based on it summarize the key features of smart innovation in biosphere reserves. The smart innovation is interpreted as a comprehensive ecosystem of solutions based on the use of digital technologies, data analytics, and interconnected systems enhancing process efficiency and support the sustainable development of regions. The paper draws on the theoretical foundations of innovation theory and collaboration models, particularly the Quintuple Helix model, which emphasizes collaboration between the public sector, the business sector, the academic community, civil society, and the natural environment. Special attention is given to the application in the context of biosphere reserves, where it is essential to respect nature conservation requirements while simultaneously supporting socio-economic development. The empirical part of the paper presents selected examples of good practice in smart innovations within biosphere reserves, which are subsequently analysed and discussed in relation to theoretical frameworks. The results highlight the importance of linking technological solutions to the needs of the area and the necessity of local stakeholder participation. The conclusion emphasizes that smart innovations represent a tool for achieving a balance between biodiversity conservation and sustainable development, with biosphere reserves serving as experimental sites for their implementation.

**Keywords:** Smart innovation · biosphere reserve · innovation ecosystem

## 1 Introduction

Innovation is widely recognized as a fundamental determinant of spatial competitiveness and long-term economic performance. Regions that successfully generate, adopt, and diffuse innovations tend to achieve higher productivity, greater value creation, and improved living standards. From an economic perspective, innovation contributes to growth through three principal mechanisms, namely new products or services, qualitative improvements in existing products and their characteristics, and increases in production efficiency and organizational effectiveness.

According to the Oslo Manual, innovation is defined as the implementation of a new or significantly improved product, process, or method within business practices, workplace organization, or external relations [1]. Thus, innovation does not refer merely to

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invention but to the practical application of knowledge that creates measurable economic or social value.

Innovation is not confined only to private firms but also plays a crucial role in public sector and regional development policy. Consequently, innovation capacity becomes a central component of regional development strategies and an essential prerequisite for the sustainable competitiveness of territories [2].

A new dimension of innovation has been driven by the advances in information and communication technologies, often captured by the term "smart". Such innovations leverage modern technologies to create personalized solutions based on data analytics, thereby better meeting users' needs. Moreover, in the case of biosphere reserve, they should reflect also the specific of this type of territory and limits given by its protection. Here we can identify the gap in research, in theory as well as in practice. It lies in addressing issue of smart innovations at the intersection of innovation theory, digital technologies, and environmental management of biosphere reserves. That is why the aim of the paper is to define the smart innovations in biosphere reserve from the theoretical point of view and subsequently, identify the examples of good practices in their real conditions, based on it summarize the key features of smart innovation in biosphere reserves. So, the added value of the paper is theoretical and empirical conceptualisation of the smart innovations in context of biosphere reserves.

In the paper, the theoretical section defines the key concept of smart innovation and applies it to the context of biosphere reserves. It also uses deduction and analogy to characterize the typology of smart innovations. The second part of the paper defines the research materials and methods. The third chapter presents selected examples of good practice in smart innovation within biosphere reserves. This is followed by a scientific discussion of the identified examples in relation to theoretical foundations, concluding with a summary of the specific characteristics of smart innovation in biosphere reserves.

## 2 Smart Innovations in Biosphere Reserves

The concept of smart innovation represents a paradigm shift in contemporary economic science in understanding the relationship between technological progress and socio-economic development. Smart innovation, often associated with regional development and digital transformation, is finding increasingly wider application in the specific context of biosphere reserves (BR), where technology is becoming a tool for achieving a balance between biodiversity conservation and sustainable socio-economic development in line with UNESCO's Man and the Biosphere (MAB) program [3].

Smart innovations in the context of BRs are not just a derivative of technological determinism, but a complex ecosystem of interconnected solutions using cyber-physical systems (CPS). While Schumpeter [4] defined innovation as a process of "creative destruction," in the "smart" era, this process is transforming into continuous adaptive optimization through data flows and interconnected systems [5].

The key theoretical pillar of smart innovation is the Triple Helix model [6], which assumes synergistic interaction between universities, industry, and government. This cooperation is essential for the emergence of so-called "smart specialization," which the European Commission promotes as a strategic framework for regional development [7].

However, in the context of BR, it is necessary to expand this model with a fourth element—civil society (the so-called quadruple helix), which emphasizes the participation of local communities and citizen science [8, 9] and a fifth element – natural environment in which knowledge moves in a circular fashion from system to system, generating new knowledge and innovations oriented towards sustainable socio-ecological transformation (the so-called quintuple helix model) [10, 11].

In the context of territories, smart innovations manifest themselves through the Smart City concept. According to Giffinger et al. [12], this concept is based on six smart pillars: economy, mobility, environment, people living, and smart governance. These pillars are also adaptable to BR, where their focus is primarily on the needs of protection, sustainable and resilient development of the territory.

Smart innovations are inextricably linked to the fourth industrial revolution, which brings a fusion of technologies that blur the boundaries between the physical, digital, and biological spheres [13]. Key technologies include the Internet of Things (IoT), artificial intelligence (AI) and machine learning, big data analytics, and others [5].

Critical discussion in the field of smart innovation points to the need to move from a purely technological focus to an anthropocentric approach known as Society 5.0. This concept, defined primarily for the Japanese government [14], envisions the use of smart innovation to address global challenges such as the climate crisis, in line with the UN Sustainable Development Goals (SDGs). Biosphere reserves are "learning sites" where smart innovations contribute to ecosystem resilience and a deeper understanding of complex systems [8].

In scientific literature (e.g., according to authors such as Schiavone [15], Greco, and Bencardino [16] or in the context of EU Smart Specialisation strategies), smart innovation can be defined as the process of applying digital technologies, data analytics, and connectivity to existing or new products, processes, and services in order to increase their efficiency, adaptability, and value to the user, often integrating aspects of sustainability and networking. Simply put, smart innovation is not just about doing something "better," but about adding "intelligence" to the system—the ability to collect data, learn from it, and respond autonomously or semi-autonomously to changes in the environment. The difference between traditional and smart innovation is not just in the use of more modern technology, but in the overall approach to solving the problem. While traditional innovation focuses on improving functionality, smart innovation adds a layer of intelligence and connectivity. Traditional innovations are characterized by static, independent functioning, while smart innovations are dynamic and often part of a network. For example, data collection in smart innovations is automatic and continuous, maintenance is provided by an algorithm, device decision-making is independent or semi-autonomous, and updates are done remotely.

While traditional innovation makes things better, smart innovation makes things smarter. Smart innovations use a feedback loop, where data from use continuously optimizes the process. On the other hand, some authors also draw attention to negative externalities of smart innovations. For example, Zuboff [17] introduces the term "surveillance capitalism," where human experience becomes a free resource for hidden commercial practices. This asymmetry of power is a major barrier to the socially just implementation of smart innovations. It is therefore essential to ensure that smart innovations in BR

primarily serve the good of the community and the protection of nature, and not just commercial interests. When introducing smart innovations into the BR environment, it is therefore important to bear in mind that they should serve as a catalyst for ecosystem resilience, not as a substitute for nature conservation

### 2.1 Taxonomy of Smart Innovations in BR

The scientific classification of smart innovations goes beyond the scope of conventional product innovation [5]. According to Rowley [18] and Quinta et al. [19], they can be categorized based on their functional application and technological depth. They list the following types of innovations - incremental smart innovations (optimization of existing systems using sensors, e.g., adaptive lighting), radical (disruptive) smart innovations (the emergence of completely new data-based business models, such as the "Product-as-a-Service" model) and socio-technical innovations (solutions where technology serves as a mediator of social change, e.g., blockchain in participatory budgeting).

According to the degree of originality, innovations can be divided into imitative and original. Imitative innovations involve the adoption or adaptation of solutions already implemented elsewhere and verified in practice. In contrast, original innovations represent the realization of entirely new ideas, concepts, or technological solutions [20].

In biosphere reserves, based on these authors, empirical evidence, and our own research [1, 5, 26] we have identified the following types: technical and technological innovations, process innovations, economic, process, and social innovations.

Technical and technological innovations form the core of digital transformation in BR, focusing on the physical properties of products (hardware, sensors) and changes in scientific know-how and algorithms [22]. In BR, they are transformed into so-called "Conservation Tech," which is a transition from isolated machines to cyber-physical systems (CPS). Most often, these can be IoT networks, e.g., for real-time monitoring of microclimate, soil moisture, and groundwater levels, which is key to predicting fire risk and drought impacts. Fassnacht et al. [23] for example, write about AI in phytocenology in the form of multispectral imaging from drones and satellites, with the aim of identifying, for example, invasive species or bark beetle calamities using neural networks. A very interesting possibility for technical innovation is the creation of a digital twin of BR. The creation of virtual models of BR (Digital Twins) based on satellite data and ground sensors can be used to simulate the impacts of climate change or the spread of invasive species [24, 25], but also the extinction of certain species or the impacts of human activity on biodiversity. Beyond the traditional static modeling tools, digital twin is a dynamic, virtual representation of a physical object continuously updated using sensor data and near-real-time information. A digital twin reflects the current state and behavior of its real-world counterpart, enabling ongoing analysis and prediction.

Process innovations are generally linked to the substantial changes in production or delivery methods, including improvements in service provision. In case of biosphere reserves, they are focused on implementing new or significantly improved methods of management and nature conservation. According to Davenport [26], this involves a radical rethinking of processes with the aim of achieving significant improvements in costs and quality.

One form of this can be, for example, Precision Conservation, which means a transition from periodic field research to real-time monitoring. This form helps to maximize data collection while minimizing anthropogenic impact (human impact on nature).

Economic innovations are changing the market structure and internal organization of local communities in biosphere reserve. They are mainly focused on monetization strategies. The smart economy in biosphere reserver is changing the way local communities profit from nature conservation without degrading it. In practice, this may involve the tokenization of ecosystem services, the use of blockchain for transparent payments for ecosystem services (PES). Local farmers can receive digital tokens for measurable increases in biodiversity on their land [27, 28].

Process innovations are changing culture and management [29], or substantial changes in production or delivery methods, including improvements in service provision [1]. In biosphere reserves, the most significant innovation in recent years is a participatory biosphere reserve management. This form can be further developed, e. g. to e-Governance of biosphere reserves through transparent decision-making processes on land use via digital platforms, reducing conflicts between conservationists and farmers [5]. Another process innovation could be various forms of smart ecotourism, e.g., through the use of augmented reality in visitor education, without the need to build infrastructure in core areas of biosphere reserve. Another possibility is to penetrate land cultivation with an emphasis on biodiversity protection through the use of small GPS-controlled mechanization, which would, for example, optimize fertilization and grazing. This would prevent soil erosion and damage to watercourses. Another process innovation could be the introduction of blockchain for local organic products. The implementation of a digital certificate of origin (Smart Label) for BR products will allow consumers to verify the "environmental footprint" of a product via a QR code.

Social innovation focuses on addressing societal challenges through new forms of collaboration [30]. Phills et al. [31] define social innovation as a solution that is more effective, sustainable, and equitable. In the UK, they reinforce the quadruple helix model, where civil society joins universities, industry, and government [32]. In context of social ecology and environmental problems social innovations are broadly associated with the quintuple helix model [33]. To the one of the modern forms how to develop the social innovation in biosphere reserves belong tools of participative governance and tools of Citizen Science, where, for example, mobile applications enable local residents and tourists to map the occurrence of protected or invasive species, thereby building social capital and increasing environmental awareness [34, 35]. Another form is smart education using AI or virtual reality, e.g., in information centers, which simulate historical developments, or impact of various natural phenomena and teach visitors the rules of behavior in nature.

In the next parts of the paper, based on the use of AI and review of available documents and websites, we identify and present the examples of good practices in smart innovation in biosphere reserves that can serve as inspirations for others.

## 3 Material and Methodology

This paper employs a theoretical analysis to develop a framework for smart innovations. Based on the general definition of innovation and innovation in smart development we analogically define the smart innovation and apply it in context of biosphere reserves. Subsequently, we use a deductive approach to define the various types of smart innovations supported by the modern technologies, examples of which we analyse in the analytical section of this paper.

The research part of the paper presents the selection of smart innovation across the biosphere reserves on the European continent identified as the best cases. The research sample consisted of 205 biosphere reserves on the European continent which are recognised by UNESCO and published on its website (https://www.unesco.org). However, biosphere reserves were not investigated individually but by countries. An AI tool was used as a key supporting tool for the initial mapping and preliminary identification of relevant innovative solutions in biosphere reserves. The analysis was carried out through a single prompt: "Analyze (selected country) biosphere reserves in three steps. I need to know if there are specific good examples of practice that use biosphere reserves (1) in data collection, (2) in the publication of data by a biosphere reserve or other entity, (3) the use of this data for maps, visualizations, applications, and subsequently public policy. " Then we checked the results and verified them with reality. It was done through the secondary research of relevant official documents, websites and social networks of individual biosphere reserves. If the identified innovation was confirmed, we elaborate it as example of good practice to demonstrate theoretically defined innovations. The list of good practice is not exhaustive, but it presents a set of representative examples illustrating the categories of the possible smart innovations in biosphere reserves as starting point for further research. The data collection took place in the period from September 2025 to February 2026.

Based on the analysis of examples of smart innovations and comparison with the theoretical framework, we elaborated the comparative evaluation of the smart innovations (Table 1) regarding the selected features (e. g. type of innovation, impact, stakeholders' participation, etc.). The selection of the features is based on innovation and smart governance theory. The evaluation of these features was based on expert opinion of authors and results of the conducted survey. Subsequently, we identified the key features of smart innovation in biosphere reserves and challenges for the future development.

## 4 Research Finding and Discussion

Biosphere reserves are internationally recognized model areas designated for the practical application of interdisciplinary knowledge aimed at understanding and maintaining the relationship between humans and the natural environment, as well as managing change, including conflict prevention and biodiversity conservation. The impacts of current global challenges emerge this model of territorial functioning even more clearly due to its focus on eliminating negative impacts of global challenges, but also on striking a balance between nature and humans and building the territory's resilience. Preserving the resilience of ecosystems and their ecosystem services—such as access to drinking

water, food production, soil fertility, climate regulation, and aesthetic values—along with the protection of biodiversity, is a fundamental prerequisite for eliminating poverty and promoting human health and well-being [36]. The development of modern technologies influences strongly the possibilities to strength the resilience of biosphere reserves, to map and analyse the territory and make policy decisions based on data and evidence. These possibilities are reflected in smart innovations which are gradually implemented also in this type of territory.

### 4.1 Best Examples of Smart Innovation in Biosphere Reserves

To the most advanced smart innovations in biosphere reserves and digital monitoring belong an integrated environmental sensor network in North Devon Biosphere. The system uses Internet-of-Things (IoT) technologies to collect real-time data on hydrology and ecosystem conditions, including water levels, rainfall, soil moisture and water quality [39]. These sensors transmit data to a central digital platform where they are integrated with additional environmental datasets. The resulting data infrastructure supports evidence-based decision-making [40]. The approach represents a model of a "digital biosphere reserve" or environmental digital twin, demonstrating how automated monitoring can support landscape management and provide real-time environmental intelligence. A comparable example of smart environmental monitoring can be found in the Archipelago Sea Biosphere Reserve, where automated marine monitoring systems are used to observe coastal ecosystem conditions. Sensor-equipped monitoring stations and research buoys collect continuous data on marine biodiversity, contaminants, marine litter, energy, including underwater noise, hydrographical conditions and others in the Baltic Sea [41]. These data are integrated into national environmental monitoring systems managed by the Finnish Environment Institute, making them accessible for environmental assessment, research or management [42]. Together, these examples demonstrate how biosphere reserves can apply sensor networks and real-time environmental data systems to improve ecosystem monitoring and evidence-based environmental governance. The Doñana Biological Station in Doñana Biosphere Reserve also operates networks of automated environmental sensors measuring hydrological and climatic variables in wetland ecosystems [43, 44]. These systems provide continuous environmental observations that complement traditional ecological surveys. In addition, researchers and field rangers use mobile applications such as CyberTracker to collect georeferenced biodiversity observations directly in the field [45]. This combination of sensor networks and digital field data collection significantly improves the efficiency and spatial accuracy of ecological monitoring, providing high-resolution data on ecosystem dynamics and biodiversity trends.

Another emerging smart innovation in biosphere reserve monitoring is the use of environmental DNA (eDNA) techniques to detect species presence through genetic material found in water or soil samples. This method allows researchers to identify fish, invertebrates and other organisms without direct observation or capture, enabling faster and less invasive biodiversity monitoring. In coastal ecosystems such as the Wadden Sea Biosphere Reserve, eDNA sampling is increasingly used to complement traditional ecological surveys and improve biodiversity assessments [46, 47]. Satellite remote sensing has also become an important tool for biosphere reserve management. Many reserves use

Copernicus Sentinel satellite data to monitor vegetation dynamics, wetland extent, forest cover changes and land-use patterns across large areas. These datasets provide consistent long-term observations that complement field measurements and allow managers to detect ecosystem changes and environmental pressures at landscape scale. The presented set of examples can be classified as technical and technological innovations with the strong impact on the policy making on territorial resilience. All collected data are relevant sources of information for the qualified decisions reflecting the real conditions in the territories and provide the possibility to simulate future development.

Social innovation as citizen science has become an increasingly important innovation in biosphere reserves monitoring systems. A good example is Kristianstads Vattenrike Biosphere Reserve, where public participation and citizen research is integrated into environmental monitoring and awareness programmes. Volunteers contribute observations on biodiversity and environmental conditions, while spatial information about the biosphere reserve is made accessible through digital mapping tools such as the Naturkartan outdoor platform [48, 49]. Similar approaches can also be found in several other European biosphere reserves. For example, the Dyfi Biosphere in Wales implemented the COBWEB citizen observatory project, enabling residents to collect environmental data using mobile devices [50]. In Archipelago Sea Biosphere Reserve, biodiversity observations from citizen scientists are integrated through global platforms such as iNaturalist, contributing to species monitoring in coastal ecosystems worldwide [51]. In Nordhordland Biospehre Reserve in Norway, the public database and open map portal Artsoservasjoner is used also as a citizen science tool for reporting and viewing various biodiversity observations [62]. These initiatives illustrate how citizen science can complement professional monitoring, increase data availability and strengthen local engagement in biosphere reserve management.

Another example of biosphere reserves smart innovations can be found in Sierra Nevada Biosphere Reserve, where the Sierra Nevada Global Change Observatory (OBSNEV) operates a long-term ecological monitoring infrastructure. The observatory integrates field observations, climate monitoring stations and satellite remote sensing data to track ecological and socio-environmental changes in mountain ecosystems [52]. Importantly, the observatory does not only collect data but also curates and publishes them as open datasets, making them accessible for scientific research and environmental governance. The Wadden Sea Biosphere Reserve thus represents one of the most sophisticated examples of international environmental monitoring in Europe. Through the Trilateral Monitoring and Assessment Programme (TMAP), Denmark, Germany and the Netherlands coordinate ecosystem monitoring across the entire Wadden Sea region [53]. The system harmonises monitoring protocols for biodiversity, water quality, sediment dynamics and habitat changes, allowing datasets to be directly comparable across national borders. Data generated through the programme are used to produce ecosystem maps, environmental indicators and policy assessments. This collaborative framework demonstrates how biosphere reserves can serve as platforms for transboundary data governance, enabling large-scale ecosystem monitoring beyond national administrative boundaries. The observatory with its infrastructure can be classified as institutional and process innovation that enhance the management of the biosphere reserve and provides a framework for developing data-driven policies.

Another emerging smart technical and technological innovation in biosphere reserves is the use of remote sensing and drone technologies for ecosystem monitoring. For example, in the Entlebuch Biosphere Reserve in Switzerland, researchers have tested the use of unmanned aerial vehicles (UAVs) to monitor recreational pressure and track the movement of visitors in sensitive alpine habitats. Drone imagery allows researchers to identify footprints, ski and snowshoe tracks and spatial patterns of visitor use in protected areas with high accuracy and relatively low cost [54]. Similar remote sensing approaches are increasingly used in biosphere reserves to monitor wetland dynamics, forest cover changes and vegetation health, often combined with satellite data from programmes such as Copernicus. These technologies provide detailed spatial data that help managers better understand landscape dynamics and manage human activities in ecologically sensitive areas. Recent advances in artificial intelligence and automated species recognition are also being applied in protected areas and biosphere reserves. In the Swiss National Park, which forms the core area of the Engiadina Val Müstair Biosphere Reserve, researchers have developed camera-trap monitoring systems combined with machine learning algorithms to automatically identify animal species and behaviors from large volumes of image and video data [55]. These camera networks continuously record wildlife activity and generate extensive biodiversity datasets that would be extremely time-consuming to analyse manually. AI-assisted monitoring can also significantly improves the efficiency of biodiversity observation and enables long-term monitoring of wildlife populations across large and remote landscapes.

Smart innovations in biosphere reserves also include the use of digital data sources to monitor tourism and recreational use of landscapes. In several protected areas, researchers have analysed geotagged photographs from platforms such as Flickr and other social media sources to identify spatial patterns of visitor use in protected areas [56, 57]. These datasets allow managers to map popular routes, seasonal visitation patterns and areas of potential ecological pressure. Combined with traditional visitor counters and mobile data analysis, this approach provides a cost-effective method for understanding tourism dynamics and supporting sustainable visitor management in biosphere reserves. This innovation contains the features of economic, social and technical innovation. Because the tourism is a key development sector in many biosphere reserves, the integration of appropriate, data-driven measures to regulate tourism, while preserving the uniqueness of the biosphere reserve, is a fundamental prerequisite for development of biosphere reserve.

An important dimension of smart process and technological innovations in biosphere reserves is the accessibility and sharing information through open digital platforms and dashboards. In Portugal, a relevant initiative is the CPLP Network of Biosphere Reserves, presented through the online platform Reservas da Biosfera da CPLP portal. This digital platform connects biosphere reserves from Portuguese-speaking countries and provides a shared interface for communication, documentation and exchange of knowledge among reserve managers, researchers and policy actors. The platform includes an interactive dashboard that visualises key information about the biosphere reserves within the CPLP network. The dashboard presents spatial and descriptive data such as the location and

boundaries of biosphere reserves, total area and distribution across countries. It also provides information on ecosystems and habitats, ecosystem services, conservation objectives, governance structures, economics, ongoing projects, cultural and natural heritage, science technology and innovation, well-being and quality of life, risks, itineraries and partnerships, as well as indicators related to sustainable development initiatives implemented in the reserves [58, 59]. By integrating these datasets into a single digital interface, the platform supports transparency and facilitates comparison between reserves while enabling users to explore information on biodiversity, territorial management and sustainability actions across the CPLP biosphere reserve network. Through this type of digital infrastructure, biosphere reserve networks can strengthen knowledge exchange, data accessibility and international cooperation, while providing a clear overview of the spatial distribution, ecological characteristics and management activities of participating reserves. The Nordhordland Biosphere Reserve in Norway also publishes overview dashboards in various areas, such as cultural heritage and cultural landscape, natural values, excursions in Nordhordland, the taste of Nordhordland, Wool Square, the art tour in Nordhordland, and UNESCO in the Vestland County [60]. Within Norway and this biosphere reserve, there is also the Norwegian biodiversity bank Artskart, which provides a database and open map that allows users to view specific species sightings [61].

Smart innovation in biosphere reserves does not only involve environmental data but also sustainable energy systems. The Entlebuch Biosphere Reserve provides also a strong example of how biosphere reserves can integrate renewable energy solutions into regional development strategies. The Entlebuch Biosphere Reserve is not just a model region, but also an international gold award-winning model region with the European Energy Award. The region has implemented several concrete initiatives aimed at increasing energy self-sufficiency while reducing greenhouse gas emissions with economic and social impact, influencing also the processes within the territory. One of the most prominent examples is the extensive use of biomass from local forests, where wood chips from sustainably managed forests are used in district heating systems that supply public buildings, schools and residential areas. In addition, several municipalities within the biosphere reserve have installed solar photovoltaic systems on public buildings and farms, contributing to local renewable electricity production. Small-scale hydropower plants on alpine streams also play a role in the regional energy mix, supporting decentralised renewable energy generation [63, 64]. These initiatives promote the use of local renewable resources and encourage cooperation between municipalities, farmers and energy companies.

Summary of research findings about the smart innovations in biosphere reserves evaluated by the selected criteria present Table 1.

**Table 1.** The comparison of identified smart innovations of biosphere reserves

| Area | Engiadina Val Müstair (Swizz) | North Devon Biosphere (England) | Archipelago Sea Biosphere (Finland) | Doñana Biosphere Reserve (Spain) | Sierra Nevada Biosphere (Spain) | Wadden Sea Biosphere (Germany, Denmark, Niederland) | Entlebuch Biosphere (Swiss) | Dyfi Biosphere (Wales) | Kristianstads Vattenrike Biosphere (Sweden) |
|---|---|---|---|---|---|---|---|---|---|
| **Type of innovation** | technological | technological | technological | technological, process | technological, process | technological, institutional | technological, economic | social, technological | social |
| **Technology** | AI, camera | IoT sensors | IoT sensors buoys | sensors, mobile apps, eDNA | monitoring stations, satellites | monitoring systems, databases | UAVs (drones), renewable energy | mobile applications (COBWEB) | digital mapping (Naturkartan) |
| **Objective** | wildlife monitoring | environment | marine ecosystem monitoring | biodiversity monitoring | long-term ecosystem research | transnational ecosystem monitoring | monitoring, energy production | citizen-based data collection | citizen science |
| **Function** | automated analysis | data collection, decision making | data collection, analysis | data collection, validation | analysis, data publication | analysis, policy support | data collection, energy generation | citizen science | participation, data collection |
| **Stakeholders** | research institutions | public sector research | research institution, government | research institutions, reserve management | research institution, government | governments, research institutions (3 countries) | municipalities, businesses | community, research institution | community, public sector |
| **Level of participation** | low | medium | low | medium | medium | high (institutional) | medium | high | high |
| **Geographical level** | regional | regional | national | regional | regional | international | regional | local | local |
| **Environmental impact** | high | high (water, climate monitoring) | high | very high | high | very high | high | medium | medium |
| **Economic impact** | low | indirect (policy efficiency) | medium (water management) | low | indirect | medium | high | low | low |
| **Social impact** | low | low | low | medium | medium | medium | medium | high | very high |
| **Implementation phase** | implementation | implementation | implementation | implementation | implementation | scaling | implementation | pilot implementation | implementation |
| **Data type** | image-based, ai data | real-time quantitative | continuous environmental data | hybrid (genetic, digital) | open data | harmonized datasets | spatial + energy data | crowdsourced data | participatory data |

## 4.2 Discussion

Our research has shown that there is no comprehensive theoretical and empirical framework that explains, classifies, and practically demonstrates the use of smart innovations in

biosphere reserves while maintaining a balance between nature conservation and territorial development within the reserve. Based on theoretical principles, smart innovations in biosphere reserves should be a result of the effective functioning of an innovation ecosystem based on the principles of the quintuple helix model, which emphasizes the importance of the natural environment. It is not possible to ignore the role of the other elements of this model, namely universities, industry, government, and civil society [8, 9, 10, 11, ], because the final outcome requires their interconnection and synergy. The presented examples of good practice highlight the dominant role of new technologies, which are drivers of innovation in various areas of life, in implemented processes (digital biosphere reserves), social (digital mapping tools based on citizen science), economic (tracking tools for the tourism sector), and in the institutional framework of biosphere reserves (observatories and biosphere reserve networks). Although all presented innovations as good practices highlight technological sophistication, less attention is paid to the participatory and socio-economic dimensions, which are emphasized precisely by the theory of the quadruple and quintuple helix models.

The taxonomy of smart innovations [1, 5, 21] applied to the context of biosphere reserves, identifies four main groups of innovations (technological, process-related, economic, and social innovations). Our research and analysis of best practices indicate that technological innovations predominate in practice, while social and economic innovations remain less developed. A positive exception is Kristianstads Vattenrike or Dyfi Biosphere, where we identified examples of good practice in the form of social innovations based on citizen science as a part of biosphere reserve monitoring. However, in most cases, citizen participation and economic dimension are additional features, not the main pillar of the system. This shows that participatory innovations fall short of the expectations of theoretical models, which emphasize the involvement of local actors as a key element of smart solutions in BR. The most of identified innovations are innovations with lower economic impact. We suppose that it can be caused by generally low focus of biosphere reserves´ management on development function, or by other words, local economic development as well as due to the preference of conservative approach to management of biosphere reserves (a priority is environmental protection).

It is possible that the dominance of technological aspects is due to the implementation phase of innovations, which also opens up opportunities to strengthen them in the next period by focusing on people, society, and links to local governance, civic initiatives, and regional economic models. This would also eliminate the risk that the technological pre-phase of smart innovations might overshadow the original purpose of smart innovations, which is to support the transformation of socio-ecological systems, rather than merely their technical monitoring. This presumption corresponds with the progressive development of Society 5.0 that aims to tackle social challenges and achieve a sustainable, inclusive, people-oriented society and link it with the specifics of biosphere reserves development.

Zuboff [17] points out, in the context of progressive technological solutions, the potential problem of "surveillance capitalism," to which sensor-based systems and interconnected data platforms may contribute. For biosphere reserves as UNESCO model areas, it is therefore crucial to ensure data protection and transparency in data handling. While technological innovations increase the efficiency of monitoring, they simultaneously create new risks associated with unequal access to data, its control, and commercial use—which can lead to a violation of the MAB program's principles and jeopardize the relationship with the local community.

The innovations presented here focus primarily on monitoring and assessing climate change and natural phenomena, with the aim of using this information to formulate policies that reflect future developments and strengthen the region's resilience. This confirms that smart innovations are not a universal package of technologies but must reflect the ecosystem and management specifics of the biosphere reserves. At the same time, empirical data show that the transferability of innovations is limited by the context of the area, and it is not possible to create a uniform model of a smart biosphere reserve or a universally replicable smart innovation within a biosphere reserve. This also confirms the importance of applying a place-based and place-sensitive approach in the development of biosphere reserves [37, 38].

A key finding is that the identified examples of good practice in smart innovation within biosphere reserves focus on monitoring but less on transformative capacity. Their use for strategic decision-making or long-term planning is often less evident. This suggests that smart innovations in BRs have not yet fulfilled the full potential attributed to them by theory—namely, the ability to enable comprehensive socio-ecological transformation of the territory, support adaptive management, and foster interconnected learning among system actors. Given that this is still a relatively under-researched topic, there is significant room for further progress in this area, not only in terms of scientific research but also in the practical formulation of public policies.

## 5 Conclusions

Smart innovations in biosphere reserves represent a rapidly evolving field that integrates digital technologies, environmental science, and the principles of sustainable development. Biosphere reserves as "living laboratories" defined by experts create a space for the initiation and development of innovation not only for monitoring the state of ecosystems but also for supporting adaptive management, participation, and regional cooperation. An analysis of theoretical foundations and examples of good practice shows that technological excellence is today the most visible pillar of smart innovation—from IoT sensor networks, satellite data, digital twins, and UAV technologies to AI-supported systems for biodiversity monitoring. These solutions significantly improve the quality, accuracy, and availability of environmental data, thereby strengthening the ability of biosphere reserves to respond quickly to changes in ecosystems and fulfil their role as model sites of the UNESCO MAB Program.

At the same time, it appears that technological innovations currently dominate over socio-participatory, process-oriented, and economic innovations, which would utilize technology and data as means of implementation and are, at the same time, essential for the transformative management of biosphere reserves. To a greater extent, synergistic collaboration among scientific institutions, public administration, the business sector, local communities, and the natural environment is desirable. The participation of local actors should be an integral part of managing innovation processes. A challenge for the near future is to strengthen participatory mechanisms, transparent decision-making, and community-oriented innovation supported by digital solutions, but with a central focus on people, which would lead to more inclusive and equitable land management.

Another important aspect of smart innovations is that they must reflect the uniqueness of the BR ecosystem and management. It follows that smart innovations are not a universally applicable package of technologies, but a modular set of solutions that must be adapted to the ecological, social, and managerial conditions of each territory.

The relevant attention should also be paid to the issue of data quality, transparency, and how the data is used. For smart innovations to strengthen socio-ecological and economic resilience, they must be implemented transparently and in accordance with the principles of nature conservation, and not at the expense of local communities or ecological values.

Although our methodological approach has its limitations, the examined examples of good practice can be considered a reflection of current trends in smart innovation within biosphere reserves. Examples of good practice in smart innovation highlight the significant potential for implementing data-driven and evidence-based policy-making and managerial measures in biosphere reserves. but it is necessary to effectively integrate this not only into nature conservation, but also into the social and economic spheres and participatory land management. Only then can biosphere reserves become authentic living laboratories where innovations emerge as a result of the interconnection of people, technology, and the natural environment—and not as a collection of isolated technological experiments.

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## References

1. OECD: Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data. 3rd edn. OECD Publishing (2005)
2. Vitálišová, K., et al.: Innovations in the cultural and creative local development. Acta Aerarii Publici. **15**(2), 41–55 (2018)
3. UNESCO: Lima Action Plan for UNESCO's Man and the Biosphere Programme (2016–2025) (2017)
4. Schumpeter, J.A.: The Theory of Economic Development. Harvard University Press, Cambridge (1934)
5. Vaňová, A.: Trendy v rozvoji miest. Belianum, Banská Bystrica (2021)
6. Etzkowitz, H., Leydesdorff, L.: The dynamics of innovation: from national systems and "mode 2" to a triple helix of university–industry–government relations. Res. Policy. **29**(2), 109–123 (2000)
7. Foray, D.: Smart Specialisation: Opportunities and Challenges for Regional Innovation Policy. Routledge, London (2014)
8. Schultz, L., et al.: Adaptive management, ecosystem management, and beyond. Conserv. Biol. **25**(4), 662–671 (2011)
9. Alfonso, O., Monteiro, S., Thompson, M.: A growth model for the quadruple helix. J. Bus. Econ. Manag. **13**(5), 849–865 (2012)
10. Galvão, A., et al.: Triple helix and its evolution: a systematic literature review. J. Sci. Technol. Policy Manage. **10**(3), 812–833 (2019)
11. Grundel, I., Dahlström, M.: A quadruple and quintuple helix approach to regional innovation systems in the transformation to a forestry-based bioeconomy. J. Knowl. Econ. **7**, 963–983 (2016)
12. Giffinger, R., et al.: Smart Cities: Ranking of European Medium-Sized Cities. Vienna University of Technology (2007)

13. Schwab, K.: The Fourth Industrial Revolution. World Economic Forum (2016)
14. Fukuyama, F.: Identity: the Demand for Dignity and the Politics of Resentment. Farrar, Straus and Giroux, New York (2018)
15. Schiavone, F., et al.: Advanced Perspectives and Trends in Digital Transformation of Firms, Networks, and Society. Springer (2021)
16. Greco, I., Bencardino, M.: The paradigm of the modern city: smart and senseable cities for sustainable growth. In: ICCSA. Springer (2014)
17. Zuboff, S.: The Age of Surveillance Capitalism. PublicAffairs, New York (2019)
18. Rowley, J.: The smart innovation engine: building a sustainable future. Int. J. Innov. Manag. (2017)
19. Quinto, I., et al.: Smart innovation: a new paradigm for the digital age. J. Strateg. Innov. Sustain. (2018)
20. Zaušková, A., Madleňák, A.: Otvorené inovácie – teória a prax. Księży Młyn, Łódź (2012)
21. Vitálišová, K., et al.: Conceptualization of Smart Cities/Regions as Innovative Ecosystems – Working Paper (2026)
22. Arthur, W.B.: The Nature of Technology: What it is and how it Evolves. Free Press, New York (2009)
23. Fassnacht, F.E., et al.: Review of studies on tree species classification from remotely sensed data. Remote Sens. Environ. **186**, 64–87 (2016)
24. Grieves, M.: Digital Twin: Manufacturing Excellence through Virtual Product Representations. White Paper (2014)
25. Pringle, R.M.: Upgrading conservation to the 21st century. Science **355**(6324), 451–452 (2017)
26. Davenport, T.H.: Process Innovation: Reengineering Work through Information Technology. Harvard Business School Press, Boston (1993)
27. Catalini, C., Gans, J.S.: Some simple economics of the blockchain. Natl. Bur. Econ. Res. (2016)
28. Farley, J., Costanza, R.: Payments for ecosystem services: from local to global. Ecol. Econ. **69**(11), 2060–2068 (2010)
29. Teece, D.J.: Business models, business strategy and innovation. Long Range Plan. **43**(2–3), 172–194 (2010)
30. OECD/Eurostat: Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation. 4th edn OECD Publishing (2018)
31. Phills, J.A., Deiglmeier, K., Miller, D.T.: Rediscovering social innovation. Stanf. Soc. Innov. Rev. (2008)
32. Mulgan, G.: Social Innovation: What it Is, why it Matters and how it Can be Accelerated. The Young Foundation, London (2007)
33. Carayannis, E.G., Campbell, D.F.J.: Democracy of climate and climate for democracy: the evolution of quadruple and quintuple helix innovation systems. J. Knowl. Econ. **12**(4), 2050–2082 (2021)
34. Bonney, R., et al.: Citizen science: a developing tool for predictive ecology. Bioscience **59**(11), 977–984 (2009)
35. Nam, T., Pardo, T.A.: Conceptualizing smart city with dimensions of technology, people, and institutions. In: Proceedings of the 12th Annual International Digital Government Research Conference (2011)
36. Vitálišová, K., et al.: Marketing as a management tool of biosphere reserves to achieve agenda 2030 goals. In: Uniting Marketing Efforts for the Common Good, pp. 131–148. Springer, Cham (2023)
37. Iammarino, S., Rodríguez-Pose, A., Storper, M.: Regional inequality in Europe: evidence, theory and policy implications. J. Econ. Geogr. **19**(2), 273–298 (2019)
38. Rodríguez-Pose, A., Bartalucci, R., Lozano-Gracia, N., Dávalos, M.: Overcoming left-behindedness: moving beyond the efficiency versus equity debate in territorial development. Reg. Sci. Policy Pract. **16**(12), 100144 (2024)

39. North Devon Biosphere: North Devon Biosphere Environmental Dashboard. (2026). https://biosphere-drip-ekahfybmebgybjg9.ukwest-01.azurewebsites.net/
40. North Devon Biosphere: Smart Biosphere (2026). https://www.northdevonbiosphere.org.uk/smart-biosphere.html
41. HELCOM: HELCOM Map and data service (2026). https://maps.helcom.fi/website/mapservice/
42. Finnish Environment Institute (SYKE): Environmental data – Data for the future (2026). https://www.syke.fi/en/environmental-data
43. Consejo Superior de Investigaciones Científicas (CSIC): Doñana Biological Station. (2026). https://www.ebd.csic.es/en
44. Dynamic Ecological Information Management System - Site and dataset registry (DEIMS-SDR): Doñana Long-Term Socio-ecological Research Platform – Spain (2026). https://deims.org/bcbc866c-3f4f-47a8-bbbc-0a93df6de7b2
45. CyberTracker: Doñana Biological Station, Spain (2026). https://cybertracker.org/use/donana-biological-station-spain/
46. Wadden Sea World Heritage: Wadden Sea Quality Status Report (2025). https://www.waddensea-worldheritage.org/unesco-edna-programme-maps-350-species-wadden-sea
47. UNESCO: eDNA Expeditions Dashboard (2022). https://dashboard.ednaexpeditions.org/
48. Vattenriket: Citizen research (2026). https://vattenriket.kristianstad.se/medborgarforskning/
49. Naturkartan: Naturkartan map (2026). https://www.naturkartan.se/en/explore
50. CORDIS – EU research results: Citizen Observatory Web COBWEB (2024). https://cordis.europa.eu/project/id/308513
51. iNaturalist: Observations map (2026). https://www.inaturalist.org/observations
52. El Observatorio del Cambio Global de Sierra Nevada (OBSNEV): Thematic Areas (2026). https://obsnev.es/en/monitoreo/ambitos-tematicos/
53. Wadden Sea World Heritage: Trilateral monitoring and assessment programme (TMAP) (2026). https://www.waddensea-worldheritage.org/trilateral-monitoring-and-assessment-programme-tmap
54. Weber, D., Knaus, F.: Using drones as a monitoring tool to detect evidence of winter sports activities in a protected mountain area. Manag. Policy Issues **9**(1), 30–34 (2017)
55. Mountain Research Initiative: Swiss National Park Selected As Technology Testing Ground for Nature Conservation (2021). https://mountainresearchinitiative.org/news/swiss-national-park-selected-as-technology-testing-ground-for-nature-conservation/
56. Wood, S., et al.: Using social media to quantify nature-based tourism and recreation. Sci. Rep. **3**, 2976 (2013). https://doi.org/10.1038/srep02976
57. Mancini, F., Coghill, G.M., Lusseau, D.: Using social media to quantify spatial and temporal dynamics of nature-based recreational activities. PLoS One **13**(7), e0200565 (2018)
58. Reservas da Biosfera da CPLP: CPLP Biosphere Reserves Network platform map (2023). https://www.reservasdabiosfera.pt/painel-de-dados/?area=0&catg=0
59. UNESCO: National Report PORTUGAL, UNESCO Man & the Biosphere Programme (2024). https://articles.unesco.org/sites/default/files/medias/fichiers/2025/09/PORTUGAL%20National%20Report%202025.pdf
60. Nordhordland UNESCO Biosfaere: Get to know the biosphere reserve in maps (2026). https://map.nordhordlandbiosphere.no/
61. Artsdatabanken: Artskart (2026). https://artskart.artsdatabanken.no/
62. Artsdatabanken: Artsobservasjoner (2026). https://mobil.artsobservasjoner.no/
63. UNESCO Biosphäre Entlebuch: Sustainable energy (2026). https://www.biosphaere.ch/de/biosphaere/nachhaltigkeit-energie/nachhaltige-energie
64. UNESCO Biosphäre Entlebuch: Energy Forum (2026). https://www.biosphaere.ch/de/informieren/organisation/foren/energieforum

# Development Agency as Source of Social Innovation in Catching-up Region: Evidence from Slovakia

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**Abstract.** This article examines the activities of the Development Agency of the Banská Bystrica Self-Governing Region and evaluates their contribution to regional development from a social innovation perspective in Banska Bystrica Self-Governing Region. The paper positions development agency within the wider discussion on social innovation emphasising their ability to create novel institutional structures in response to ongoing socio-economic problems in catching-up regions. These regions often face structural challenges (demographic decline, economy problems, inadequate access to public services). Within this situation, social innovations can serve as a crucial driver in activating local sources, strengthening collaboration among regional actors and implementing innovative approaches to governance and/or service delivery. From a methodological perspective, we used secondary research (qualitative analysis of institutional, internal and strategic documents) combined with empirical evidence gained from unstructured interviews with employees of the development agency. The investigation concentrates on two areas of the agency's activities: support for regional economic development through project preparation, and the support and development of outpatient healthcare facilities. The results point out that the agency's activities are practical examples of social innovation, as they create new ways of cooperation among regional authorities, municipalities, and other relevant actors. These initiatives reinforce local institutional capacities, improve access to external funding opportunities, and support the enhancement of healthcare services delivery. The findings further imply that development agency can act as facilitator of socially innovative approaches capable of mitigating regional inequalities and promoting sustainable development.

**Keywords:** catching-up region · regional development · social innovation · development agency · Banska Bystrica Self-governing Region

## 1 Introduction

Innovations have been recognised as an integral part of modern society and crucial condition for the achievement of countries striving to maintain competitiveness and resilience. They are a central mechanism of development, as they generate new ideas, practices and processes that improve the functioning and effectiveness of economies

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and societies. In the era of fast development of artificial intelligence and ongoing digital transformation, the scope of innovation has broadened beyond strictly technological or economic domains. That's why is increasing emphasis placed on forms of innovation that address societal challenges and try to respond to the needs of municipalities, regions and whole society.

Within this wider conceptual framework, social innovation has attracted growing attention. It encompasses novel or enhanced approaches aimed at tackling societal issues e.g. unemployment, inequalities, social exclusion and insufficient access to public services. Its primary purpose is to foster positive social change, encourage collaboration among public actors, private sector representatives and civil society with the aim to improve the quality of life of local communities. The significance of social innovation is particularly evident in the context of regional development, because it represents an important tool for addressing place-specific challenges and for promoting novel forms of collaboration, entrepreneurial activities and bottom-up based initiatives.

This is markedly relevant in less developed or catching-up regions, which frequently face structural constraints including population outflows (mostly among younger people), elevated unemployment, a high share of long – term unemployed persons, and comparatively lower levels of economic activity. In such situation, social innovation could support the activation of local potential, create new opportunities for sustainable development, strengthen social cohesion.

By adopting socially innovative approaches, we can react more effectively to the needs of local communities while simultaneously supporting long-term development. In this regard, social innovation can offer a way how to reduce regional inequalities and identify suitable and novel solutions for advancement of catching-up regions.

The paper is structured as follows. In the literature review, we present the concept of innovation, with particular attention paid to social innovation and to development agencies as supporting institutions that contribute to creating favourable conditions for the economic and social development of regions. The following part deals with the research design, including the analytical framework employed and the data sources underpinning in the paper. The third section provides an analysis and discussion of the empirical results concerning the activities of the Development Agency of the Banská Bystrica Self-Governing Region. In the final section we conclude the key results and emphasize selected positive contributions of the Agency's activities to the development of the Banská Bystrica Self-Governing Region.

## 2 Literature Review

Innovations are generally regarded as an essential source of sustainable development in modern countries. Traditionally, they have been understood in connection with creation of new knowledge and its application in economic and social practice (Skokan [1]). A seminal contribution to the theory of innovation was created by Schumpeter. He defined innovation as the introduction of new combinations of production factors and emphasized its pivotal role in the evolution of capitalism. In Schumpeter's view [2], innovation includes, for instance, the development of new products, the adoption of novel production techniques, the exploration of new markets, and the emergence of new form of industrial organization.

According to OECD [3] we can adopt a broader interpretation of innovation, describing it as a process, which involves a development and implementation of new or substantially improved products, services, processes, or organizational changes that create economic or social value. Innovation is not limited to technological advancement but also encompasses organizational and social changes that transform the functioning of companies, institutions and society as a whole.

We can classify innovation from several perspectives. One of the most widely used typologies is based on the methodology of the Oslo Manual (2018), which distinguishes four principal categories of innovation:

- Product innovations refer to introduction of a new or substantially enhances goods or services. These innovations contain improvements in technical characteristics, components, or functional properties of a product.
- Process innovations involve the adoption of new or significantly improved delivery techniques or production which increases efficiency or enhance the quality of output.
- Organizational innovations encompass the implementation of new methods in business practices, workplace arrangements, or external interactions.
- Marketing innovations include the application of novel marketing approaches, distribution channels for goods and services, or business models [3].

From another perspective, we can classify innovation according to their degree of novelty and impact. In this regard, a distinction is drawn between incremental innovations, which represent gradual enhancements of existing products/processes and radical innovations, which introduce significant organizational or technological shifts and may lead to transformation across entire industries or societal systems [4].

Dabard and Mann [5] introduce in their work the notion of sustainability innovations. They conceptualize those innovations as multi-level and multi-actor processes that generate novel ways of answering societal needs while simultaneously promoting social and ecological balance and equity. Unlike conventional innovations, which are often primarily oriented toward technological or economic performance, sustainability innovations adopt a systemic approach which integrates technological, organizational, behavioural and social dimensions. Their overarching objectives is to enhance resilience of socio-economic systems, improve overall well-being and promote collaboration within diverse stakeholders in specific institutional and territorial conditions.

A related, though conceptually distinct, approach is reflected in the work of such authors such as Phills et al. [6] and Mulgan [7] who focused on the concept of social innovation. This concept has attracted growing scholarly attention in recent decades. According to these authors, we understand social innovation as the development of new solutions to social challenges that are more effective, sustainable, or equitable than existing alternatives, while also creating new forms of social interaction and cooperation. It involves novel configurations of social practices that contribute to addressing societal problems and reshaping existing social relations and institutional frameworks. Social innovations often emerge in situations where traditional public policies or market mechanisms prove insufficient in responding to evolving societal needs [8].

Polačková [9] speaks about following characteristics of social innovations. First feature is their interdisciplinary nature, as complex societal challenges are approached from multiple fields, enabling a more comprehensive understanding of the issues. Another key

attribute is cross-sectoral involvement, since both the design and implementation of solutions typically require the participation of actors from all sectors of the society. Social innovations are also inherently multi-layered, with problem-solving processes unfolding across different stages and levels of intervention [9]. In addition, they demonstrate a capacity for scalability, meaning that their effect can extend beyond the initial context and contribute to broader systemic change. A further important aspect is the transformation of relationships among stakeholders, which may involve changes in established power structures as well as the development of new collaborative models.

In general, social innovations seek to provide more effective responses to societal problems than previously utilized approaches while adhering to core principles of ethics and social cohesion. An important characteristic of social innovation is also its participatory nature, as it frequently develops through collaboration among public institutions, private organizations, non-governmental organizations, and local communities [10] and thereby generating new governance arrangements and collective capacities [11].

In recent years, social innovation has also become an important topic in the fields of regional studies and regional development. According to Moulaert et al. [12]., social innovations represent a significant instrument for addressing social and economic challenges in regions, particularly in less developed or peripheral areas.

In the regional context, social innovations may contribute, for example, to:

- improving access to public services (e.g., healthcare or social services),
- strengthening social inclusion and the integration of marginalized groups,
- supporting local economic development,
- fostering community initiatives and civic participation, and
- enhancing the overall quality of life of regional populations.

A key characteristic of social innovation lies in its capacity to mobilize local resources and actors while generating new forms of collaboration among public institutions, the private sector, and civil society [11]. In many cases, social innovations therefore represent an effective mechanism for addressing regional disparities and promoting sustainable regional development [12].

Within the context of public policy, social innovations are increasingly perceived as an important instrument for the modernization of public administration and the improvement of public service delivery. Their importance becomes apparent in contexts where public actors operate under financial constraints and face increasing societal expectations concerning higher quality of public services.

In recent years, increasing attention has also been paid to the role intermediary organisations in facilitating socially innovative processes. Socially innovative initiatives typically emerge through the collaboration of diverse actors who mobilise resources and develop novel solutions to locally perceived challenges [13]; however, their effectiveness often depends on the presence of actors capable of coordinating these interactions and providing institutional support. From this point of view, development agencies can be considered as key intermediatory actors that operate at the intersection of public administration, local communities and external funding structures. They can create platforms for cooperation among public institutions, private sector actors, non-governmental organisations, and local communities, thereby contributing to the search for new solutions to regional socio-economic challenges [12]. Moreover, such organisations may

enhance local capacities and support "pathways to impact" by enabling the realisation of specific development goal, including increasing employment opportunities, improved infrastructure or supporting local tourism [13].

Development agencies may be established by regional self-governments and other public administration bodies. They may also operate as non-profit organisations or public-law associations formed through the cooperation of actors from the private, public, and non-profit sectors. In this sense, development agencies can be understood as catalysts of social innovation, fostering initiatives aimed at improving quality of life, strengthening social inclusion, and supporting sustainable regional development.

Regional development agencies or development agencies emerged as instrument for implementing regional policy and promoting socio-economic development at regional level. Their primary role is to initiate and coordinate development activities, support the business environment, prepare and implement regional development projects, and enhance the ability of regions to access external financial resources, such as those provided by national or European programmes [14]. In this context, development agencies may function as institutional facilitators of regional development.

We consider development agencies as an essential component of the institutional infrastructure of regions, because they contribute to the mobilisation of regional resources, the promotion of innovation processes, and the enhancement of the competitiveness of regional economies [15].

## 3 Material and Methodology

The objective of this paper is to identify, drawing on the results of an analysis of selected areas of activity of the Development Agency of the Banská Bystrica Self-Governing Region (hereafter DABBSK), its contribution to social innovation. The paper further examines how the outcomes of the Agency's activities may support the development of a catching-up region.

The research is predominantly based on secondary data sources covering the period from the establishment of DABBSK in 2018 to 2025. The secondary research focused primarily on official documents, including annual reports, the statute of DABBSK, financial statements, internal documents as well as other information published on the official website of the DABBSK (https://dobrykraj.sk). Furthermore, we analysed strategic development documents of the Banská Bystrica Self-Governing Region (hereafter BBSK) and relevant documents submitted to the Assembly of the BBSK. This analysis made it possible to assess the institutional setting, operational focus, and principal activities carried out by DABBSK.

To complement the secondary research, primary research was conducted to provide a more comprehensive picture of the activities of DABBSK and its role in the development of BBSK. We carried out primary research through qualitative inquiry, specifically via unstructured interviews with selected representatives of DABBSK (the Director of DABBSK, Project specialist from the Regional economic development department, and the Head of the Outpatient care support department) between May and July 2025. These interviews yielded additional insights into the practical implementation of development activities and DABBSK's engagement with relevant stakeholders. The findings derived

from primary and secondary research were subsequently compared with the results of the author's previous research.

Empirical research and qualitative document analysis were combined in this paper. We employed methods of analyses and synthesis to identify key patterns, institutional practices, and development effects associated with the activities of the DABBSK. The concluding section builds on the results of this comparative analysis and synthesis to highlight key findings suggesting that development agency can function as important catalyst of social innovation. Such innovations may contribute to new approaches to regional governance and development and may also be transferable to other lagging or structurally disadvantaged regions.

The paper deliberately focuses on social innovation and the institutional context of regional development, while technical dimension (e. g. IoT or Big Data) does not form part of its research framework.

## 4 The Development Agency of the Banská Bystrica Self-Governing Region

The DABBSK was established pursuant to resolution no. 38/2018 of the Council of the BBSK, adopted on 26 April 2018. Its activities are generally focused on the provision of services of public interest aimed at supporting regional development and employment, as specified in detail in its Statute. The founder of DABBSK is the Banská Bystrica Self-Governing Region, which accordingly defined the scope of its activities in Article III of the Statute [16].

Any assessment of DABBSK's activities should consider the broader regional context. The Slovak Republic is divided into 8 self-governing regions. The BBSK covers an area of 9 454 $km^2$. In the long term, BBSK has ranked among the least developed regions of the Slovak Republic, with only the Prešov Self-Governing Region exhibiting less favourable indicators. The developmental lag of BBSK is particularly evident in the field of human resources, as reflected in the region's declining population, high risk of social exclusion rate, higher unemployment rates in its southern districts compared to the national average, and a persistently high proportion of long-term unemployed persons (Table 1).

**Table 1.** Selected characteristics of the BBSK

| Indicator | 2024 | 2010 |
|---|---|---|
| Number of inhabitants | 613,356 | 653,186 |
| Unemployment rate | 6.73% | 18.86% |
| GDP per capita (in EUR) | 18,082 | 9,258 |
| At-risk-of-poverty or social exclusion rate | 23.1% | 20.3%* |

Source: Own elaboration based on [17].
Note: * Data for 2015.

These trends have resulted in a deteriorating standard of living and an expansion of poverty-affected areas, particularly in the southern and eastern parts of the region. Five of the thirteen districts of the BBSK – Lučenec, Poltár, Revúca, Rimavská Sobota, and Veľký Krtíš have been classified as "least developed districts" pursuant to Act No. 336/2015 Coll. On the Support of Least Developed Districts [18].

For these reasons, a stronger involvement of the representatives of the BBSK appears necessary in order to address these negative trends and to stimulate positive developmental changes in the region. During the analysed period, the activities of the DABBSK were oriented toward several key areas: tourism and rural development; support for the regional economy; support for and development of outpatient healthcare facilities; employment support; the social economy; and the promotion of entrepreneurship and innovation.

In line with the objective of the paper, the following section focuses on presenting the research findings related to support for the regional economy and the support and development of outpatient healthcare facilities.

### 4.1 Support for Regional Economic Development

During its initial years of operation, DABBSK primarily focused on the preparation of strategic development documents aimed at strengthening regional economic development and improving the effectiveness of regional policy interventions. One of the key outputs of this phase was the Action Plan for the Brezno District. In close cooperation with BBSK, the DABBSK also played an important role in initiating and coordinating activities aimed at addressing structural disparities in the least developed districts of the Slovak Republic located within the territory of BBSK, including Rimavská Sobota, Poltár, and Lučenec.

Those activities were embedded within a broader national policy framework aimed at addressing catching-up or disadvantaged regions. The data-analytical centre of DABBSK contributed to the evidence-based development or regional policy by preparing socio-economic analyses at the district level and by producing analytical and strategic background materials for project in which the regional government was involved [19].

Between 2018 and 2019, DABBSK developed a complex and diversified position within the regional development framework. Notably, it functioned as an applicant under the Action Plan for the least developed districts, while currently preparing project proposals for a range of external funding schemes on behalf of entities established by BBSK, as well as regional tourism organisations. Alongside their intermediary roles, DABBSK also acted as a direct beneficiary and project promoter, submitting own initiatives within multiple funding schemes.

From 2019 onwards, the DABBSK progressively broadened the scope of its project activities to include targeted assistance for small municipalities with fewer than 1,000 inhabitants which typically face constrains in administrative and technical capacity when accessing external financial sources. This activity was later expanded to municipalities with populations of up to 5,000 inhabitants. Consequently, project preparation and implementation have become the central pillar of the DABBSK activities within the wider complex of regional development policy.

Next part of the paper focuses on the preparation and implementation of projects for municipalities located within BBSK as well as for other legal entities established by BBSK and for projects in which DABBSK serves as an eligible applicant. The preparation of project proposals and the submission of applications for non-repayable financial contributions was and is fee-based service.

Table 2 presents selected indicators related to project preparation activities for the period 2021–2024 [20–24]. In particular, the table reports the total amount of eligible expenditures (hereinafter "TEE") associated with approved projects, as well as the amount of non-repayable financial contributions (hereinafter "NFC") that these projects have attracted to the territory of BBSK. From an analytical perspective, NFC represents a more precise indicator than TEE, as it reflects the net inflow of external financial resources after accounting for project co-financing.

**Table 2.** Indicators of Support for regional economic development

| Indicator | 2021 | 2022 | 2023 | 2024 |
|---|---|---|---|---|
| Expenditure on regional economic development support | 153,676 | 128,898 | 180,577 | 192,255 |
| Revenue from project preparation services | 12,421 | 18,507 | 22,283 | 26,498 |
| TEE of approved projects | 5,300,573 | 1,692,419 | 3,421,401 | 13,196,639 |
| NFC of approved projects | 3,895,029 | 1,448,439 | 2,803,240 | 12,197,482 |
| External funding (TEE)/1 EUR expenditure | 34.49 | 13.13 | 18.95 | 68.64 |
| Leverage ratio | 25.35 | 11.24 | 15.52 | 63.44 |

Source: Own elaboration based on [20–24].

The leverage ratio indicates the extent to which public expenditures allocated to regional economic development support generate additional external financial resources. As presented in Table 2, one euro of expenditure generated between EUR 11.24 (EUR 13.13) in 2022 and EUR 63.44 (EUR 68.64) in 2024 in external funding inflows to the territory of BBSK, demonstrating a substantial leverage effect of project preparation activities. The particularly high value recorded in 2024 reflects the successful acquisition of a large-scale externally funded project and highlights the capacity of the regional development agency to mobilise significant external financial resources for regional development, indicating a high level of funding efficiency and demonstrate the capacity of project preparation activities to mobilise external financial resources for regional development.

In 2024, the project SPACE – One-Stop Contact Points for Youth in BBSK was approved, with total eligible expenditures amounting to EUR 12.14 million. The approval of this large-scale project significantly increased the overall volume of both TEE and NFC recorded in 2024. Consequently, the observed increase in financial indicators in that year can be attributed primarily to the successful acquisition of a major external

funding project. The findings of the analysis indicate that the funds allocated to this priority were deployed efficiently and produced a significant multiplier and leverage effect by facilitating the inflow of external development finances into the BBSK.

There is a total of 516 municipalities located within the territory of BBSK, of which only 24 are towns. Only 43 municipalities have population exceeding 2,000 inhabitants, and merely nine surpass the threshold of 5,000 [17]. These data underscore the predominantly rural nature of the BBSK.

In many instances municipalities face constrains in administrative, financial and professional capacities, which limit their ability to engage effectively in external funding schemes. Within this context, the project preparation services delivered by DABBSK represent a key enabling mechanism, supporting the realisation of local as well as regional development initiatives that would otherwise contribute not only to the advancement of individual municipalities but, indirectly, to the overall socio-economic development of the BBSK.

As illustrated in Table 3, in the period 2021–2024 municipalities implemented 65 projects prepared by DABBSK, with a TEE approaching EUR 3.9 million. By June 2025, the cumulative value of all approved projects had exceeded EUR five million [23]. This points to the increasing relevance of institutional project support mechanisms in reinforcing the capacity of small municipalities to access external funding and to implement local development initiatives.

**Table 3.** Projects prepared for municipalities

| Indicator | 2021 | 2022 | 2023 | 2024 | Total |
|---|---|---|---|---|---|
| Number of projects | 12 | 25 | 19 | 9 | 65 |
| TEE | 679,726 | 872,895 | 1,714,451 | 629,672 | 3,896,744 |
| NFC | 645,251 | 802,340 | 1,616,020 | 629,472 | 3,693,083 |
| Average project size | 56,644 | 34,916 | 69,963 | 59,950 | – |

Source: Own elaboration based on [20–24].

Beyond the cooperation with municipalities DABBSK has also developed project proposals for a diverse set of actors from the territory of BBSK, e.g., secondary schools established by BBSK, registered social enterprises, and organisations active in the tourism. A considerable proportion of approved projects has likewise comprised initiatives implemented directly by DABBSK.

In the period 2021–2024, 16 projects prepared for these entities were approved and subsequently implemented, with overall TEE reaching EUR 19.7 million, of which EUR 16.65 million was covered by NFC. An important milestone was the approval and implementation of the project SPACE – One step contact Points for Youth in BBSK in 2024 representing a large-scale intervention focused on strengthening youth support infrastructure in the region (Table 4).

The findings further suggest that, since its establishment in 2018, DABBSK has facilitated the mobilisation of more than EUR 27 million in external funding into the territory

**Table 4.** Projects prepared for other entities

| Indicator | 2021 | 2022 | 2023 | 2024 | Total |
|---|---|---|---|---|---|
| Number of projects | 7 | 3 | 3 | 3 | 16 |
| TEE (EUR) | 4,620,847 | 819,524 | 1,706,950 | 12,566,967 | 19,714,288 |
| NFC (EUR) | 3,249,778 | 646,099 | 1,187,220 | 11,568,010 | 16,651,107 |

Source: Own elaboration based on [20–24].

[19–25], thereby making a substantial contribution to the development of BBSK. We consider expenditures allocated to the area of regional economic development support efficiently utilised, further they have generated substantial leverage effect in mobilising external financial resources.

From a broader regional development perspective, the mobilisation of external funding through project preparation activities may also generate a regional development multiplier effect, as investments implemented through externally funded projects stimulate local economic activity, improve public infrastructure, and enhance institutional capacity within the region. Moreover, institutional project-support mechanisms can strengthen the absorptive capacity of regional and local actors, thereby increasing their ability to access and effectively utilise external development funding [26, 27].

Through the activities of DABBSK, BBSK effectively fulfils its statutory responsibility defined in Sect. 4 (1) of Act No. 302/2001 Coll. On Self-Governing Regions [28], which assigns regional governments the task of ensuring the comprehensive development of their territory.

Table 5 presents an overview of successfully implemented projects by DABBSK, classified according to their programme priorities. In terms of TEE, the employment support priority clearly emerges as the predominant category. Within this priority area, DABBSK implemented in examined period five projects with TEE of EUR 16.5 million, while the overall financial allocation for all projects and all programme priorities approached EUR 17 million.

This allocation of financial resources reflects the strategic focus of regional development interventions on labour market support and employment-oriented measures, which represent a central policy objective within both national and regional development strategies and the EU cohesion policy framework.

**Table 5.** Projects implemented by DABBSK

| Programme Priority | TEE (EUR) | Number of projects |
|---|---|---|
| Tourism and rural development | 231,360 | 7 |
| Support and development of outpatient clinics | 80,000 | 1 |
| Employment support | 16,522,384 | 5 |
| Support for entrepreneurship and innovation | 5,500 | 2 |
| Total | 16,839,244 | 15 |

Source: Own elaboration based on [24].

### 4.2 Support and Development of Outpatient Healthcare Facilities

Since 2019, DABBSK has undertaken a range of activities focused on the support and development of outpatient healthcare services. These efforts have been driven by the declining accessibility of outpatient medical care for the population across the Slovak Republic. DABBSK concentrates on sustaining existing outpatient facilities, especially in districts experiencing a shortage of medical practitioners.

At present, the availability of outpatient healthcare constitutes a nationwide challenge in the Slovak Republic with further deterioration anticipated in the coming years. This trend is documented in analytical reports and datasets published by the Ministry of Health of the Slovak Republic [29–31], which regularly updates the classification of districts based on the accessibility of outpatient healthcare services. These assessments reveal pronounced territorial disparities in healthcare provision and emphasise the increasing importance of interventions from the regional level aimed at preserving access to essential services.

The first pilot clinic operated by DABBSK was a paediatric outpatient clinic established in the Detva district on 1 September 2019, following the termination of practice by two physicians as of 31 December 2018 [32]. As of 30 June 2025, the portfolio of outpatient clinics operated by DABBSK has expanded to twelve facilities. The spatial distribution of these clinics is illustrated in Fig. 1.

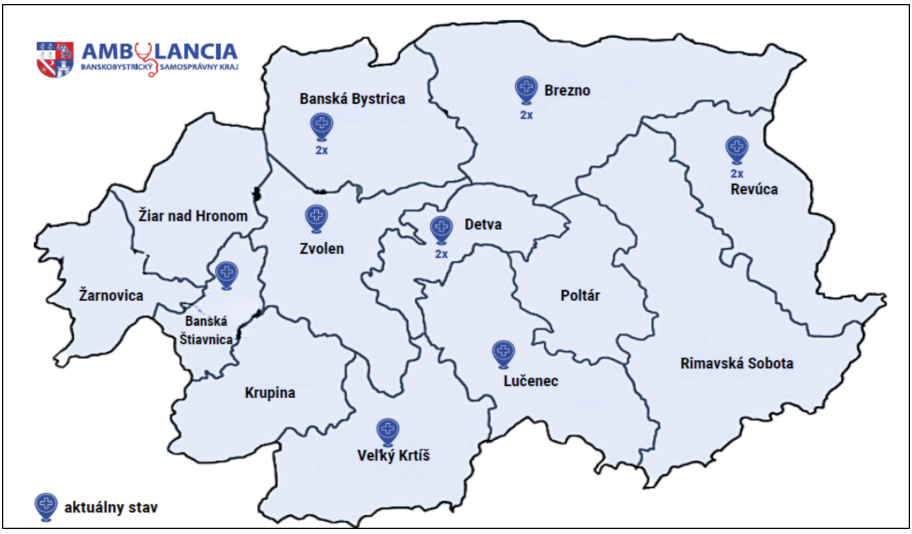


**Fig. 1.** Outpatient clinics operated by DABBSKSource: DABBSK, based on [32].

The following Table 6 provides an overview of the structure of outpatient clinics (as of 30 June 2025) and the districts in which the clinics operated by the DABBSK are located.

**Table 6.** Outpatient clinics operated by DABBSK

| Outpatient clinic type | District |
|---|---|
| General outpatient clinic (children and adolescents) | Detva, Brezno (2), Zvolen, Banská Štiavnica |
| General outpatient clinic for adults | Lučenec, Banská Bystrica, Revúca |
| Pulmonology outpatient clinic | Detva |
| Cardiology outpatient clinic | Revúca |
| Cardiology and internal medicine outpatient clinic | Veľký Krtíš |
| Endocrinology and diabetology outpatient clinic | Banská Bystrica |

**Source:** Own elaboration based on [32].

An important component of ensuring the provision of outpatient medical care is the active recruitment of new physicians for outpatient clinics in the BBSK. DABBSK provides recruited physicians with comprehensive operational support, including material and technical facilities as well as administrative assistance aimed at reducing bureaucratic burden. In addition, a motivation system for employees of DABBSK outpatient clinics has been introduced, incorporating non-financial benefits with the potential to attract new physicians to regional healthcare facilities.

Support measures also include a residency programme implemented by BBSK, within which DABBSK offers enhanced conditions for residents and actively recruits certified physicians for outpatient clinics across the region. Residents participating in the programme may receive a monthly allowance of EUR 1,000 and, upon completion, employment in a regional outpatient clinic with full material, technical, and administrative support. In 2024, DABBSK cooperated with seven physicians—five residents in general practice for children and adolescents and two in general practice for adults [32]. These initiatives contribute to the recruitment of qualified physicians and help maintain the accessibility of outpatient healthcare services for the region's population.

The strategic objective of DABBSK is to ensure the long-term financial sustainability of outpatient clinics operated by the DABBSK, with the aim of achieving balanced financial performance, whereby operating costs are covered by revenues and income equals or exceeds expenditures.

Currently, a considerable proportion of the financing of these outpatient facilities continues to rely on subsidies from the BBSK budget. As the number of operated clinics expands, it can be anticipated that own-source revenues will gradually increase, accompanied by a corresponding reduction in the level of regional budget support.

According to DABBSK projections, financial contributions from BBSK allocated to the operation of outpatient clinics are expected to decline from 2028 onwards [33]. Based on our analysis, this assumption appears plausible and may even be realised at an earlier stage. Nonetheless, a certain level of reliance on subsidies from BBSK budget is likely to remain.

In addition to the financial burden imposed on the BBSK budget, it is essential to acknowledge the wider positive effects associated with the operation of outpatient clinics managed by DABBSK in the region. Enhanced access to outpatient healthcare services contributes to a range of interconnected regional development outcomes.

Enhanced availability of outpatient healthcare contributes to improved health outcomes for the population in the region by increasing access to preventive examinations, strengthening patient education and awareness and enabling earlier detection of illnesses. These elements can help reduce healthcare costs by allowing treatment to begin at earlier stage of disease. Moreover, better access to healthcare services boosts, according to our opinion, the overall attractiveness and competitiveness of a region. In Slovak Republic, where several areas still struggle with insufficient healthcare access, inhabitants tent to prefer living in places where medical services are easily accessible. Such favourable conditions could also encourage the return of skilled professionals – including remote workers – along with their families to regions with available healthcare services.

Environmental gains arise from shorter travel distances for medical consultations leading to reduced greenhouse gas emissions and more positive environmental footprint. The availability of outpatient clinics likewise contributes to retaining qualified human capital within the region, including physicians, healthcare personnel, and potentially related professions such as pharmacists. In addition, the establishment of medical services may encourage the return of young and qualified individuals to the region. This aspect is particularly relevant for the southern districts of BBSK, which have long experienced the outmigration of educated young people; the arrival of healthcare professionals may help stimulate gradual changes in these migration patterns.

Taken together, these effects interact synergistically and contribute to strengthening the overall competitiveness and attractiveness of the BBSK. The activities related to healthcare provision in which DABBSK acts as an operator of outpatient clinics can be evaluated positively, particularly regarding their contribution to ensuring the accessibility of healthcare services for residents of the self-governing region. These activities reflect the fulfilment of one of the core responsibilities of the BBSK, as defined in § 4 of Act No. 302/2001 Coll. on Self-Government of Higher Territorial Units [28], which stipulates that a self-governing region, in the exercise of its competencies, is responsible for the comprehensive development of its territory and for addressing the needs of its inhabitants, including participation in solving problems affecting multiple municipalities within the region.

## 5 Discussion and Conclusion

The aim of this paper was to examine selected activities of DABBSK and to identify their contributions within the framework of social innovation. The findings indicate that the agency's primary contribution lies in promoting the public interest, as reflected in the outcomes observed across the analysed areas. The activities, measures and projects implemented within its programme priorities are interconnected and complementary, generating a significant synergistic effect.

Innovation and the capacity to develop innovative products and services represent key components of the productive environment that can stimulate or constrain regional development. In this context DABBSK can be regarded as an example of social innovation

within the institutional conditions of Slovakia. Although the agency has been operating only since 2018, its activities have already produced significant contributions within the public sector and generated tangible benefits for the socio-economic development of the BBSK.

The empirical results further support arguments within the social innovation literature that new institutional arrangements and collaborative practices may provide effective responses to societal challenges that cannot be adequately addressed through conventional market or public policy mechanisms [6, 7]. In the BBSK, characterised by a fragmented settlement structure and limited administrative capacities of many municipalities, the provision of project preparation services by DABBSK significantly strengthens the absorptive capacity of local governments. Since its establishment, DABBSK has secured almost EUR 27 million for the region through projects prepared for municipalities and other entities. In this way, DABBSK has contributed to the development of cooperation, knowledge exchange and the coordination of regional development activities (Cooke [34]).

By facilitating access to external development funding and providing technical expertise, the agency enables municipalities to participate more actively in development programmes and to implement initiatives that would otherwise remain unrealised due to institutional constraints.

The financial outputs of project preparation initiatives reveal that limited public expenditures in DABBSK catalyse significantly higher volumes of external financial resources. Besides the direct financial inflow, these activities strengthen administrative capacities among regional and local stakeholders as well as institutional learning processes. In this regard, DABBSK serves not only as intermediaries for financial resources, but they are facilitators of institutional capacity-building within regional government system.

Our findings align with Moulaert et al. [12] emphasize the importance of social innovation in addressing socio-economic problems in catching-up regions. DABBSK fosters new cooperation forms and governance arrangements and interconnects various stakeholders in the BBSK. Such institutional networks and configurations help redefine relationships among regional actors, creating favourable conditions for socially innovative development processes.

We understand activities of DABBSK aimed at support and development of outpatient healthcare facilities as a highly illustrative example of social innovation. These interventions respond to systemic service deficiencies through innovative institutional arrangements while simultaneously producing wider socio-economic impacts, such as improved quality of life, increased regional attractiveness, and the potential to retain or attract qualified professionals to the region.

Amid declining access to outpatient care in Slovakia, DABBSK's role as outpatient provider will expand across several BBSK districts. These activities constitute a key public-interest intervention to preserve healthcare accessibility as well as an example of socially innovative institutional arrangements addressing gaps in healthcare accessibility. By implementing novel organisational mechanisms to ensure availability of outpatient medical care in the BBSK, DABBSK strengthens the regional service infrastructure.

Research findings highlight the crucial role of the development agency in BBSK, a region facing structural challenges and limited innovation capacity [35]. Although this study examines only one development agency, the results suggest that development agency is vital part of the regional institutional system. Our empirical evidence indicates that DABBSK does not merely support innovation but actively co-produces it by shaping actor networks, fostering collective learning and promoting the integration of diverse stakeholders' interests [11]. In this context, we consider it plausible that the DABBSK model could also be applied in other regions of the Slovak Republic, such as the Prešov and Košice self-governing regions, as they face similar challenges to those encountered in BBSK.

Despite our findings, the study has several limitations. The analysis is based on a single case study of one development agency and primarily relies on qualitative analysis of institutional documents and interviews, limiting the results´ generalizability and possibly not fully capturing the long-term socio-economic impacts of analysed initiatives. We suggest that further examination could therefore focus on comparative analyses of development agencies across different regions to better understand the conditions under which such organisations promote social innovation and regional development. The incorporation of a technological dimensions into the research framework could be a promising direction for future research, particularly with the regard to the interplay between social and technological innovations.

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## References

1. Skokan, K.: Konkurenceschopnost, inovace a klastry v regionálním rozvoji. Repronis (2004)
2. Schumpeter, J.A.: The Theory of Economic Development. Harvard University Press (1934)
3. OECD, Eurostat: Oslo manual 2018: Guidelines for collecting, reporting and using data on innovation, 4th edn. OECD Publishing (2018). https://doi.org/10.1787/9789264304604-en
4. Tidd, J., Bessant, J.: Managing innovation: Integrating technological, market and organizational change, 7th edn. Wiley (2021)
5. Dabard, C.H., Mann, C.: Sustainability innovations: a proposal for an analytical framework and its empirical application in the Schorfheide-Chorin biosphere reserve. Sustain. Sci. **18**, 1085–1098 (2023). https://doi.org/10.1007/s11625-022-01241-9
6. Phills, J.A., Deiglmeier, K., Miller, D.T.: Rediscovering social innovation. Stanf. Soc. Innov. Rev. **6**(4), 34–43 (2008)
7. Mulgan, G.: The process of social innovation. Innovations **1**(2), 145–162 (2006). https://doi.org/10.1162/itgg.2006.1.2.145
8. Howaldt, J., Schwarz, M.: Social Innovation: Concepts, Research Fields and International Trends. TU Dortmund University, Dortmund (2010)

9. Poláčková, Z.: Report on the State of the Social Innovation Ecosystem in Slovakia (2022)
10. OECD: Social economy and social innovation. OECD Publishing (2023)
11. Vercher, N.: The role of actors in social innovation in rural areas. Land **11**(5), 710 (2022). https://doi.org/10.3390/land11050710
12. Moulaert, F., et al.: The International Handbook on Social Innovation: Collective Action, Social Learning and Transdisciplinary Research. Edward Elgar (2013)
13. Christmann, G., Sept, A., Richter, R.: Socially innovative initiatives in deprived rural areas of Germany, Ireland and Portugal: exploring empowerment and impact on community development. Societies **14**(5), 58 (2024). https://doi.org/10.3390/soc14050058
14. Bachtler, J., Yuill, D.: Policies and Strategies for Regional Development: a Shift in Paradigm? University of Strathclyde, Regional and Industrial Policy Research Paper (2001)
15. Asheim, B.T., Coenen, L.: Knowledge bases and regional innovation systems: comparing Nordic clusters. Res. Policy **34**(8), 1173–1190 (2005). https://doi.org/10.1016/j.respol.2005.03.013
16. Rozvojová agentúra Banskobystrického samosprávneho kraja: Statute of the Development Agency of the Banská Bystrica Self-Governing Region (2018). https://dobrykraj.sk/o-nas/dokumenty/. Accessed 30 Jun 2025
17. Statistical Office of the Slovak Republic: DataCube database (2026). https://datacube.statistics.sk. Accessed 2026
18. Banskobystrický samosprávny kraj: Program hospodárskeho a sociálneho rozvoja Banskobystrického samosprávneho kraja na roky 2022–2030 (2022). https://www.bbsk.sk/storage/app/media/dokumenty/phsr/phsr-bbsk-2022-2030-uvod-a-analiticka-cast.pdf. Accessed 3 Mar 2026
19. Regional Development Agency of the Banská Bystrica Self-Governing Region: Annual report for 2018 (2019). https://dobrykraj.sk/o-nas/dokumenty/. Accessed 2026
20. Regional Development Agency of the Banská Bystrica Self-Governing Region: Annual report for 2021 (2022). https://dobrykraj.sk/o-nas/dokumenty/. Accessed 2026
21. Regional Development Agency of the Banská Bystrica Self-Governing Region: Annual report for 2022 (2023). https://dobrykraj.sk/o-nas/dokumenty/ Accessed 2026
22. Regional Development Agency of the Banská Bystrica Self-Governing Region: Annual report for 2023 (2024). https://dobrykraj.sk/o-nas/dokumenty/. Accessed 2026
23. Regional Development Agency of the Banská Bystrica Self-Governing Region: Annual report for 2024 (2025). https://dobrykraj.sk/o-nas/dokumenty/. Accessed 2026
24. Regional Development Agency of the Banská Bystrica Self-Governing Region: Internal documents (unpublished), (2025)
25. Regional Development Agency of the Banská Bystrica Self-Governing Region: Annual report for 2019 (2020). https://dobrykraj.sk/o-nas/dokumenty/. Accessed 2026
26. Bachtler, J., Mendez, C., Wishlade, F.: EU cohesion policy and European integration: the dynamics of EU budget and regional policy reform. Ashgate. (2013). https://doi.org/10.4324/9781315857916
27. Crescenzi, R., Giua, M.: One or many cohesion policies of the European Union? On the differential economic impacts of cohesion policy across member states. Reg. Stud. **54**(1), 10–20 (2020). https://doi.org/10.1080/00343404.2019.1665174
28. Act No: 302/2001 Coll. on Self-Government of Higher Territorial Units (2001)
29. Ministry of Health of the Slovak Republic: Strategy for general outpatient care until 2030 (2022). https://health.gov.sk/?vseobecna-ambulantna-starostlivost. Accessed 2026
30. Ministry of Health of the Slovak Republic: Classification of districts (2023). https://health.gov.sk/?Klasifikacia-okresov-2023r. Accessed 2026
31. Ministry of Health of the Slovak Republic: Classification of districts (2024). https://health.gov.sk/?Klasifikacia-okresov-VMS. Accessed 2026

32. Regional Development Agency of the Banská Bystrica Self-Governing Region: BBSK outpatient clinics (2025). https://dobrykraj.sk/podpora-ambulancii/. Accessed 2026
33. Banská Bystrica Self-Governing Region: Informative report: Support and development of outpatient clinics in the BBSK for the period 2019–2030 (2024)
34. Cooke, P.: Regional innovation systems, clusters, and the knowledge economy. Ind. Corp. Chang. **10**(4), 945–974 (2001). https://doi.org/10.1093/icc/10.4.945
35. Rodríguez-Pose, A., Crescenzi, R.: Research and development, spillovers, innovation systems, and the genesis of regional growth in Europe. Reg. Stud. **42**(1), 51–67 (2008). https://doi.org/10.1080/00343400701654186

# Assess Flooding Impacts in Urban Environment: Integrating Fluid-Dynamic Simulations in Smart City Digital Twin

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**Abstract.** In recent years, climate change has led to a significant increase in the frequency and intensity of extreme weather events. Among them, floodings represent one of the most critical and dramatic events that can produce casualties and huge damage in urban environments. Therefore, the development of effective tools for the prevention and management of hydrological risks is of paramount importance. In this context, the simulation of flood scenarios and their visualization represent fundamental support tools for decision makers and urban planners to assess risks and identify countermeasures. For these reasons, in this paper, a fluid-dynamic simulation engine integrated into the Snap4City Digital Twin platform is proposed, and, to allow users to observe the results, simulation outputs are encoded as an animated heatmap and visualized on interactive 3D dashboards. Experimental studies comparing the simulation results with the measurements of the 1966 historical flood of Florence, Italy, confirm the validity of the proposed approach.

**Keywords:** Flooding · Hydrological Risks · Smart City · Digital Twin · Fluid-dynamic Simulation · 3D Dashboard

## 1 Introduction

The increasing frequency of extreme events resulting from climate change [1], coupled with the expansion of built-up areas connected with urban and population growth, including the spread of residential and economic buildings, as well as mobility or critical infrastructure, requires greater attention to flood-risk mitigation for potentially exposed populations and assets. A city seeking to become resilient must equip itself with tools capable of reducing vulnerability and strengthening its capacity for rapid response. Such resilience can be fostered through a systemic approach to vulnerability assessment, intelligent hydrodynamic monitoring, the prediction of impacts under changing conditions, and the development of appropriate risk-management response systems [2, 3].

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Over the past two decades, there has been a marked increase in studies devoted to developing models for flood-impact assessment. This trend reflects the growing interest of the scientific community in producing increasingly reliable predictive tools, further enhanced by the availability of data for the accurate reconstruction of digital surface models and by real-time information on meteorological conditions, environmental variables, and contextual factors [4–7].

In this context, Smart City Digital Twins (SCDTs) [8] have emerged as fundamental technologies to support decision makers in facing emergencies and planning solutions to increase urban resilience by integrating multiple urban data sources (including hydrological, transportation, geographic, and infrastructure-related information) with advanced simulation and predictive data analytics to evaluate the effect of possible scenarios. Current experience shows that the adoption of SCDT solutions enhances the accuracy of flood-risk assessment and provides a solid basis for capital allocation, insurability evaluation, and adaptation planning, while also highlighting significant governance, legal, and behavioral constraints. Overall, this approach supports the objectives of the EU Floods Directive[1] by improving risk mapping, preparedness, and the protection of vulnerable populations.

Nevertheless, the exploitation of SCDT in evaluating the impact of floodings is hindered by limited existing hydrodynamic models able to represent flood processes in the built environment, thereby underscoring the need for more comprehensive risk mapping that accounts for multiple flood drivers and their associated impacts [9]. By contrast, simulations based on fluid dynamic models have proved to be considerably more robust, as they are based on physical support for a comprehensive representation of flood processes. However, such simulators are usually not integrated into the SCDT platform.

For these reasons, in this paper, a flooding simulation framework integrated into the Snap4City SCDT platform is proposed. By exploiting physically based models, the simulator can provide accurate reconstructions of flooding events that are visualized on 3D web-based dashboards to allow decision makers to obtain a clear and immediate understanding of the risks and identify critical areas in order to plan adequate responses. The paper is structured as follows: In Sect. 2, the fluid-dynamic simulation engine is presented. Then, in Sect. 3**,** details on ingestion and visualization of simulation results are provided, while in Sect. 4**,** an experimental validation of the simulation results is reported. Finally, conclusions are drawn in Sect. 5.

## 2 Fluid-Dynamic Simulation Engine

The selection of an appropriate engine to carry out hydrodynamic simulations into the digital twin is a critical step in developing a reliable support decision system to assess flooding risk in an urban environment. In the context of Smart Cities, a simulation tool must not only provide high physical accuracy but also guarantee computational efficiency and seamless integration into automated data pipelines. In addition, preference should be given to open-source solutions to avoid technological lock-in and allow easier and wider distribution.

[1] https://environment.ec.europa.eu/topics/water/floods_en

Among the available open-source solutions, HEC-RAS [10] (Hydrologic Engineering Center's River Analysis System) and LISFLOOD-FP [11] emerged as the most prominent 2D hydrodynamic models in the scientific community. While both models are highly capable of simulating complex fluvial dynamics, LISFLOOD-FP has been preferred following the findings of the comparative study presented in [12], in which it is indicated that LISFLOOD-FP tends to produce superior results in flat urban topographies. Additionally, LISTFLOOD-FP supports native builds for UNIX/Linux open-source operating systems as well as operating natively with standard ASCII Raster formats, facilitating its integration with GIS software (e.g., QGIS [13]) for data pre-processing.

LISFLOOD-FP is a hydrodynamic simulation software developed by the University of Sheffield. It is widely used in scientific literature for simulating fluvial and urban flood propagation due to its optimal balance between computational efficiency and result accuracy. The software is specifically designed to operate on regular raster grids (from 1x1m to 100x100m cells), making it highly suitable for high-resolution urban contexts where capturing micro-topographical features is essential. The model solves a simplified version of the 2D shallow water equations (Saint-Venant Equations [14]), which are appropriate for flows where the water depth is significantly smaller than the horizontal extent. The continuity equation of the Saint-Venant system is:

$$\frac{\partial h}{\partial t} + \frac{\partial (hu)}{\partial x} + \frac{\partial (hv)}{\partial y} = r - f \tag{1}$$

where: $h$ is the water depth, $u$, $v$ the components of the mean velocity on x and y direction respectively, $r$ the possible rain, and $f$ the infiltration (both expressed in mm/h). This equation describes how the water depth varies in time.

For solving (1), LISFLOOD-FP implements two primary numerical schemes: the Kinematic Wave Approximation and the Local Inertial Formulation, hereafter briefly introduced for completeness.

### 2.1 Kinematic Wave Approximation

The Kinematic Wave Approximation is a simple approach for water flow rate approximation based on the Manning formula [15]:

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}} \tag{2}$$

where: $V$ is the mean flow velocity in the channel, assuming a constant velocity, $R = A/P$ is the hydraulic radius (in which $A$ is the wetted cross-sectional area of the flow and $P$ the wetted perimeter length of channel boundary in contact with water), $S = \left[ -\frac{\delta(h+z)}{\delta x}, -\frac{\delta(h+z)}{\delta y} \right]$ is the channel slope, with $z$ the terrain elevation, and $n$ is the Manning's roughness coefficient.

Given a wide floodplain, in which the width of the plain is much greater than the water depth, the hydraulic radius simplifies to $R \approx h$, and the momentum equation describing

the flow rate $q = hV$ is

$$\begin{cases} q_x = \frac{1}{n} h^{\frac{5}{3}} S_x^{\frac{1}{2}} \\ q_y = \frac{1}{n} h^{\frac{5}{3}} S_y^{\frac{1}{2}} \end{cases} \tag{3}$$

where: $q_x$, $q_y$ are the flow rate in x and y directions. Finally, the continuity equation can be expressed as:

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = r - f \tag{4}$$

In summary, the Kinematic Wave model assumes that flow is controlled only by hydraulic slope and resistance to motion, eliminating acceleration terms. Even if this simplification makes the model numerically stable and computationally efficient, it fails to capture accurate water body motions.

### 2.2 Local Inertial Formulation

The Local Inertial Formulation [16, 17] is an advanced scheme that pairs the continuity Eq. (4) with updated motion equations in which local inertia terms are considered. The motion equations are defined as follows:

$$\begin{cases} \frac{\partial q_x}{\partial t} + gh\frac{\partial H}{\partial x} + g\frac{n^2 q_x |q_x|}{h^{\frac{7}{3}}} = 0 \\ \frac{\partial q_y}{\partial t} + gh\frac{\partial H}{\partial y} + g\frac{n^2 q_y |q_y|}{h^{\frac{7}{3}}} = 0 \end{cases} \tag{5}$$

where $g$ is gravity acceleration, $H = h + z$ is the water surface elevation ($h$ water depth and $z$ ground elevation), and the other terms follow the previous definitions. This formulation is not presented in terms of water flow values but in terms of dynamics. It considers that the dynamic mass of the water needs time to accelerate due to gravity ($g$) or slope ($\partial H/\partial x$) and it is contrasted by the friction (related to the Manning's coefficient $n$). This differs from the previous scheme in which acceleration happened instantly without considering the resistance of the mass of the water.

Therefore, this formulation provides a superior balance of physical accuracy and numerical stability, particularly for high-resolution urban simulations. Moreover, it enables the processing of local topography, allowing the simulation to take into account building heights, which are typically integrated by locally increasing the terrain elevation. At high resolutions, the model effectively captures the channeling effect of streets, accumulation in depressed areas, and the barrier effect of buildings.

Indeed, Local Inertia Formulation represents a significant advancement over previous methods, and for this reason, it has been selected as the numerical scheme to be used in the presented solution.

Finally, it is worth remembering that to numerically solve the partial differential equation, it is required to discretize the domain in a grid of cells (also known as a mesh).

### 2.3 Required Input Data and Produced Outputs

To execute a simulation, LISFLOOD-FP requires several configuration and geographic data files. Terrain elevation is provided in ASCII format (*.asc*), a widely adopted standard in GIS environments that can be used to encode matrices or grids. Each cell in the grid stores elevation data, enabling a discrete yet accurate representation of urban topography. In addition, LISTFLOOD-FP requires a parametrization of the surface roughness (representing the Manning's coefficient) to appropriately model the flow propagation velocity. Such data can be produced in the ASCII format too.

To constrain the resolution of the fluid-dynamic equations, boundary conditions are required. In LISFLOOD-FP, such constraints are specified using the *.bci* and *.bdy* files. The former acts as an index that specifies the domain cells in which the boundary conditions are enforced: in the case of fixed conditions (not changing during the whole simulation), their value is directly set in the *.bci* file. On the other hand, for time varying conditions in the *.bci* file, a pointer to a *.bdy* file that describes the evolution of the constraint during the simulation timespan is put. In particular, the simulation must know from where the flow enters (inlet) and exits (outlet) from the domain. In the inlet cells, the variable flow and water level are specified. Since the domain is considered closed by default, water cannot flow out of the domain without specifying outlet points. Note, however, that by using a sufficiently wide domain with respect to the water body, most cells at the border are never reached by the water. It is instead mandatory to specify the natural outlet of the water body (e.g., the cell covering the position from which the river exits the domain), and in this case, it is also possible to set a free-flow condition to allow water to flow out freely without imposing specific constraints on water levels or discharge.

Initial conditions, used to set the system state at $t = 0$, are specified in the startfile (*.asc*) in which initial water levels for each cell of the domain may be defined. However, it has been noted that improved numerical stability and better simulation results can be achieved by setting the water level at zero in any cell (including the cells covering water bodies) and then allowing the simulator to fill the domain according to the terrain elevation until the water reach a value equal to a reference level (e.g. the average water level of the water bodies in the domain).

To integrate building and other obstacle information, LISFLOOD-FP supports two main approaches for integrating such structures. Topographic modification can be performed locally by (i) increasing terrain elevation in cells corresponding to buildings, simulating them as physical obstacles, or (ii) via roughness modification, increasing local Manning's coefficients to reflect the presence of structures.

All the defined inputs together with additional parameters such as simulation time, sampling time, numerical solver to be used, the Courant–Friedrichs–Lewy (CFL) coefficient to control the numerical stability, etc., are collected in a *.par* file passed to LISFLOOD-FP to run the simulation.

In output, the simulation engine produces a series of temporal raster images in the *.wd* format, one for each time step. Each raster describes system status at a time instant in the form of a matrix, representing the grid used to define the domain, with values indicating the water height (in meters) to be added to the initial terrain elevation provided as input.

## 3 Flooding Heatmap Generation, Ingestion, and Visualization

To allow the dynamic visualization of the simulation output in an interactive dashboard of the Snap4City platform, further processing and data ingestion pipelines must be executed. Indeed, Snap4City [18] offers 3D interfaces for the visualizations of urban digital twin representation, integrating a number of real-time and historical data, including terrain elevation and 3D models of buildings and city structures [19]. Furthermore, Snap4City provides a heatmap management system: with adequate processing, flooding simulation outputs can be represented as heatmaps (describing the time-varying water level) and used for the visualization of simulation results.

The main workflow used to ingest the outputs of LISFLOOD-FP and enable their visualization into a 3D Snap4City Digital Twin dashboard is presented in Fig. 1. The water level files obtained from the simulation pass through post-processing to transform the data into suitable files to be ingested in the Heatmap Manager system. Once the time-varying heatmaps related to the flooding are ingested into the platform (with metadata and colormap information), the system generates GeoTIFF images that are served via GeoServer to the Snap4City dashboard, allowing users to interact and inspect flooding results through a web-based interface.

### 3.1 Heatmap Post-processing and Ingestion

The water level data produced by the simulation engine is not directly suitable for integration into a web-based visualization and interaction system due to its large file size. In particular, the simulator generates huge ASCII files that can reach hundreds of megabytes and would result in high latency during data transfer over the web. To address this limitation, the outputs are converted into GeoTIFF by the Heatmap Manager. In order to accomplish such a task, ASCII data are first converted into binary formats accepted by the Heatmap Manager for data ingestion.

The encoding workflow begins with the parsing of *.wd* files describing the water height, from which both header information and depth matrices are extracted. During this phase, cells with depth values below a minimum threshold of 0.01 m are discarded, as they are considered negligible and would unnecessarily increase the final file size. Subsequently, the spatial reference of the data is transformed into UTM Zones, a

coordinate reference system (CRS) suitable for compatibility and widely used as a web mapping standard. Finally, the processed data is serialized into a lightweight binary format (*.con*). In this representation, each record consists of two 32-bit integer coordinates (since UTM coordinates can be represented with integer values) and a single 32-bit floating-point value representing water depth. This structure allows for efficient data transfer and rapid ingestion of huge data. During the processing, each timestamp of the simulation generates a specific instance of the *.con* file as well as related metadata whose details are discussed in the next section.

### 3.2 Data Ingestion and Publication

The ingestion phase ensures that the encoded heatmaps are properly indexed and made accessible to the platform's visualization tools, enabling their effective use within the digital twin platform.

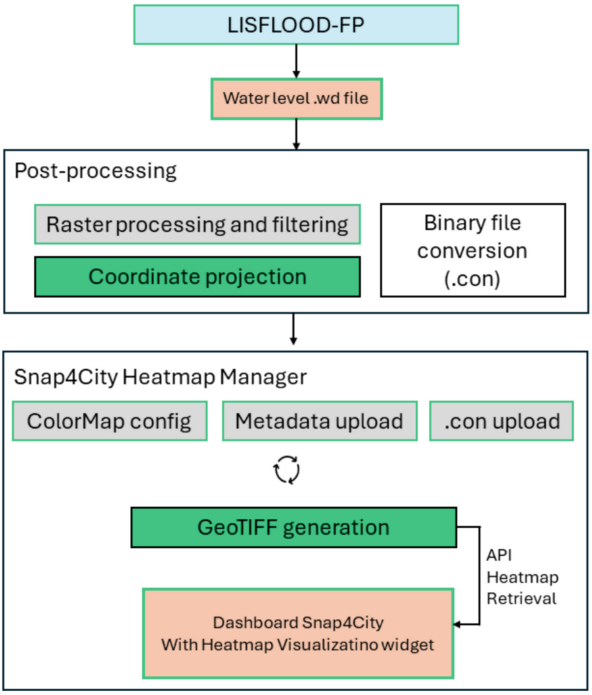


**Fig. 1.** Workflow flooding simulation data integration in Snap4City platform.

For each simulation timestep, a JSON metadata document is generated and transmitted via REST API to the Snap4City platform. This document contains key attributes required for correct data management and visualization, including the heatmap identifier, cell dimensions, ownership information, and a timestamp formatted according to the ISO 8601 standard. The inclusion of temporal metadata is essential to support time-based navigation and dynamic analysis.

In parallel, a specific color map is associated with the simulation data to convert numerical depth values into an intuitive visual representation. For example, to represent flooding, the color scale can range from dark blue, indicating maximum water depth, to light blue, corresponding to minimum values. This visual encoding enhances interpretability and allows users to quickly identify critical areas affected by flooding.

Once all data and metadata for any simulated time instant have been transmitted to the Heatmap Manager, the manager proceeds to generate GeoTIFF files. Since GeoTIFF is a well-known standard for GIS, this strategy allows the data to be consumed not only within the web-based Digital Twin but also by external spatial tools.

Finally, the created GeoTIFFs (one for each time instant) are sent to the Snap4City GeoServer to enable their distribution in different tile sizes through WMS/WCS protocols, thereby extending accessibility and supporting broader analytical workflows.

### 3.3 3D MultiDataMap Visualization and Interaction

The final visualization is delivered through a 3D MultiDataMap widget, embedded within a Snap4City dashboard, that provides an immersive representation of the flooding simulation. This environment enables users to explore both spatial and temporal dynamics of flooding in an intuitive and interactive manner.

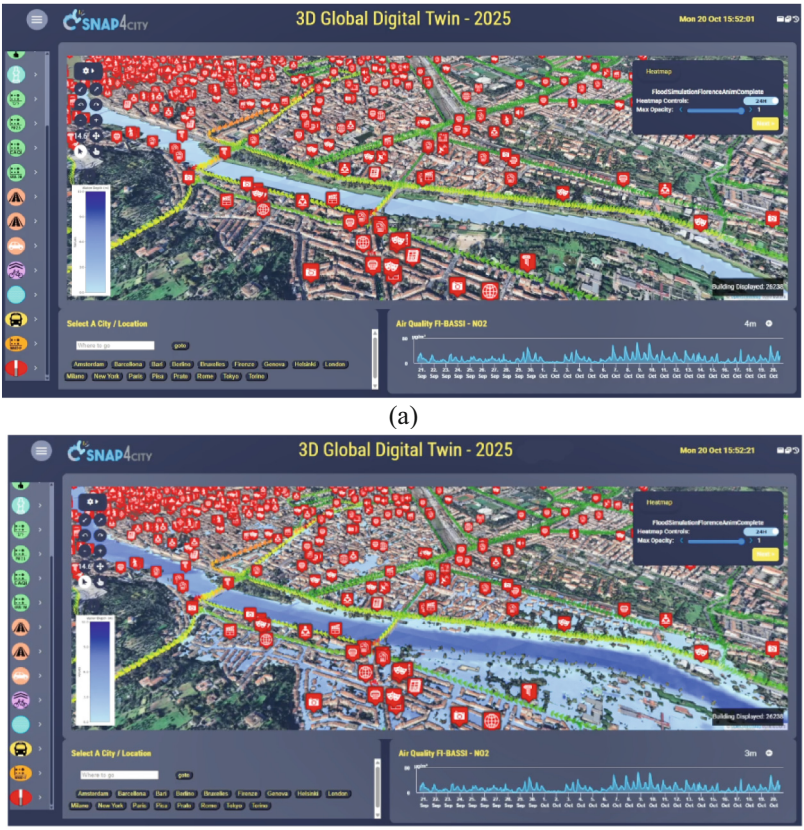


**Fig. 2.** Snap4City Digital Twin dashboard presenting flooding simulation results. In (a) the initial condition, in (b) an instant in which water overflows into city streets.

A dashboard has been configured in Snap4City using the Dashboard Manager [20] and made accessible via a web browser. The dashboard contains a specific selector that, when clicked, activates the automatic heatmap retrieval, interrogating the GeoServer (via REST APIs) and thus allowing the visualization of the flooding simulation results on the 3D map. A screenshot of the Snap4City Digital Twin dashboard with the flooding heatmap is reported in Fig. 2, in which two different time instants of the simulation are presented. Once the flooding heatmap has been loaded, the simulation results can be inspected thanks to the implemented temporal navigation and animation capability,

which allows users to observe the time-varying evolution of the flood during the simulated period. Controls to change the time instant and animate the heatmap are made available to the user with the panel placed in the top right corner of the dashboard (see Fig. 2). This temporal inspection feature allows decision-makers to analyze the progressive increase and subsequent recession of water levels across the urban area, essential for understanding the dynamics of the event and identifying critical time windows for intervention.

In addition, the visualization integrates heatmaps with high-resolution 3D building models, enhancing the contextual understanding of flood impacts. By overlaying water depth data onto the three-dimensional urban environment, users can directly compare flood levels with building elevations and assess the vulnerability of ground floors and other critical structures. This spatial correlation significantly improves the reliability of impact assessments.

The system also includes interactive controls that allow users to adjust the opacity and intensity of the heatmaps. These functionalities ensure that flood information can be effectively visualized without obscuring other relevant urban data layers. Indeed, several smart city entities are represented in the Snap4City platform and made available to users via the digital twin dashboard: position of point of interest, IoT sensors, road infrastructures, public services, etc. As a result, multiple sources of information can be analyzed simultaneously within a unified and interactive interface. This immersive 3D rendering, capable of visualizing complex flood simulation data intuitively and immediately, together with a plethora of other smart city entities, offers an operational decision-support system enabling the evaluation of urban resilience and plan emergency responses with high spatial and temporal precision.

## 4 Experimental Validation

In order to quantitatively evaluate the performance of the simulator, experiments have been carried out by comparing the results obtained with measurements taken from real flood events. In this context, data from the historic flood of Florence, Italy, happened in 1966, has been considered.

To run the simulation, a Digital Terrain Model (DTM) of the urban area has been used to model the terrain elevation and identify the bed of the Arno River. The DTM was obtained from Lidar scans in 2011. The render of the DTM is reported in Fig 3. On the other hand, buildings have been modelled into the simulation, exploiting the 3D models available on the Snap4City platform, from which building plants and heights have been obtained. To include buildings as physical obstacles, the terrain elevation was increased accordingly, performing the topographic modification required. Note that, following [21], bridges on the river have been removed since, in the domain representation used by LISFLOOD-FP, they would have appeared as barriers blocking the water flow.

To model the surface roughness, i.e., the Manning's coefficient, a spatial differentiation according to land use has been used. More specifically, three classes have been defined as follows: urban surfaces (e.g., asphalt, concrete) with roughness set to 0.025; green areas with a value of 0.05; and water bodies to which a value of 0.04 has been assigned. The visual representation of the chosen coefficients has been reported in Fig. 4, in which buildings are also highlighted.

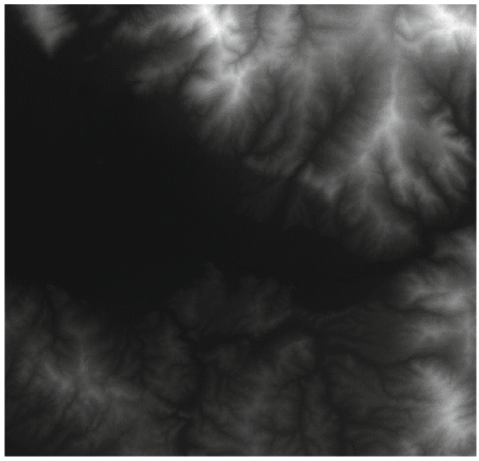

**Fig. 3.** DTM describing terrain elevation around Florence, Italy.

Regarding the boundary conditions, the inflow flow rate in the inlet has been set according to Arno's discharge measured during the flooding (from late hours of November third to the half day of November fifth, 1966). A plot of the used flow rate is presented in Fig. 5, expressed and $m^3/s$. Differently, free-flow conditions have been set in the outlet on which a terrain slope of 0.001 has been specified, going outside the simulation domain to allow a graceful outflow. Initial conditions have been defined by setting the water level to zero and then introducing a discharge of 200 $m^3/s$ to allow the simulation to fill the riverbed with water until reaching a threshold level. Such a threshold has been set to 2.5 m, i.e., the average water level of the river, and to reach this value, 1 h and 30 min of simulation time was required.

Finally, the CFL parameter of the simulation has been set to 0.03 to maintain numerical stability during high-volume inflow events. The simulation timespan has been specified at 48 h (from 4:00 PM on November third to 02:00 AM on November $6^{th}$) with a sampling time of 20 min, taking into account the time required to reach the average water level in the river as explained above.

To evaluate the balance between simulation precision and computational efficiency, two spatial cell resolutions—1 $m^2$ and 4 $m^2$—have been tested.

In order to evaluate the experiment results, ground truth data were obtained from a water depth map of the historical flood event, acquired from the databases of the Arno River Basin Authority [22]. Specifically, the simulation results were analyzed at the peak discharge. The comparison was conducted by evaluating both the areas characterized simply by overestimation or underestimation, as well as the actual error values produced by the simulation. The reference dataset provides an estimate of water elevations in different city areas with a precision of 1 or 2 m, depending on the specific zone (see Fig. 6). Two zones have a 2-m precision describing water depth spanning from 0 to 2 m and from 2 to 4 m. A third zone with 1-m precision describes water depth values from 4 to 5 m.

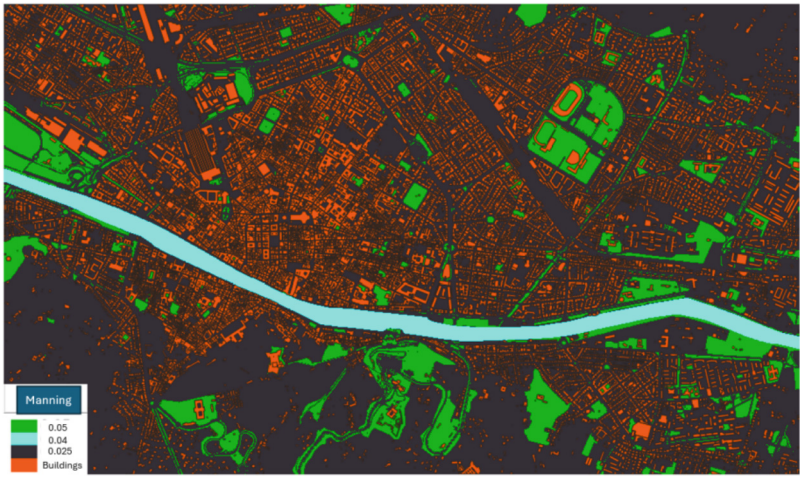


**Fig. 4.** Map of the surface roughness (Manning's coefficients) in the Florence area. Black areas indicate asphalt and concrete surfaces, green for green areas, cyan for the water body (i.e., the Arno River). In red the buildings of the city.

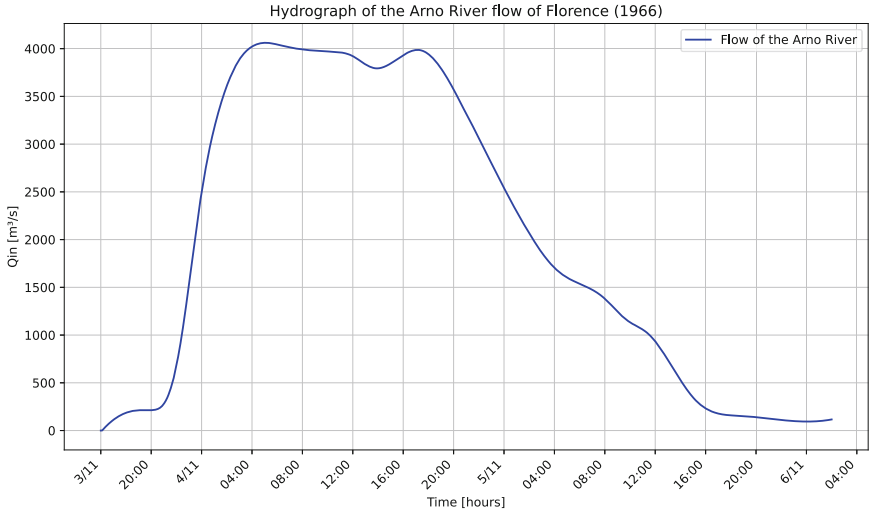


**Fig. 5.** Historic Arno's discharge measured during the 1966 flooding. From late hours of November 3rd to the afternoon of November 5th, 1966.

The estimated errors are therefore subject to this intrinsic limitation of the reference dataset and have been computed as follows. Depth values from the simulation falling within the precision intervals obtained an error of zero. In the case of overestimation (the simulation outputs higher values w.r.t. the ground truth), the error was calculated relative to the upper limit of the interval. In the case of underestimation, the error was calculated relative to the lower limit of the interval. To evaluate and summarize the errors,

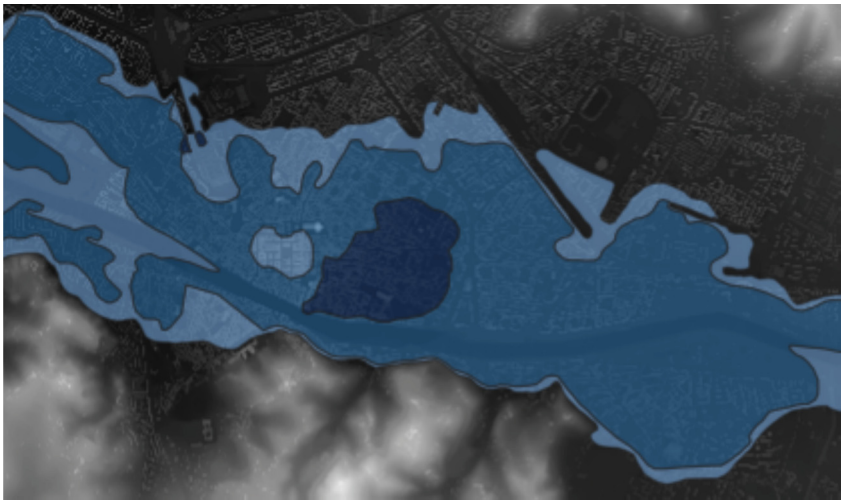

**Fig. 6.** Flooding reference map for the event of 1966 in Florence, highlighting the three zones: light-blue for water depth values between 0 and 2 meters; mid-blue for values from 2 to 4 meters; dark-blue for values from 4 to 5 meters.

the Mean Average Error (MAE) and the Root Mean Squared Error (RMSE) have been used. The obtained results, reported in Table 1, indicate that increasing the cell size to 4 $m^2$ does not significantly degrade global accuracy, with MAE varying by only 0.01 m. Differently, with cells of 4 $m^2$ the domain can be covered with a reduced number of cells (passing from 22.5 M to 5.5 M), and the simulation can be carried out in a shorter time (from 2 weeks to 4 days of computation using a workstation equipped with an 18-core 2.4GHz CPU and 32 GB of RAM). This suggests that, for operational urban flood management, the 4 $m^2$ resolution provides an optimal compromise between simulation speed and predictive reliability.

**Table 1.** Experimental results on the simulations performed on 1 $m^2$ cells and 4 1 $m^2$ cells.

| Parameter | 1 $m^2$ simulation | 4 $m^2$ simulation |
|---|---|---|
| Number of cells | 22.5 million | 5.5 million |
| Computational time | 2 weeks | 4 days |
| MAE | 1.11 m | 1.10 m |
| RMSE | 1.27 m | 1.26 m |

In Fig. 7 the absolute error map of the case using 4 $m^2$ cell size is reported, showing the 6 AM of the fourth of November, the peak of the Arno discharge (see Fig. 5). Most of the errors are due to how buildings are modelled: indeed, 3D models used are solid blocks without apertures (like fences, arcs, door, or windows) in which water usually flow, thus creating impenetrable barriers. In addition, it is important to note that the

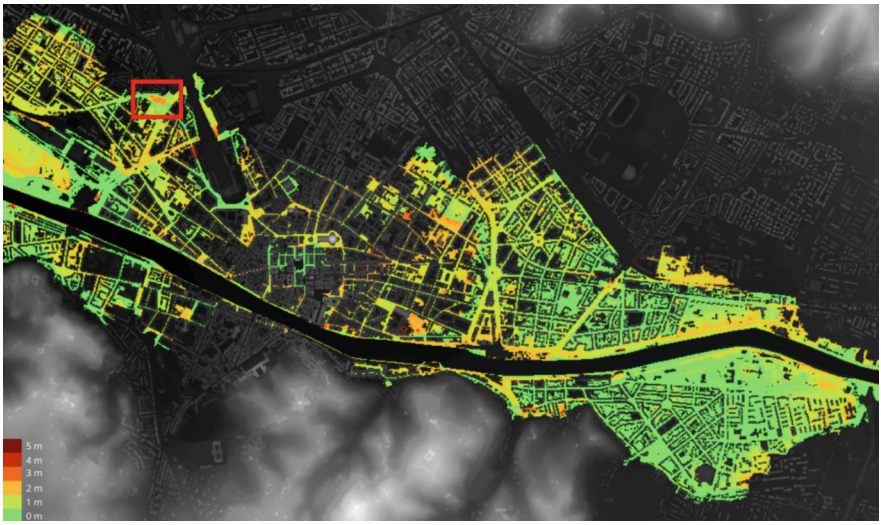


**Fig. 7.** Flooding absolute error map from the simulations using 4 $m^2$ cell compared to the data from the 1966 flooding (at 6AM of 4th of November, near the discharge peak). In the red box in the top left corner an area obtaining large errors due to changes in the urban landscape between the 1966 (year of the Florence flooding) and 2011 (year of DTM acquisition).

urban environment changed between 1966 and 2011 (when the DTM was acquired). For example, the large errors obtained in the area highlighted with the red box in Fig. 7 are due to the fact that in the area in 2011, there was a building construction site that created a huge excavation in the ground, while it was a flat area in 1966. Nevertheless, the model effectively captured the complex flood dynamics of a dense urban area such as Florence, with extreme errors occurring only in isolated areas affected by micro-topographical features or stagnation zones.

## 5 Conclusions

In this paper, a framework for evaluating flooding risks and impacts in urban scenarios has been presented. The solution leverages the LISFLOOD-FP simulation engine, exploiting the Local Inertial Formulation, for solving the fluid-dynamic problem, and it is integrated into the Snap4City Smart City Digital Twin platform that allow a seamless ingestion of the simulation results, that are encoded as series of time-varying heatmaps, and, finally provided to the users via web-based interactive 3D dashboards in which the flooding simulation can be navigated on both space and time axes.

Results obtained by simulating the historical flooding of Florence, which happened from the third to the sixth of November 1966, have demonstrated the reliability of the solution. In addition, tests considering different mesh generation (for the discretization of the domain) using cells of $1m^2$ and $4m^2$ have shown that wider cells provide a significant reduction of computational times without a strong loss in accuracy.

Therefore, the proposed solution realizes a concrete data-driven and simulation-based support decision tool to help decision makers in analyzing flooding dynamics,

identifying critical areas, and, thus, planning emergency responses and countermeasures to improve the smart city resilience.

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## References

1. Schreider, S.Y., Smith, D.I., Jakeman, A.J.: Climate change impacts on urban flooding. Clim. Chang. **47**, 91–115 (2000). https://doi.org/10.1023/A:1005621523177
2. de Oliveira, A.K.B., et al.: Evaluating the role of urban drainage flaws in triggering cascading effects on critical infrastructure, affecting urban resilience. Infrastructures **7**(11), 153 (2022). https://doi.org/10.3390/infrastructures7110153
3. Hsu, C.-W., Liu, C.-F., Stearns, L., Brody, S., Mostafavi, A.: Spillover effects of built-environment vulnerability on resilience of businesses in urban crises, 106376. Sustain. Cities Soc. **127** (2025). https://doi.org/10.1016/j.scs.2025.106376
4. Hammond, M.J., Chen, A.S., Djordjević, S., Butler, D., Mark, O.: Urban flood impact assessment: a state-of-the-art review. Urban Water J. **12**(1), 14–29 (2015). https://doi.org/10.1080/1573062X.2013.857421
5. Gao, P., Gao, W., Ke, N.: Assessing the impact of flood inundation dynamics on an urban environment. Nat. Hazards **109**, 1047–1072 (2021). https://doi.org/10.1007/s11069-021-04868-6
6. Zandsalimi, Z., Feizabadi, S., Yazdi, J., et al.: Evaluating the impact of digital elevation models on urban flood modeling: a comprehensive analysis of flood inundation, Hazard mapping, and damage estimation. Water Resour. Manag. **38**, 4243–4268 (2024). https://doi.org/10.1007/s11269-024-03862-4
7. Dong, B., Xia, J., Wang, X.: Comprehensive flood risk assessment in highly developed urban areas, 132391. J. Hydrol. **648** (2025). https://doi.org/10.1016/j.jhydrol.2024.132391
8. Adreani, L., et al.: Digital twin framework for Smart City solutions. In: DMSVIVA 2022 - Proceedings of the 28th International DMS Conference on Visualization and Visual Languages, pp. 1–8 (2022). https://doi.org/10.18293/DMSVIVA22-012
9. Sebastian, A., Juan, A., Bedient, P.B.: Chapter 5 - Urban Flood Modeling: Perspectives, Challenges, and Opportunities, Editor(S): Samuel Brody, pp. 47–60. Baukje Bee Kothuis, Coastal Flood Risk Reduction, Elsevier, Yoonjeong Lee (2022)
10. Brunner, G. W.: HEC-RAS River Analysis System. Hydraulic User's Manual. Version 1.0 (1995)
11. Bates, P., Trigg, M., Neal, J., & Dabrowa, A.: Lisflood-fp. User manual. School of Geographical Sciences, University of Bristol. Bristol, UK (2013)
12. Moghim, S., Gharehtoragh, M.A., Safaie, A.: Performance of the flood models in different topographies. J. Hydrol. **620**, 129446 (2023)
13. QGIS software.: https://qgis.org/ (Accessed on 30th Mar 2026)
14. de Saint-Venant, A.J.C.: Théorie du mouvement non-permanent des eaux, avec application aux crues des rivières et à l'introduction des marées dans leur lit. CR Acad. Sci. Paris. **73**(147–154), 237–240 (1871)

15. Manning, R.: On the flow of water in open channels and pipes. Trans. Inst. Civil Eng. Ireland **20**, 161 (1891)
16. De Almeida, G.A., Bates, P., Freer, J.E., Souvignet, M.: Improving the stability of a simple formulation of the shallow water equations for 2-D flood modeling. Water Resour. Res. **48**(5) (2012)
17. Bates, P.D., Horritt, M.S., Fewtrell, T.J.: A simple inertial formulation of the shallow water equations for efficient two-dimensional flood inundation modelling. J. Hydrol. **387**(1–2), 33–45 (2010)
18. Adreani, L., Bellini, P., Colombo, C., et al.: Implementing integrated digital twin modelling and representation into the Snap4City platform for smart city solutions. Multimed. Tools Appl. **83**, 37121–37146 (2024). https://doi.org/10.1007/s11042-023-16838-0
19. Adreani, L., Colombo, C., Fanfani, M., Nesi, P., Pantaleo, G., Pisanu, R.: A photorealistic 3D city modeling framework for Smart City digital twin. In: 2022 IEEE International Conference on Smart Computing (SMARTCOMP), pp. 299–304, Helsinki, Finland (2022). https://doi.org/10.1109/SMARTCOMP55677.2022.00071
20. Bellini, P., Fanfani, M., Nesi, P., Pantaleo, G.: Snap4City dashboard manager: a tool for creating and distributing complex and interactive dashboards with no or low coding, 101729. SoftwareX. **26** (2024). https://doi.org/10.1016/j.softx.2024.101729
21. Neal, J.C., Bates, P.D., Fewtrell, T.J., Hunter, N.M., Wilson, M.D., Horritt, M.S.: Distributed whole city water level measurements from the Carlisle 2005 urban flood event and comparison with hydraulic model simulations. J. Hydrol. **368**(1–4), 42–55 (2009). https://doi.org/10.1016/j.jhydrol.2009.01.026
22. Arno River Basin Authority: Flood Hazard Map – Discharge, (2015). http://www.adbarno.it/adb/?page_id=5372 (Accessed on 12 Mar 2026)

# Understanding Short-Term Rental Monitoring for Sustainable Data-Driven Destination Management

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**Abstract.** Short-term rentals have gained importance in tourism accommodation sector and their expansion has been driven by digital platforms. This expansion has not yet been fully reflected in official statistical systems which can present challenges for monitoring and governance of short-term rental activity. The study provides a structured overview of data sources for short term-rentals and comparisons between platform-derived and official statistics. Using AirDNA and official statistics from 24 local destinations in Slovakia, the results show that there are significant differences in capacity to accommodate visitors indicating unregistered short term rental activities. The findings also highlight the supplementary nature of these data sources as well as the new registration system introduced by the european union and the need for data-supported management of destinations.

**Keywords:** Short-Term Rentals · Data-Driven Destination Management · Platform-Based Data · Official Tourism Statistics · EU Regulation

## 1 Introduction

The Short-Term Rentals (STRs), which now represents an important part of the worldwide tourism accommodation market, has experienced a very rapid expansion over the last ten years. The advent of online platforms such as Booking.com and Airbnb have caused a complete transformation in the manner in which accommodations are marketed and consumed [2]. With these on-line platforms, property owners can now lease their private homes to tourists and short-term visitors, thus generating new types of housing supplies that differ greatly from those provided by hotels. Therefore, STRs have progressed from being a small type of tourist accommodation related to the "sharing economy" into one of the most significant sectors of the tourism industry in numerous locations [5, 9].

Growth of peer-to-peer accommodations has received considerable attention in a number of different contexts (e.g., the overall development of the sharing economy; the emergence of new forms of digital platforms) as well as the ways in which these digital platforms enable individual stakeholders to generate additional revenue by monetizing unused resources (such as an extra room or even an entire property). For example, the

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emergence of STR platforms can provide hosts with additional sources of income while providing tourists with alternative, and in many cases, less expensive alternatives for their accommodations [9]. Many destinations are seeing an increase in STR capacity and diversity of the accommodation base, particularly in locations that lack sufficient hotel infrastructure [17].

Research has expanded rapidly over the past decade, reflecting the importance of this phenomenon in tourism, urban studies and housing research [5]. Studies have examined various aspects of the STR market, including its economic effects, impacts on the hotel industry, implications for housing markets and challenges related to regulation and governance [1, 4].

Despite the growing importance of short-term rentals, for many years this segment of the accommodation sector remained largely outside traditional statistical and regulatory frameworks [11]. Unlike hotels and other registered accommodation establishments, STRs hosts were often not required to report their activities to public authorities. Official tourism statistics frequently failed to capture the real scale of STRs activity.

This lack of reliable data created several governance challenges. Without comprehensive information about the number of listings, rental frequency, or geographical distribution of STR properties, policymakers have had limited ability to assess the actual size and development of the STR market. As a result, policy debates and regulatory responses were often based on incomplete or indirect data sources rather than systematic evidence [4].

Another challenge arises from the spatial concentration of STR activity. Research shows that STRs tend to cluster in areas with high tourism demand, particularly in historic city centres and popular urban neighbourhoods. Such spatial concentration may intensify tourism pressure and change the character of local communities [16]. Without adequate monitoring systems, local authorities may struggle to identify these spatial patterns and evaluate their impacts on urban environments.

Monitoring is an important factor in helping regulators enforce their policies. Cities are implementing new policies that regulate STRs through a variety of means, such as requiring property owners to register with the city, limiting how many times per year an owner can rent out their property and prohibiting entire home rentals [13]. These types of regulatory tools are less effective if there is no way to monitor whether those who rent out their properties comply with local regulations. If city officials do not have reliable data from platforms or official host registries, it can be very challenging to enforce such laws.

Furthermore, insufficient monitoring may create an uneven competitive environment between traditional accommodation providers and STR hosts. Hotels are typically subject to strict regulatory requirements, including safety standards, taxation and statistical reporting obligations. In contrast, many STR hosts historically operated with fewer regulatory obligations, which raised concerns regarding fair competition within the tourism accommodation sector [4]. Recently, the European Union has introduced new regulatory frameworks, which are expected to require digital platforms to share data with public authorities [11].

Therefore, the aim of the study is to provide a structured overview of short-term rental data sources, highlight key differences between platform-derived and official statistics and demonstrate these differences through an empirical case study.

## 2 Monitoring STRs as a Tool for Sustainable Data-Driven Destination Management

The monitoring of short-term rentals can be considered as an important component of sustainable data-driven destination management. Data on STR serves as basis for governance. The systematic analysis of such data enables destination management organizations to identify emerging pressures, including overtourism, housing market distortions and spatial imbalances. It informs the design and implementation of targeted regulatory measures (e.g., zoning, caps or dynamic restrictions). Data-driven monitoring enhances the capacity for adaptive, evidence-based decision-making and supports a more balanced integration of economic benefits with social equity and environmental sustainability objectives.

### 2.1 The Need for Data on Short-Term Rentals

In addition to regulatory and tourism statistical concerns, the growth of STRs is associated with additional social-economic implications, primarily regarding urban housing market conditions. There are an increasing number of studies that empirically demonstrate how increased numbers of STRs can impact housing supply and price levels within tourist destination cities.

Several studies have found that the growth of Airbnb listings can contribute to rising housing prices and rental costs. For example, research conducted in Boston identified a positive relationship between Airbnb activity and increases in rental prices, suggesting that the conversion of residential properties into STRs may reduce the supply of long-term housing [10]. Similarly, Barron et al. [1] found that increases in Airbnb listings across the United States were associated with measurable increases in both rents and housing prices.

The growth of STR platforms has several implications that are far reaching. Wachsmuth and Weisler [16] argue that the expansion of STRs could be an impetus to a form of tourism driven gentrification as it creates conditions under which property owners would choose to convert long term housing into more lucrative short term tourist accommodations. The process may create changes in the social composition of neighborhoods and potentially reduce available housing for local residents.

At the same time, STR's can be a source of positive financial impact on their host communities. The activity generated by STRs may cause visitors to spend money in their neighborhoods, help support local small business and create new income generating options for local residents [9]. As such the primary challenge facing policy makers is how to balance the possible economic positives from STR activity, with the negatives they are creating in regard to the housing market and community.

To achieve effective regulation of STR markets, government officials must have access to credible, consistent and accurate data that allow them to assess the scale,

dynamics and geographic location of short-term rental activity. Without this type of data, policymakers are unable to create evidence-based regulations or measure the success or failure of implemented regulatory measures.

### 2.2 The Role of Data Sharing and Regulatory Frameworks

Recognizing the challenges associated with STRs, governments and international organizations have increasingly focused on improving transparency and data availability in the STR sector. Several policy initiatives aim to establish mechanisms that enable public authorities to access reliable data about STR activity while respecting privacy and data protection requirements. Destination management organisations (DMOs) should be able to quickly respond to these rapid changes and challenges [7].

Improved data sharing between digital platforms and public authorities can significantly enhance the monitoring of STR markets [11]. Access to reliable data allows policymakers to identify active listings, analyse spatial distribution patterns and evaluate the intensity of STR activity across different locations.

Hotels, who often represent hotel associations, express concerns over the inequality of regulations and the competitive disadvantage they face in comparison to their competitors offering STR accommodation. For example, hotels and STR's offer similar types of accommodation, but are regulated under different systems of law, especially when it comes to taxes. Hotels may feel unfairly disadvantaged by the lack of regulations of STR accommodation. Additionally, many times STR listings appear side-by-side with hotel listings. Therefore, the lines between STR and hotels become increasingly blurred [15].

Data will enable policy makers to develop evidence-based policies that regulate the industry appropriately and assist in enforcing current laws and regulations.

Additionally, increased transparency helps to resolve issues such as taxation, safety standards and regulatory enforcement. Authorities' ability to collect accurate information about both hosts and properties will enable them to better collect taxes owed by STR providers and enforce compliance with applicable law. The creation of a fair and equitable marketplace between STRs and hotels is aided by these developments [4].

### 2.3 The Importance of Local-Level Measurement

While national and international regulatory frameworks are important for improving transparency in the STR sector, the measurement of STRs at the local level remains particularly crucial. The impacts of STR activity are often highly localized, with significant differences between cities, regions and neighbourhoods.

Local authorities require detailed and spatially disaggregated data to understand how short-term rentals affect local housing markets, tourism flows and community dynamics, as well as to improve regulatory enforcement, limit the expansion of the informal economy and ensure proper taxation of STR activities. Measuring STR activity at the municipal level allows policymakers to identify areas with high concentrations of listings and monitor potential pressures related to tourism intensity or housing availability.

In addition, local-level measurement enables the development of targeted policy responses adapted to specific local conditions. While some destinations may experience

challenges related to overtourism and housing shortages, others may benefit from STR development as a tool for tourism diversification or regional economic development. Accurate data are therefore essential for designing policies that balance tourism growth with the protection of residential housing and community well-being.

As such, an improved way to monitor and measure short-term rentals in communities is emerging as a major priority among local governments and scholars. The availability of reliable data serves as the basis for informed decision making in government through evidence based governance and enables the formulation of sustainable tourism policy with consideration given to both the positive economic effects and negative societal effects.

Although there is growing research regarding STR's, many gaps exist with regards to comparing, assessing the reliability of, and measuring the policy relevance of various STR data sources, especially at the local level. The majority of existing research has examined the effects of STR on housing markets, tourism dynamics, and urban changes, whereas very little focus has been placed on the underlying data systems that affect how these phenomena are being collected and interpreted as data.

The recent introduction of Regulation (EU) 2024/1028 of the European Parliament and of the Council [6] marks a significant shift towards the institutionalisation of STR data through mandatory registration systems and platform data-sharing obligations in the European Union (EU). In addition to these studies, however, very little has been done to identify how new regulations are likely to affect the current limitations of STR data, as well as increase the reliability and transparency of STR data, and enable better use of STR data in local destination management. This study therefore adds a contribution to the scientific literature with the comparison of local platform-based STR data with official local STR data and analysis of possible discrepancies in measurement and the consequences for local tourism governance.

## 3 Methodology

This study uses a comparative and exploratory research approach in order to identify the differences at a local level (number of accommodation units and estimated revenues) and evaluate the potential applications to data driven destination management among platform derived short term rental data and official tourism statistics.

The aim of this paper is to provide a structured overview of short-term rental data sources, highlight key differences between platform-derived and official statistics and demonstrate these differences through an empirical case study using AirDNA data at the local level.

The analysis is based on two primary data sources. The first source of data was provided by AirDNA. AirDNA is a private company that offers commercial analytics about STRs at the level of individual listings. The data collected from AirDNA included, among other items, the total number of active listings for STRs as well as the estimated revenue generated by these listings. Second, official data on accommodation establishments and tourism income were sourced from the Statistical Office of the Slovak Republic, which collects data from legally registered accommodation providers through mandatory statistical reporting.

The type of unit used to measure is different within each dataset. Official datasets are usually measured by "establishment," with establishments able to contain multiple rooms or units. AirDNA's dataset is measured based on listings, which most often represent one single rental unit. Therefore, it is important to take into account the differences in measurement types when comparing these results. It could also limit comparison in terms of the actual total number for each dataset.

The study focuses on 24 selected destinations in Slovakia where STR activity was identified. The selection of these areas represents a mix of city based local tourism destinations with adequate data regarding STRs collected by AirDNA, along with other areas such as mountainous or spa areas that are well-established regional destinations. The geographic area of analysis corresponds to the municipal level of analysis (NUTS 4/LAU) since this is an appropriate scale for destination planning and policy making at a local level. In addition to empirical evidence, the study also draws upon additional contextual information regarding Eurostat's experimental statistical data collection and the European Union's legal regulatory framework [6].

## 4 Results

### 4.1 Comparison of STR Data Sources

The availability and source of data on short-term rentals varies. Data can be obtained from commercial STR analytics platforms, open-data platforms, Eurostat experimental statistics and from STR registration systems (Table 1).

Commercial STR analytics platforms (e.g. AirDNA, Lighthouse, Rabbu, Airbtics, AllTheRooms) offer the most granular data, typically at the listing level and in near real-time. Their datasets include performance indicators such as pricing, occupancy and revenue, making them suitable for market intelligence and investment. Their data collection relies primarily on web scraping and API integrations from major STR platforms. Although they provide highly granular data, covering listings, neighbourhoods and cities, however they are not aligned with official statistical classifications such as NUTS2 and NUTS 3 (see Table 1), which limits their comparability in policy contexts (Fig. 1).

Open-data platforms for STR provide medium to high data availability, often in the form of periodic snapshots with partial geographic or platform coverage. These datasets are widely used for research, transparency initiatives and housing market monitoring [3, 12]. Their sources include web scraping projects (e.g. Inside Airbnb), municipal open-data portals and academic datasets. Similar to commercial platforms, they offer fine spatial granularity at the listing and neighbourhood levels, but their coverage is inconsistent and often fragmented across cities.

Eurostat's experimental statistics represent a shift toward harmonised and officially validated STR data at the European level. These datasets are based on direct data-sharing agreements with major platforms (Airbnb, Booking, Expedia) and provide aggregated indicators such as guest nights and stays. Their primary purpose is to support official statistics, policy analysis and cross-country comparability. However, this standardisation comes at the cost of reduced spatial granularity, with data typically available at NUTS 2 (monthly) and NUTS 3 (annual) levels and only limited city-level detail (capital cities,

**Table 1.** Data sources on STR

| Source | Data Availability | Purpose | Data Source | Granularity (NUTS) |
|---|---|---|---|---|
| Commercial STR analytics platform | Very high (listing-level, pricing, occupancy, revenue, near Real-Time) | Market intelligence, investment analysis, revenue optimization | Web scraping/ API integrations | Listing, neighbourhood, city |
| Open-data platforms for STR | Medium–high (listing-level, periodic snapshots, partial coverage depending on city/platform) | Research, transparency, policy analysis, housing market monitoring | Web scraping (e.g. Inside Airbnb), municipal open-data portals, academic datasets | Listing, neighbourhood, city, |
| Eurostat experimental statistics | Medium (aggregated EU-wide indicators) | Official statistics, policy analysis, comparability | Direct data sharing agreements with platforms | NUTS 2 (monthly), NUTS 3 (annual), selected cities |
| STR registration systems (EU regulation) | Potentially very high (mandatory reporting) | Regulation, taxation, housing policy, transparency | Mandatory platform reporting to national authorities | Listing-level, LAU, NUTS 3, NUTS 2, national |
| Commercial STR analytics platform | Very high (listing-level, pricing, occupancy, revenue, near Real-Time) | Market intelligence, investment analysis, revenue optimization | Web scraping/ API integrations | Listing, neighbourhood, city |

Source: Own elaboration

cities with 200.000 or more inhabitants, and other selected cities with relevance for tourism).

STR registration systems introduced under the new EU regulatory framework represent a significant transformation in the STR data ecosystem. By mandating platform reporting to national authorities, these systems are expected to provide highly comprehensive and reliable data, potentially covering the entire market. Their purpose extends beyond analysis to include regulation, taxation, housing policy and transparency. Importantly, these systems enable multi-level spatial aggregation, from individual listings and local administrative units (LAU) to NUTS 3, NUTS 2 and national levels, thereby bridging the gap between granularity and standardisation.

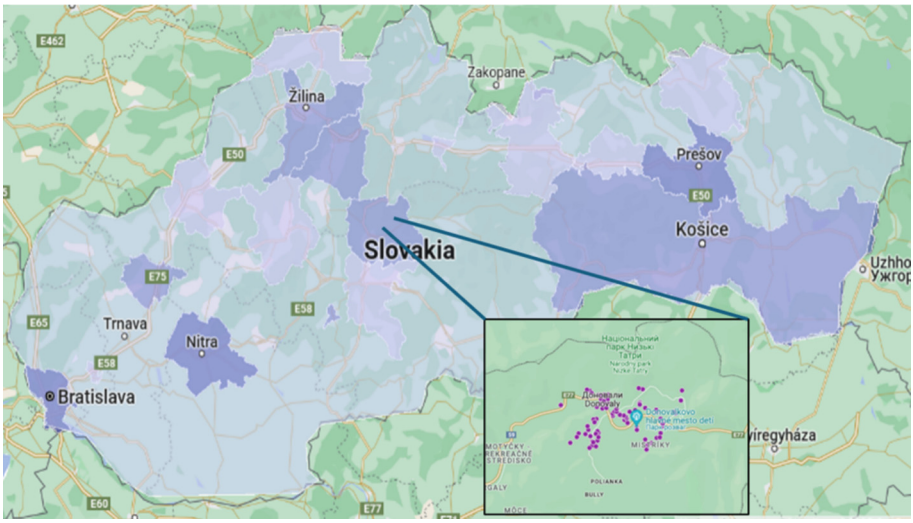


**Fig. 1.** The example of data granularity from AirDNA

So far, the most granular data is provided by commercial STR analytics platforms. Therefore, we illustrate the data availability and comparability of these commercial platforms and national statistics.

### 4.2 Data from National Statistics vs Commercial Platforms

The use of AirDNA as a representative commercial data source reflects the current practice in STR research and data-driven destination management, where platform-derived datasets are frequently employed to complement incomplete official statistics. This approach is particularly relevant in contexts where informal or unregistered accommodation is not captured by statistical reporting systems. By comparing these two data sources (Table 2), the analysis highlights both the added value of high-granularity platform data and the limitations of relying solely on official statistics.

The table presents a comparative overview of short-term rental activity across 24 selected local destinations in Slovakia, where STR listings were identified using AirDNA data. All these tourist destinations have been characterized as having reasonably high visitor demand. An obvious difference exists between both data sets. Statistics provide data on formally registered accommodations that are legally permitted to participate in tourism activities. Formally registered accommodations are required to submit information regarding their tourism-related activities through standardized statistical surveys that are mandatory. By contrast, AIRDNA records all accommodation types available for short-term rental offers via online platforms, regardless of whether these operators are officially registered. As a result, informal or unregistered accommodation providers, who are not included in official statistics, are reflected in the AirDNA dataset.

The comparison reveals that in 20 out of the 24 analysed destinations, the number of accommodation facilities identified by AirDNA exceeds those reported by official

**Table 2.** Comparison of data on accommodation facilities from national statistics and commercial STR platforms

| No. | Destination | Accom. Facilities (Stat. Office) | Accom. Facilities (AirDNA) | Difference (abs.) | Tourism Income (Stat. Office, in thousands of EUR) | Tourism Income (AirDNA, in thousands of EUR) |
|---|---|---|---|---|---|---|
| 1. | Senec | 30 | 51 | 21 | 3 572 | 356 |
| 2. | Nitra | 40 | 92 | 52 | 5 943 | 2 072 |
| 3. | Piešťany | 39 | 122 | 83 | 25 598 | 461 |
| 4. | Trenčín | 41 | 120 | 79 | 4 416 | 448 |
| 5. | Trenčianske Teplice | 27 | 19 | -8 | 10 878 | 109 |
| 6. | Bojnice | 30 | 50 | 20 | 4 167 | 384 |
| 7. | Rajecké Teplice | 24 | 31 | 7 | 5 645 | 285 |
| 8. | Žilina | 47 | 131 | 84 | 5 915 | 838 |
| 9. | Martin | 35 | 109 | 74 | 2 617 | 506 |
| 10. | Banská Štiavnica | 81 | 130 | 49 | 2 883 | 1 079 |
| 11. | Donovaly | 62 | 95 | 33 | 3 506 | 761 |
| 12. | Kováčová | 10 | 4 | −6 | 696 | 33 |
| 13. | Banská Bystrica | 42 | 198 | 156 | 4 560 | 1 151 |
| 14. | Zvolen | 19 | 35 | 16 | 3 146 | 205 |
| 15. | Demänovská Dolina | 104 | 55 | −49 | 21 276 | 544 |
| 16. | Liptovský Mikuláš | 105 | 238 | 133 | 9 832 | 1 680 |
| 17. | Liptovský Ján | 34 | 37 | 3 | 5 225 | 278 |
| 18. | Vysoké Tatry | 210 | 278 | 68 | 39 657 | 3 639 |
| 19. | Poprad | 81 | 179 | 98 | 6 807 | 755 |
| 20. | Kežmarok | 17 | 33 | 16 | 778 | 153 |
| 21. | Spišská Nová Ves | 15 | 22 | 7 | 1 254 | 99 |
| 22. | Prešov | 45 | 82 | 37 | 3 185 | 282 |
| 23. | Košice | 176 | 601 | 425 | 20 889 | 3 722 |

(*continued*)

**Table 2.** (*continued*)

| No. | Destination | Accom. Facilities (Stat. Office) | Accom. Facilities (AirDNA) | Difference (abs.) | Tourism Income (Stat. Office, in thousands of EUR) | Tourism Income (AirDNA, in thousands of EUR) |
|---|---|---|---|---|---|---|
| 24. | Bardejov | 38 | 29 | −9 | 4 245 | 75 |
| **Sum** | | **1352** | **2741** | **1389** | **196 691** | **19 916** |
| **Average** | | **56** | **114** | **58** | **8 195** | **830** |
| **St. deviation** | | **50** | **126** | **92** | **9 405** | **1 013** |
| **Min** | | **10** | **4** | **−49** | **696** | **33** |
| **Max** | | **210** | **601** | **425** | **39 657** | **3 722** |

Source: Own elaboration

statistics. The differences are substantial, reaching up to 425 units in absolute terms (e.g. in Košice). In aggregate, AirDNA identifies 2,741 accommodation units compared to 1,352 recorded in official statistics, resulting in a total difference of 1,389 units. This suggests a significant volume of accommodation capacity that remains outside the scope of official statistical monitoring and in some cases also from official registers of accommodation providers and taxpayers.

A similar pattern is observed in tourism income estimates. While official statistics report substantially higher total revenues, reflecting the inclusion of formal, often larger-scale accommodation providers, AirDNA captures a smaller but non-negligible share of income generated through platform-based rentals, which typically consist of a high number of small-scale units generating lower revenue per unit. The difference between these two types of accommodation illustrates a "volume vs. scale" paradigm in the way that traditional suppliers generate greater revenue through fewer properties and platform based rental property owners do with multiple individual properties. Due to the lack of formal registration, such activity may fall within the grey economy.

The table illustrates the limitations of relying solely on official statistics for understanding the full scope of tourism accommodation supply. At the same time, it also provides evidence of the additional benefits that can be derived from using platform-based data to identify areas within the tourism industry that have not been previously identified as being part of the formal or traditional tourist supply chain. The results show how important it is to use multiple data sets to better understand and manage destinations through more complete and accurate data-driven destination management.

The differences in the definitions and methods of AirDNA versus official sources limit direct comparison, as well as comparisons of listings versus formally registered accommodation establishments, and/or estimates of revenue vs. reported income. Additionally, the lack of clarity regarding how they collect their data and model their outputs makes it difficult for others to reproduce results, which can limit the strength of conclusions drawn from empirical studies. Although AirDNA is a very detailed and valuable

data source, all users should exercise caution when using AirDNA's outputs and combine them with official statistics whenever possible, to allow for a much more complete and accurate study of dynamic behavior in short term rentals.

This limitation can be overcome by new EU regulation. The adoption of Regulation (EU) 2024/1028 on short-term rental data marks a turning point, introducing mandatory registration systems and obligations for platforms to share data with national authorities. This framework is expected to significantly enhance data completeness, accuracy and spatial granularity, enabling access to listing-level information that can be aggregated across multiple territorial levels (from local administrative units to national and EU scales).

It reflects a transition from fragmented, platform-driven data collection towards a more integrated and regulated data ecosystem. This shift has important implications for data-driven destination management, as it improves the capacity of public authorities and destination management organisations to monitor, regulate and strategically manage tourism development.

These results are subject to many limitations that affect the interpretation of these results. As an example, data from platforms (such as AirDNA) is based upon estimates which do not account for all of the short-term rentals. Also, there are issues with how data is defined and collected by different sources. This will impact the ability to compare officially reported numbers with those found through platforms.

## 5 Conclusion

Until now, destination management has relied on a combination of statistics, commercial short-term rental analytics platforms and open-data platforms. The new regulation introduces mandatory registration systems and platform data-sharing obligations, which will significantly improve data completeness and coverage of the entire STR market. A key benefit is the availability of listing-level data, which can be aggregated to LAU, NUTS3 and NUTS 2 levels. DMOs will be able to identify hotspots and spatial concentration of STRs and monitor tourism pressure at neighbourhood level. With access to reliable data, public authorities can enforce registration and compliance, monitor illegal or unregistered rentals, improve tax collection and design targeted housing and tourism policies.

This shifts destination management from reactive to proactive and evidence-based decisions. Improved data availability enables DMO's and municipalities to achieve equilibrium between tourism growth and residential need, limits concentration of STR and supports sustainable tourism development.

This study's findings are also subject to additional interpretations based on the changing role of DMOs as they become embedded into smart data governance frameworks. Recent studies [8, 14] describe DMOs in a more contemporary role than that of merely coordinator/ marketer. They are now described as knowledge actors at the center of destination networks, thus, capable of influencing development outcomes. This inclusion of STR data is a critical component which enables the DMOs to perform their new role.

In addition to functioning as traditional knowledge generators, DMOs are becoming required to perform several other functions including acting as data miners, knowledge

hubs and boundary spanners [8]. Acting as data miners, DMOs can use STR data to identify hidden trends in tourist demand or location specific concentrations of tourist accommodation supply or informal accommodations. Furthermore, by acting as data miners, DMOs can address the previously identified deficiencies in the quality and quantity of available data from official and platform-based sources. Acting as knowledge hubs, DMOs can act as an intermediary to gather multiple types of data sets (commercial, official and regulatory), redistribute this information among relevant stakeholders and enable stakeholders to make informed decisions using empirical evidence. Finally, by acting as boundary spanners, DMOs can link destination systems at the local level with access to external knowledge sources (national statistical offices, digital platforms, emerging European Union regulatory structures). In doing so, DMOs may be able to mitigate some of the data-related challenges they currently experience [8], management related challenges and methodology related challenges.

The observed discrepancies between AirDNA and official statistics highlight the fragmented nature of current data ecosystems, which requires active mediation and interpretation. In this regard, DMOs play an important role in translating data into actionable knowledge, facilitating stakeholder coordination and supporting policy interventions. Moreover, the upcoming EU regulation on STR data further reinforces this transformation by providing more comprehensive and standardized data inputs, thereby strengthening the capacity of DMOs to act as smart leaders in data-driven destination management. Thus, future research should focus on how the implementation of the EU regulation will affect data quality, availability and integration across different sources. The regulation also creates new opportunities for research in data-driven destination management by enabling more precise analyses at the local level.

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## References

1. Barron, K., Kung, E., Proserpio, D.: The effect of home-sharing on house prices and rents: evidence from Airbnb. Mark. Sci. **40**(1), 23–47 (2021). https://doi.org/10.1287/mksc.2020.1227
2. Bei, G.: The spatial effect of short-term rental regulations: the comparison between Barcelona and Paris. Cities **158**, 105603 (2025). https://doi.org/10.1016/J.CITIES.2024.105603
3. Cox, M., & Haar, K.: Platform failures: How short-term rental platforms like Airbnb fail to cooperate with cities and the need for stronger regulations to protect housing. A study by Corporate Europe Observatory (2020). https://corporateeurope.org
4. Dogru, T., Mody, M., Suess, C.: Adding evidence to the debate: quantifying Airbnb's disruptive impact on ten key hotel markets. Tour. Manag. **72**, 27–38 (2019). https://doi.org/10.1016/j.tourman.2018.11.008
5. Dolnicar, S.: A review of research into paid online peer-to-peer accommodation: launching the annals of tourism research curated collection on peer-to-peer accommodation. Ann. Tour. Res. **75**, 248–264 (2019). https://doi.org/10.1016/j.annals.2019.02.003

6. European Parliament and Council of the European Union: Regulation (EU) 2024/1028 on short-term rental data collection and sharing. Official Journal of the European Union (2024)
7. Gajdošík, T., Gajdošíková, Z.: DMOs as Data Mining Organizations? Reflection over the Role of DMOs in Smart Tourism Destinations. In: Computer Science On-line Conference Lecture Notes in Networks and Systems, **228**, pp. 290–299 (2021). https://doi.org/10.1007/978-3-030-77448-6_28
8. Gajdošík, T., Marciš, M., Gajdošíková, Z., Brouder, P.: The role of DMOs in sustainability transitions. A smart network approach. Tour. Recreat. Res., 1–13 (2025). https://doi.org/10.1080/02508281.2025.2598883
9. Guttentag, D.: Airbnb: disruptive innovation and the rise of an informal tourism accommodation sector. Curr. Issue Tour. **18**(12), 1192–1217 (2015). https://doi.org/10.1080/13683500.2013.827159
10. Horn, K., Merante, M.: Is home sharing driving up rents? Evidence from Airbnb in Boston. J. Hous. Econ. **38**, 14–24 (2017). https://doi.org/10.1016/j.jhe.2017.08.002
11. Koster, H.R.A., van Ommeren, J., Volkhausen, N.: Short-term rentals and the housing market: quasi-experimental evidence from Airbnb in Los Angeles. J. Urban Econ. **124**, 103356 (2021). https://doi.org/10.1016/J.JUE.2021.103356
12. Murray, C.K., Sweeney, G., Munday, M.: The sharing economy and urban tourism: evidence from inside Airbnb data. Curr. Issue Tour. **23**(23), 2928–2945 (2020). https://doi.org/10.1080/13683500.2019.1674188
13. Nieuwland, S., van Melik, R.: Regulating Airbnb: how cities deal with perceived negative externalities of short-term rentals. Curr. Issue Tour. **23**(7), 811–825 (2020). https://doi.org/10.1080/13683500.2018.1504899
14. Novotny, M., Dodds, R., Walsh, P.R.: The destination marketing organization as an intelligent agent: evaluating engagement in knowledge management practices. Int. J. Tour. Res. **26**(1) (2024). https://doi.org/10.1002/jtr.2605
15. Pantazi, T., Vlachos, V.: Regulation of short-term rentals: policy responses from Europe. In: Springer Proceedings in Business and Economics, pp. 107–125 (2025). https://doi.org/10.1007/978-3-031-90054-9_8/
16. Wachsmuth, D., Weisler, A.: Airbnb and the rent gap: gentrification through the sharing economy. Environ. Plann. A: Econ. Space **50**(6), 1147–1170 (2018). https://doi.org/10.1177/0308518X18778038
17. Zervas, G., Proserpio, D., Byers, J.: The rise of the sharing economy: estimating the impact of Airbnb on the hotel industry. J. Mark. Res. **54**(5), 687–705 (2017). https://doi.org/10.1509/jmr.15.0204

# Smart, Safe, and Health Cities (SSHC 2026)

# Integrating Computational Design and Space Syntax in Urban Planning and Design Education: A Data-Driven Pedagogical Model

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**Abstract.** Despite the increasing integration of computational tools in urban planning and design education, the structured application of space syntax as a configuration-based organisational framework within urban design studio pedagogy remains underexamined. While computational technologies are widely used for performance simulation and digital modelling, their role in systematically structuring the urban planning and design studio workflow from spatial diagnosis to validated design intervention has received limited focused investigation. This study addresses this gap by proposing a data-driven computational pedagogical model that embeds space syntax within a sequential and iterative studio framework. The aim is twofold: to formalise a reproducible workflow integrating computational procedures into studio education and to examine how algorithmic spatial evaluation enhances analytical coherence and evidence-informed decision-making. The research adopts a multi-phase methodology combining axial analysis, visibility graph analysis (VGA), agent-based simulation, and empirical observations (gate count and behavioural mapping), followed by post-intervention recalculation and statistical validation. The findings revealed that the strengthened social logic of space following the intervention demonstrates not only enhanced spatial coherence, but also the successful integration of algorithmic reasoning into the educational process.

**Keywords:** Computational Design · Urban Design Education · Urban Planning Education · Pedagogical Model · Space Syntax · Didactic Approach · Urban Park

This paper is the result of the joint work of the authors. 'Abstract', 'Results' (with all sub-paragraphs) and 'Conclusion' wrote jointly by the authors. RA wrote 'Introduction'. CG wrote 'Material and Methods' (with all sub-paragraphs). MD wrote 'Discussion'. CG coordinated and supervised the paper.

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## 1 Introduction

Computational design is the use of algorithmic procedures, data-driven modelling, and simulation-based techniques to aid analytical rationale and judgment in spatial design [1]. Computational design in urban analysis goes beyond digital representation to include graph-based models of street networks, metric analysis of spatial configuration [2], visibility calculation [3], and agent-based simulations of movement behaviour [4]. Furthermore, computational design allows designers to evaluate accessibility, connectivity, and behavioural potentials using quantifiable metrics [5]. Urban environments can be studied as physical artefacts and as dynamic, rule-based systems [6], as well as through the prism of performance testing, comparison, and refinement [7]. As a result, computational design is important in mediating between hypothetical spatial concepts and empirical urban phenomena, in support of more stringent and empirically well-founded methodologies of urban analysis [8].

A pedagogical model in studio-based education refers to the framework according to which the process of learning, the development of designs, and the acquisition of knowledge are systematically structured and directed [9]. In the context of urban design studios, a pedagogical model outlines the sequential analysis procedures, describes the connection between theoretical abstractions and their practical implementation, and establishes the evaluative standards used in making design decisions [10]. The model controls how students perceive spatial problems, how they transfer observations of empirical data to strategic proposals, and how they support their design solutions [11]. It is no longer limited to instructional methods; rather, the pedagogical model can serve as a formal architecture of learning that coordinates the interactions of analytical tools [12], empirical data [13], and creative synthesis [14]. As a result, the form of the pedagogical model directly influences the level of reasoning, methodological clarity, and analytical consistency which define the studio setting [15].

The pedagogical models that have been widely researched in scholarly studies in design education comprise reflective practice [16], participatory approach [17], experiential learning [18], and problem-based design [19] models. The issue of integrating digital and computational tools into architectural and urban design studios has been investigated many times, namely parametric modelling [20], gamification [21, 22], and simulation environments [23]. These efforts show an increasing concern with integrating computational thinking into design education. Nevertheless, the systematic implementation of space syntax as a configuration-based analytical concept in the studio setting, despite the growing use of computational technologies, is understudied in comparison. While space syntax has been extensively applied in the study of urban spaces in order to explore spatial configuration [24, 25, 26], equitable socio-spatial accessibility [27, 28, 29], and movement dynamics [30], there has been a dearth of focused research on its application as a pedagogical structuring tool that provides a systematic way of guiding the studio process from spatial analysis to design intervention. This gap shows that the graph-based computational approach, which is also referred to as space syntax, should be treated not only as a form of analytical support, but as an organisational logic that can guide the pedagogy of the urban design studio.

To address this gap, the objective of this study is to create and introduce a systematised data-driven pedagogical framework that incorporates the aspect of computational

design into the learning process of the urban design studio. In particular, the research paper aims to reveal how configuration-based computational tools can be utilised as an organisational guide through the sequential phases of spatial diagnosis, analytical appraisal, and design intervention in a studio setting. The objectives of this study are twofold: first, to codify an executable workflow for the integration of computational processes into the studio process; and second, to investigate how embedded computational processes can be utilised to improve the quality of evidence-based decision-making in student projects.

In this study, computational design specifically refers to the use of space syntax analysis tools. Being a graphical method of computation, space syntax converts spatial arrangements into relational data that is subject to algorithmic mathematical computations to produce measurable indices [31]. It measures urban configuration and the topological relationship between spaces and introduces a methodical approach to assessing spatial performance, as opposed to using an intuitive method alone, which offers a coherent structure for evaluating urban structure and behavioural potential [32].

## 2 Material and Methods

This study adopts a multi-phase methodology: in Phase 1, students conducted an analytical diagnosis through axial analysis (macro-scale configurational assessment using integration and connectivity metrics), micro-scale visibility evaluation using VGA, and empirical observation techniques, including gate counts and static snapshot behavioural mapping. These analytical outputs formed the basis of the students' initial assignments. In Phase 2, students translated the findings into spatial interventions (rearrangement proposals), followed by a reanalysis of both axial and VGA models to assess the impact of proposed modifications. Phase 3 introduced evaluation and feedback, where pre–post comparisons and performance verification were conducted. Building upon these stages, Phase 4 synthesised the structured workflow into the formulation of the computational pedagogical model as a reproducible framework. Finally, Phase 5 positioned the model within a broader academic context through comparison with traditional studio pedagogy and a strategic SWOT analysis. This phased methodology integrates analysis, intervention, validation, and critical reflection into a coherent, iterative research and pedagogical process. These methodological phases are presented in Fig. 1.

### 1.1. *Case Study and Analytical Sub-units*

The case study is the city of Cagliari in Italy and it serves as a testbed in practice by which the computational pedagogical model is put into application and tested. In particular, the case of 'Giardini Pubblici' is chosen as the representative analytical subunit of the projects that were developed in one of the studios because of the completeness of the computational workflow, the consistency of the empirical observations, and the fact that configurational metrics were turned into spatial design proposals, which were clear. The 'Giardini Pubblici' is an old public garden in Cagliari and is a transitional green corridor between the medieval fortified core of the city and subsequent urban extensions of the city. It combines landscaped promenades, axial, terraced, and panoramic visual access routes to the Gulf of Cagliari.

It is architecturally and culturally enclosed and has important civic and heritage attributes, including the *Civic Art Gallery*, and it is also near the *Roman Amphitheatre* and *Buoncammino promenade.* All these characteristics contribute to the twofold nature of the park as a recreational and a cultural intersection in the urban texture. The significance of such green corridors and greenery landscapes within the historic core of Castello neighbourhood has been substantiated in prior studies [33].

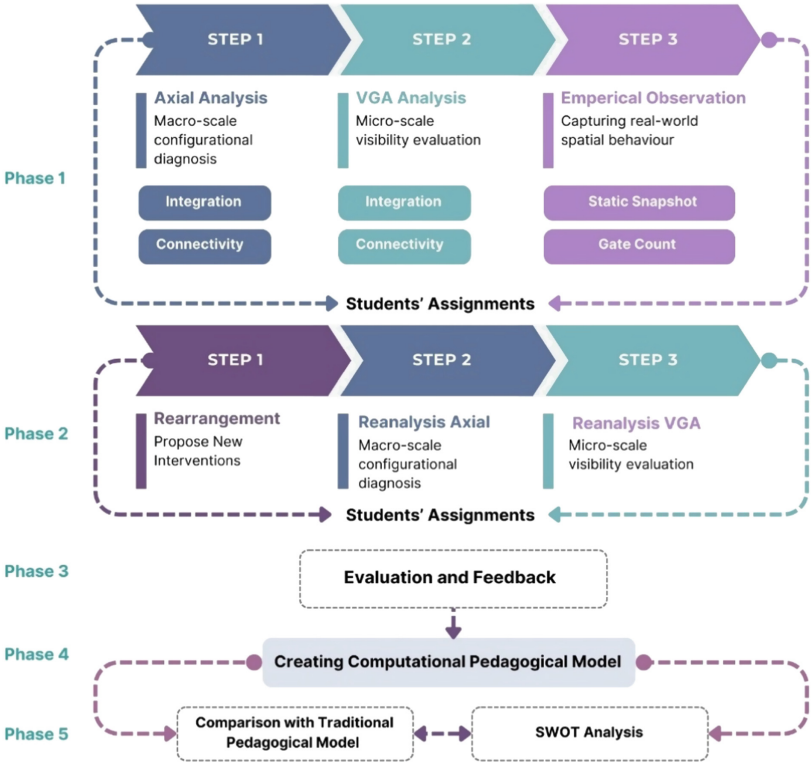


**Fig. 1.** Research method framework illustrating the sequential phases of the study

## 1.2. *Analytical Tools*

This analytical framework of the work is organised into two toolsets that are complementary to each other: (1) space syntax configuration analysis and (2) empirical observation. Although the computational component represents spatial structure and the possibility of movement by algorithmic processes of graphical processes, the empirical component records the observed patterns of use and activity in urban space. Together these tools allow a multi-layered evaluation of the performance of the space to combine the configurational measurements that may be quantified with the field-based mobility data. This two-fold analytical framework constitutes the main methodological premise that the computational pedagogical model is brought to bear in the studio setting.

Space syntax computational processes, which view urban space as a type of relational graph, produce quantitative measures of spatial organisation. Three major analytical tools were used in the workflow of the studio: axial analysis, VGA, and agent-based simulation. DepthmapX was used to implement these tools so as to adhere to consistency in spatial modelling and metric extraction. A combination of these calculation processes formed a range of analytical processes that interrelated macro-scale accessibility, micro-scale visibility, and dynamic movement modelling. The implementation of these tools into the studio allowed testing spatial configurations in measurable indicators before design intervention, which formed the basis of the computational framework of the suggested pedagogical model.

In order to supplement the computational analysis based on configuration, tools of empirical observation were used to record actual movement pattern and spatial utilisation in the sample public space which were chosen. Whereas space syntax represents possibility of behaviour using algorithmic processes, observational techniques describe behavioural manifestations in the same space. The observational part was a combination of quantitative pedestrian flow measurement with qualitative-spatial mapping of activities that made it possible to validate behaviour and put computational results in context.

The intensity of pedestrian flow was quantified by means of a structured gate count method. Each of the public urban spaces had 3–5 the observation gates at their main points of entry within a diameter of 500 m. The choice of the location of gates was guided by street network structure and movement corridors that were expected to be formed as a result of the axial analysis. People who crossed a given observation line at the gates were counted by hand after a predetermined period at every gate. Directional recording of movements was to be used to record inbound and outbound movements. The obtained data produced quantitative flow measures that allowed comparing them with spatial integration and connectivity measures obtained through the network analysis.

### 1.3. *Integration of Computational and Observational Analysis*

The multidirectional nature of computational and observational analysis is built in a progressively and mutually reliant workflow as opposed to separated processes and forms a configuration-behaviour correlation model. On a macro level, the axial integration and connectivity measures have been compared to the data on the number of gates to study the correspondence of the spatial centrality and the observed pedestrian flow. VGA findings at the micro level were superimposed to behavioural mapping outputs to determine the level of correlation between visual integration and movement activity patterns. The agent-based simulations also brought about dynamic modelling which helped to compare simulation movement distribution with empirical data. This cross-validation of spatial potential and actual behaviour was made possible through this multi-layered analytical synthesis, which served as a feedback mechanism in the studio. The combination of configurational measures, behavioural evidence, and simulation results enabled achievement of the process of establishing the design interventions using integrated, performance-grounded analytical foundation, which is the operational centre of the computational pedagogical model.

### 1.4. *Feedback and Evaluation*

This stage was aimed at verifying the spatial effect of the suggested interventions by the students in terms of their systematic reanalysis and feedback. Having prepared rearrangement proposals, which were made by initial configurational and empirical results, the students rebuilt the axial and VGA models in the constant computer parameters. The value of integration and connectivity was re-calculated and compared with the pre-intervention results to evaluate the changes in spatial accessibility, permeability, and structural coherence. This phase served as a performance verification tool, in that, the design choices were not merely justified conceptually they were quantitatively evaluated as well. The repeated comparison between the current and suggested settings formed a feedback-based refinement cycle, ensuring analytic responsibility and, therefore, completing the diagnosis-intervention cycle.

1.5. *Creation of the Computational Pedagogical Model*

This phase formalised the structured studio practice into a coherent computational pedagogical model. The model was abstracted into a reproducible methodological framework based on the sequential and iterative processes followed during the studio, the macro scale analysis, micro scale evaluation, empirical observation, synthesis and validation. This stage passed beyond the output of students and formalised the logic of the procedures that the studio was based on and made it a transferable pedagogical model. This study conceptualises computational analysis as the organisational foundation of the design process, integrating algorithmic rigour, empirical grounding, and model validation into a cohesive educational framework.

1.6. *Model Effectiveness through Comparative and Strategic Assessment*

This phase tested the usefulness of the computational pedagogical model on two levels, the comparative analysis with the traditional studio pedagogy and the systematic SWOT evaluation. The comparison demonstrated the change to intuitively based, critique-based, and performance-proven workflows to a sequential, data-based and performance-validated workflow. The SWOT analysis also analysed internal strengths and weaknesses as well as external opportunities and threats to implementation and scalability. Combined, these evaluations resulted in a critical analysis of the pedagogical worth of the model, its operational viability and strategic applicability in the modern teaching of urban design. This step was used to make sure that the proposed framework did not only exist as the theoretically articulated one, but it was also systematically reviewed with regard to its scholar strength and practical flexibility.

## 3 Results

### 3.1 Macro-Scale Configurational Diagnosis

The axial line analysis of the 500 m diameter around ‘Giardini Pubblici’ is shown in Fig. 2 depicting three configurational indicators, i.e. Integration, Connectivity and Entropy. All these measures indicate the macro-scale spatial organisation of the surrounding street network and its possible impact on the accessibility patterns.

The Integration map (Fig. 2–01) shows the accessibility of the street portions in the given 500 m diameter. Warmer colours (yellow to red) denote streets which are more

integrated and hence more readily accessible by all the other routes within the network whereas cooler colours (blue to green) denote routes which are more segregated or marginal. The findings show that the major street pathways near the study area have a greater value of integration, and they constitute the principal movement routes in the region. Conversely, secondary and inner residential streets lessen the amount of integration, meaning that they lose configurational centrality. The same trends indicate that the park is placed along structurally important routes, which supports its possible accessibility on the wider urban scale.

The number of directly connected axial lines per street segment (Fig. 2–02) is taken as the Connectivity map, which indicates the level of local-level linkage intensity. Warmer-coloured streets have more immediate connections, which means that they are more permeable locally and have more intersections. The analysis exposes that the intersections which are situated along the main streets surrounding the park have a high degree of connectivity and serve as local nodal points to the network. On the other hand, less curvy or cul-de-sac-like segments depict low values of connectivity. With the high connectivity and high integration along specific axes, there are spatial corridors that have a local and global significance in the network structure.

The Entropy graph (Fig. 2–03) shows the level of structural predictability and hierarchy of the street network. A smaller value of entropy (cooler colours) suggests more distinct spatial hierarchy and more differentiation of central and peripheral routes, whereas a large value of entropy (warmer colours) suggests more intricacy and less hierarchical structure of the network. The findings show moderate entropy throughout the 500 m diameter, implying a partially structured network characterised by highly integrated paths alongside more localised segments. The fact that distinctly detectable high-integration corridors are available suggests that the surrounding urban fabric has a readable spatial hierarchy as opposed to an equally complex arrangement.

### 3.2 Micro-Scale Visibility Evaluation

The visibility graph of ‘Giardini Pubblici’ (Fig. 3) is a micro-scale analysis, which demonstrates the visual integration, visual connectivity, and distributes agent-based movement within the park boundary. In contrast to the axial analysis, focusing on macro-scale street network structure VGA analyses internal relationships between spatial permeability and co-visibility and indicates the ways in which the internal organisation of the park forms a visual representation of accessibility and movement opportunities. The visual Integration graph (Fig. 3–01) quantifies the visual accessibility of every point in the park with regard to all the rest of the visible points. Warm colours (yellow to red) signify locations of high visual integration, which convey spatial locations that are centrally located visually and more prone to undergo elevated degrees of co-presence and encounter. Darker colours (blue to green) signify visually segregated or marginalised areas. The findings indicate that the primary longitudinal axis of the park has the greatest value of visual integration, which is its main internal route. The secondary pathways and peripheral green regions have lower value of integration implying lower visual exposure. This measure is especially helpful in determining what may potentially be the objects of social interaction and place of greater visibility, which can determine gathering and passive surveillance patterns. Visual connectivity graph (Fig. 3–02) provides the number of

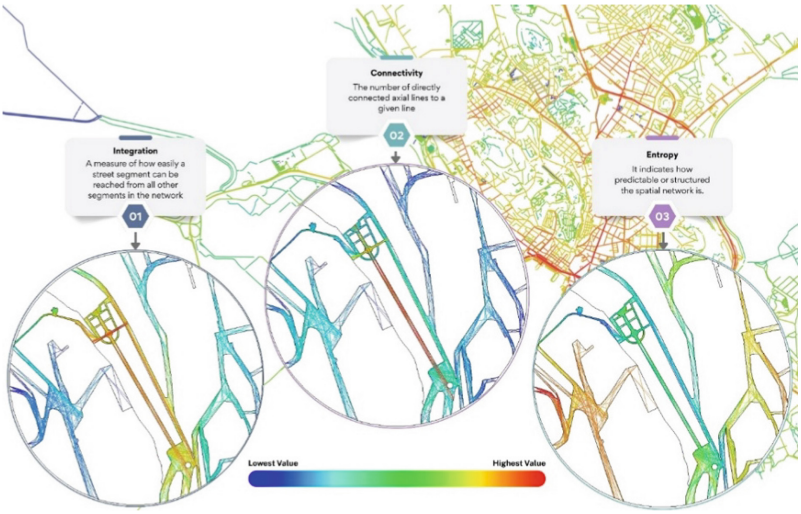


**Fig. 2.** Axial line analysis within a 500 m diameter surrounding 'Giardini Pubblici': (1) Integration, (2) Connectivity, and (3) Entropy. Source: Authors elaboration.

immediately visible points at every point in the park. It is a local permeability of visuals as opposed to universal accessibility. The regions that are better connected depict more visual fields and highly aware of immediate space. It can be analysed that open linear corridors and central intersections will have high connectivity values, whereas enclosed and vegetated areas have low visual connectivity values. This measure is applicable in assessing spatial openness, legibility, and safety perception because the more visual the connection between areas, the more conducive it becomes to succinct orientation and tracing spatial control.

The agent-based simulation (Fig. 3–03) is a model that has probabilistic movement of pedestrians using the underlying VGA structure. The gradient of colour shows spots where there are more agents and less agents throughout the simulation, which approximates the possible distribution of pedestrian density. The findings indicate that the simulated movement is focused along high-integration central axis, and there is moderate accumulation of the agents in the intersection nodes and few in the periphery areas. This dynamic output gives a behavioural projection based on spatial configuration. Notably, the agent distribution graph is a strategic tool that is used to ascertain where the potential areas for walkability will be positioned. In this way, the position of gates may be identified to capture varying degrees of movement by examining high, medium and low simulated agent concentrations. As an illustration, one of the gates can be situated along the transitional area of high agent concentration (high agent density), another in a moderate-density area, and the other in a low-density peripheral region. This makes sure that the empirical flow data reflect different spatial conditions as opposed to dwelling on dominant routes only.

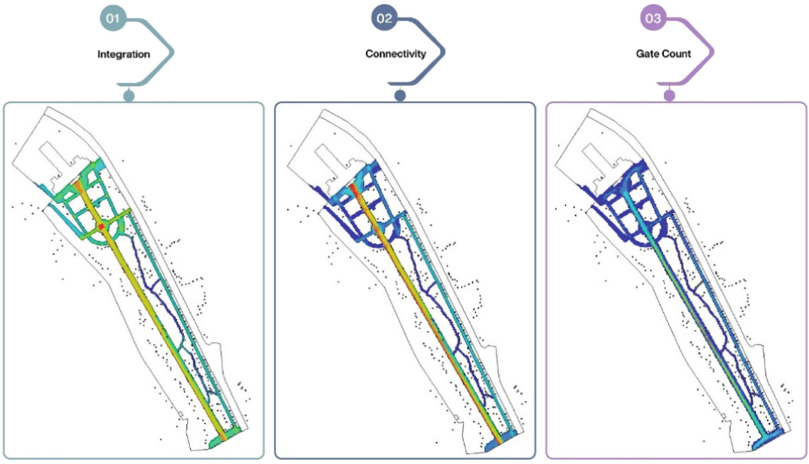


**Fig. 3.** VGA of 'Giardini Pubblici': (1) visual integration, (2) visual connectivity, and (3) Pre-processing of agent-based movement distribution. Source: Authors elaboration.

### 3.3 Empirical Observation

The gate count analysis was performed to measure the level of pedestrian flows at the main access points of 'Giardini Pubblici' in Cagliari. This scheme evaluates the amount of people entering and leaving the park via specific entry points to allow movement distribution and any access route that is mostly used to access the park. There are three main entrances of 'Giardini Pubblici', which were considered as the main gates in this study. These entrances are distributed for space connecting the park with the urban flows of various directions around it. Two planned observation sessions were held so as to give variability of data collection in time. The initial observation was carried out on a weekday (Thursday) at around 11: 00 a.m. on sunny conditions and the other one on Sunday at about 2: 00 p.m. on partially sunny conditions. The duration of stay in each gate was maintained at 15 min where both the inbound and out bound pedestrian movements were recorded. The observations carried out in various times and in diverse environmental conditions made possible comparative analysis with intensity of flowing and offered an understanding of how the temporal and contextual factors can affect movement patterns of pedestrians in the park. Figure 4 shows the outcomes of the observations of the number of gates made at the three main entrances of the park (a) Observation 1 (Thursday, 11:00 a.m.), (b) spatial location of the gates, and (c) Observation 2 (Sunday, 2:00 p.m.). The graphs are used to display the number of pedestrians that come in and out through each gate in 10 min intervals.

The Gate 3 had the highest pedestrian flow during the weekday observation, then Gate 1, and finally, Gate 2 had a relatively low intensity of movement. The inbound and outbound movements were largely equal at Gates 1 and 3, implying a consistent bi-directional circulation. The increased flow at Gate 3 may be attributed to its connection with the *Buoncammino* recreational and historical area, whereas Gate 1 benefits from its proximity to the city centre and the historic core. The gate 2 which is situated on the

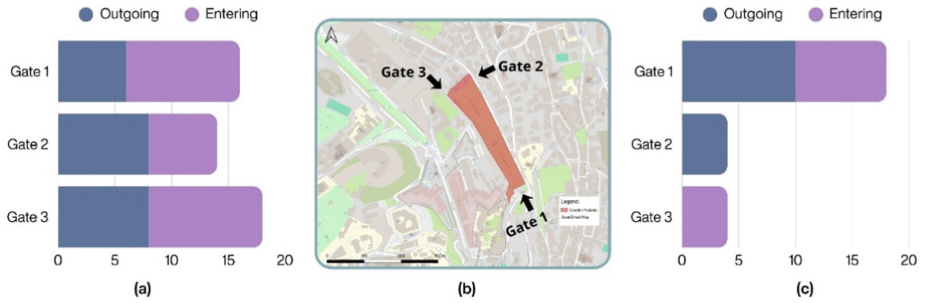


**Fig. 4.** Gate count observation results at the three main entrances of the park: (a) Observation 1 (Thursday, 11:00 a.m.), (b) spatial location of Gates 1, 2, and 3, and (c) Observation 2 (Sunday, 2:00 p.m.). Source: Authors elaboration.

*Viale San Vincenzo* showed average level of activity meaning that it plays a second role in overall park accessibility during the weekdays (Fig. 4a).

The fact that the situation on the weekend is different also shows a clear redistribution of pedestrian flows. The amount of entering movements at Gate 1 is very high than on the weekday session; this is a sign that the movements were more attracted towards the city-centre direction during leisure time. Gates 2 and 3, on the other hand, exhibit a significantly lower intensity of movement, indicating that weekend leisure visits can be better directed towards the southern entrance. The directional imbalance at the gate 1 shown by the larger number of incoming counts than outgoing counts could be the peak arrival times instead of the constant circulation records. The lower flows at the other gates show that there is a time change in the most stable access paths when the circumstances are of the weekend (Fig. 4c).

### 3.4 Synthesis and Design Translation

In the synthesis and design translation phase, the analytical outputs of the computational pedagogical workflow were converted into spatial design strategies systematically. Instead of considering configurational measures and behavioural observations as distinct analytical task, this step meant that they be explicitly incorporated into the design interventions formulation. The students were advised to consider the values of the axial integration, visibility, agent-based move, and the number of gates altogether and use them as their rationale to support the spatial changes, programmatic redistribution, and circulation restructuring. This step was aimed at creating an explicit traceable connection between proposed design solutions and data-driven diagnosis with the purpose of securing that any intervention can be analytically based. By synthesising the above in this structured way, space syntax functioned not just as a form of evaluation, but as an organisational logic through which the transition of spatial analysis to design decision-making is carried out.

Figure 5 demonstrates the results of configurations of the proposed design interventions based on recalculated simulations of integration, connectivity, and agent-based movement. According to the post-intervention integration graph, the central longitudinal axis is reinforced and, at the same time, the accessibility in the secondary pathways

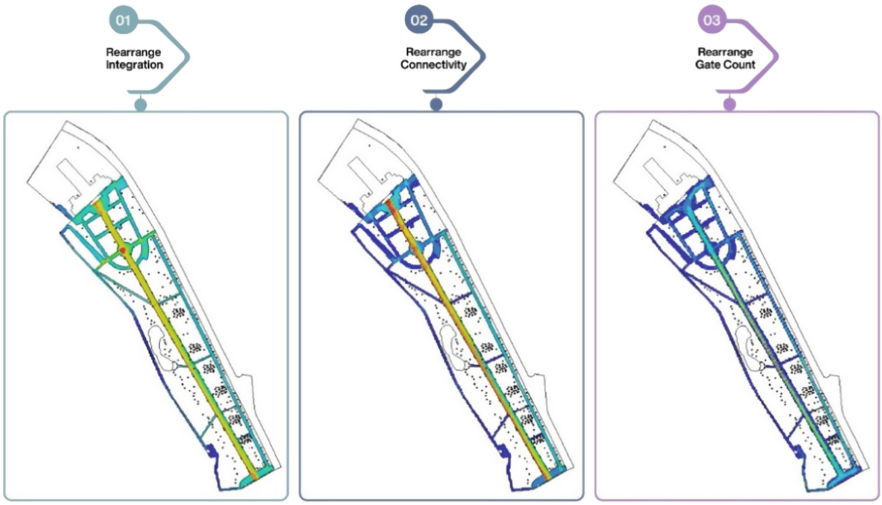


**Fig. 5.** VGA of 'Giardini Pubblici' with new interventions: (1) visual integration, (2) visual connectivity, and (3) agent-based movement. Source: Authors elaboration.

is enhanced. The values of integration are more evenly distributed in comparison with the original condition, and it may indicate improved spatial coherence and a decreased segregation of peripheral areas. The connectivity graph also shows more local connection between the internal paths that had been broken in the past, especially around the recently added landscape elements like the pond and the reorganised circulation paths. These changes enhance transversal interconnections and enhance inter-permeability in the park. The revised agent-based simulation demonstrates a less biased flow of people on the site. Although the central corridor consistently remains as the main pathway, the movement intensity is now stretched out to newly activated space such as ecological corridors and gathering nodes. The redistribution shows that the interventions are effective in reducing the over-concentration along one axis and promoting spatial diversification of use.

The scatterplots of visual connectivity and visual integration of the 'Giardini Pubblici' configuration in the form of (01) existing condition (pre-intervention) and (02) proposed design (post-intervention) are shown in Fig. 6. The points on it are the spatial nodes of the VGA, that is, the visual permeability of the area (connectivity) and the visual accessibility of the entire area (integration). Under the current state (01), the correlation between connectivity and integration will yield strong positive relationship, with the value of $R^2$ of 0.816. This means that the difference in connectivity can be attributed to integration by about 81.6%, indicating a comparatively intelligible spatial structure whereby locally observable regions would be more likely to coincide with accessibly global locations. Nevertheless, the local/global spatial performance is not entirely consistent according to the scatter of the values of the mid-range.

After the suggested interventions (02), the correlation is even better, and the $R^2$ value goes to 0.829. This growth is the sign of a better correspondence between local connectivity and global integration of the internal configuration of the park. The closer

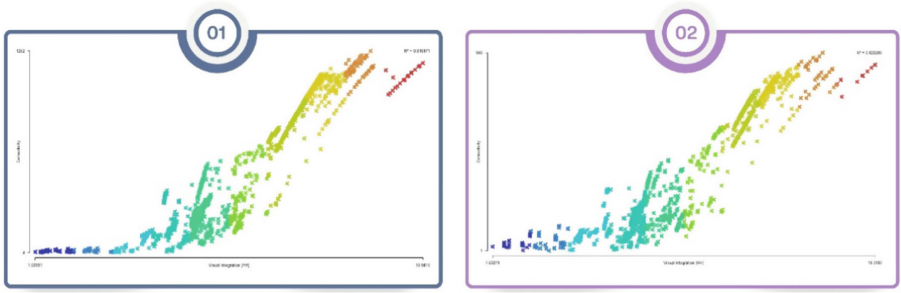


**Fig. 6.** VGA scatterplots, illustrating the correlation between visual connectivity and visual integration: (01) existing configuration (pre-intervention) and (02) proposed configuration (post-intervention). Source: Authors elaboration.

the points are to the regression trend, the greater the spatial legibility; this suggests that high local permeability is accompanied by enhanced visual accessibility throughout these areas. This, in configurational terms, is a more intelligible structurally consistent spatial system. The growth of $R^2$ within the intervention model indicates that the proposed design improves internal logic of the spatial network, which minimises fragmentation and supports the connection between centrality of global networks and visibility at the local level. This statistical upgrade supports the fact that the interventions do not only bring ecological and programmatic improvements, but they also statistically reinforce configurational performance.

### 3.5 Computational Pedagogical Model

The computational pedagogical model in Fig. 7 is a structured, sequential, and iterative workflow of the incorporation of computational spatial analysis into the urban design studio process. The framework starts by configurational diagnosis at the macro-scale level where axial maps are built and integration and connectivity measures are computed to help set up baseline spatial hierarchy and accessibility patterns. These are then followed by micro scale visual analysis through VGA which allows them to determine the internal spatial permeability and configuration in detail. To be able to link computation findings to actual movement and activity patterns, empirical observations such as gate count and statically snapshot behaviour mapping are then added. The synthesis and design translation phase superimposes both computational and empirical outcomes to create spatial interventions that are directly based on analytical evidence. Most importantly, the model ends in an evaluation and iterative validation step where post-intervention measures are recalculated and statistically compared to pre-intervention states which provides a feedback mechanism that allows refinement and performance checks. The two iterative cycles, analysis and feedback, make the studio a closed-loop performance-driven system instead of a linear design process in which diagnosis, intervention, and validation are interdependent computation phases (Fig. 7).

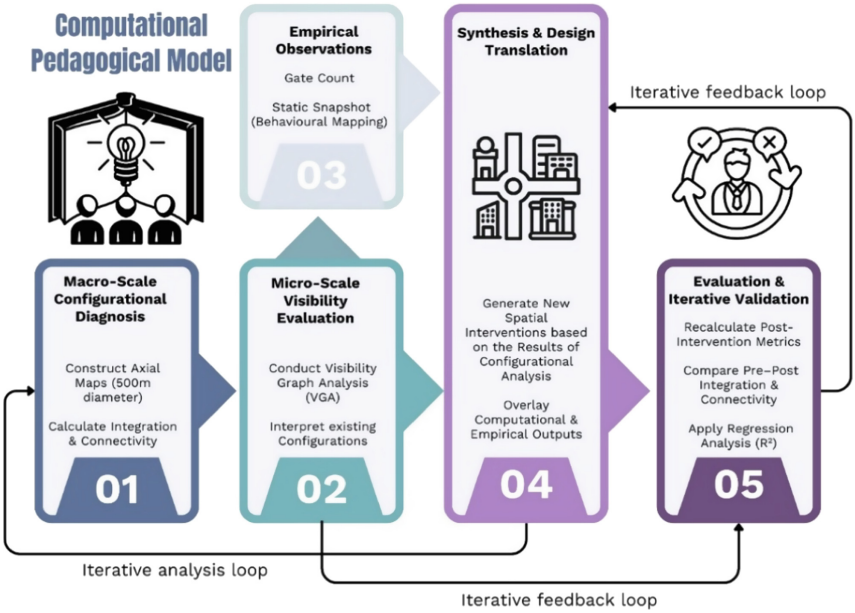


**Fig. 7.** The Computational pedagogical model. Source: Authors elaboration.

## 4 Discussion

The findings described in the current paper prove not just that there are quantifiable changes in spatial organisation and distributions of movements, but, more crucially, that there is a pedagogical significance to framing an urban design studio through the lens of a computational analysis. The gradual reduction in scope (from the macro-scale axial analysis to micro-scale visibility modelling, empirical observation, and statistically validated testing carried out after the intervention) made the workflow between the diagnosis and the design decision-making transparent and traceable. Instead of using intuition and being guided solely by aesthetic arguments, students had to base their proposals on quantifiable spatial signs and behavioural facts. This organised procedure helped to turn computational analysis into a secondary technical practice as well as an organisational rationale for the whole studio. The amplified relationship between connectivity and integration after the intervention demonstrates not only enhanced spatial coherence, but also the success of the integration of algorithmic reasoning into the educational process. In this regard, the pedagogical model transforms the studio from a critique-based format into a data-driven, methodologically explicit learning structure.

A comparison of the computational pedagogical model and the conventional urban design studio indicates a paradigm change in the design education structure and rationale (Fig. 8). The traditional forms of studio are usually based on exploration via intuition, successive critique, and informal decision-making where analytical reasoning is usually tacit as opposed to structured. The development of the design is rather linear, and reviewing is done mainly through qualitative feedback at the stages of the development.

The SWOT analysis reveals that the efficiency of the computational pedagogical model is based mostly on its systematic analysis structure and incorporation of quantifiable validation systems into the studio processes. Even though one has to take weaknesses (such as time constraints, cognitive overload, and the potential for excessive emphasis on quantitative indicators) into consideration, the proposed pedagogical model is operational rather than merely conceptual, and its limitations can be mitigated through systematic guidance and a more balanced incorporation of qualitative factors. These outlined opportunities also enhance the applicability of the model, especially the transferability of the model to studio settings, its ability to complement the new computational technologies and its ability to build stronger research-grounded design education. Although threats like institutional rigidity, lack of computer resources and methodological change resistance are likely to impair implementation, they do not weaken internal coherence of the model. Rather, they emphasise the systemic change that is needed to synchronise the modern design education knowledge with information-driven urban analysis. In sum, the SWOT analysis shows that the pedagogical model is effective, as it methodically aligns analytical rigour, computational validation, and design translation in an iterative process that increases the transparency, accountability, and methodological depth in urban design studios (Fig. 9).

In contrast to recent research in the field of computational and performance-oriented design education, the current study broadens and redefines the function of computational approaches within the urban design studio. Dogan and Yang [34] refer to performance-based urban design education based on climate mitigation, energy efficiency, and mobility modelling, whereas Van Ameijde and colleagues [35] refer to data-driven analytics to connect the gap between research and schematic design to achieve socially sustainable results. In the same manner, Hensel & Srensen [36] and Brown [37] also anticipate performance-oriented and interactive computational environments, which integrate environmental simulation and optimisation in the architectural design procedures. Zhang [38] focused on structured computational tools based on the web, which reduce the barriers to learning and systematise the workflow integration.

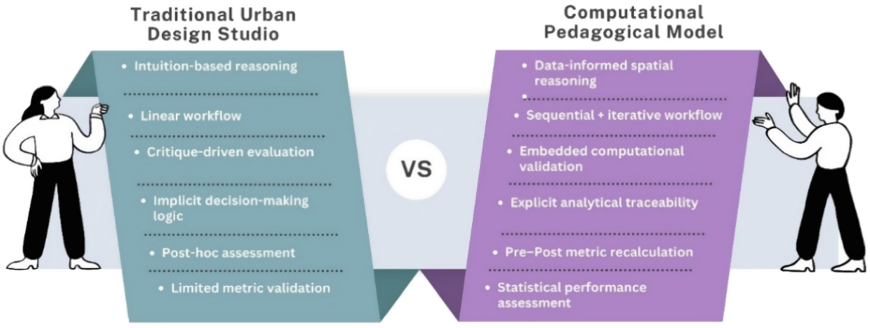


**Fig. 8.** Qualitative comparative analysis between the computational pedagogical model and the traditional urban design studio. Source: Authors elaboration.

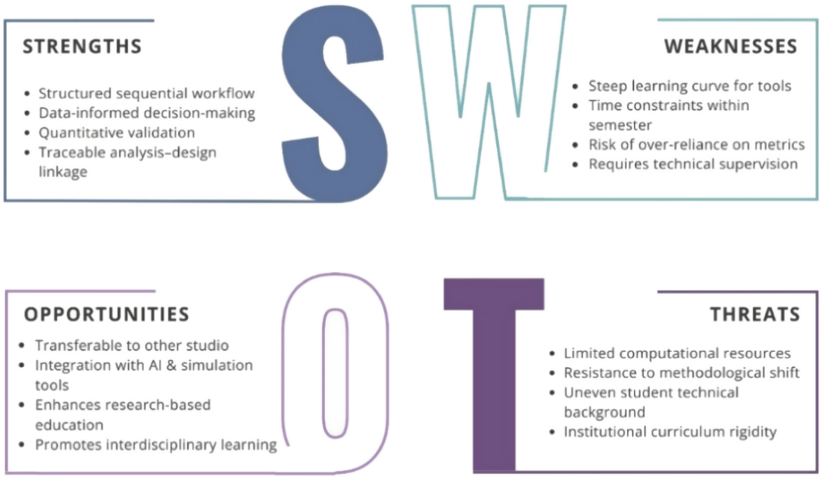


**Fig. 9.** SWOT analysis of the computational pedagogical model, illustrating its internal strengths and weaknesses, as well as external opportunities and threats. Source: Authors elaboration.

Unlike these works, which are mostly focused on performance simulation, integration of tools, ecological awareness, or building technical skills, the current research establishes space syntax as a performance assessment tool but rather as a logic that organises the whole pedagogical process of an organisation. Instead of considering solely the building-scale simulation or generative optimisation, this paper incorporates configurational analysis, empirical observation, and statistical validation in a sequential and iterative studio model at the urban scale. The important contribution here is then the formalisation of computational analysis as a methodological system of closed loop where diagnosis and intervention are to be conducted and validation is to be made, thus making studio pedagogy a temporisation to become a performance-validated and analytically traceable process of urban design.

The main limitation of this study lies in the generalizability of the pedagogical model, as it was tested within a single case study. The next step in research might be to increase the application of the model to a variety of universities and model studio typology to determine scalability and adaptability. The differences in learning outcomes, quality of design and methodological transparency could be further measured by comparative studies using traditional and computationally structured studios. Furthermore, the incorporation of new technologies, i.e., artificial intelligence, real-time city data feed, or parametric optimisation software, could contribute to the increased analytical power and the pedagogical significance of the model. The longitudinal studies of the effect of exposure to computational workflows on professional practice would also be an interesting source of information on the long-term effects of this educational methodology.

## 5 Conclusion

This paper introduced a computational pedagogical framework that reframed space syntax from a supporting analysis instrument into a structuring rationale intertwined with the curriculum of the urban design studio. The originality of the study lies in the formalised configuration-based spatial analysis as a closed-loop methodological system, reproducible as a macro-scale diagnosis, micro-scale visibility assessment, empirical observation, synthesis, and iterative validation through one structured workflow. The first objective of the study was fulfilled by creating and operationalising an analytical sequence which could be clearly defined and was transferable, and which made the procedures transparent and the methods consistent. The second objective was fulfilled by demonstrating how algorithmic spatial assessment, regression analysis, and post-intervention recalculation enhanced the coherence of the analysis and based the design decision-making on quantifiable metrics. Along with its concrete spatial discoveries, this paper also serves as a contribution to the reinvention of urban design pedagogy, proposing a shift from an intuitively based studio culture towards a more performance-and-data-driven and iteratively validated pedagogical paradigm, which would re-focus academic training on the analytical requirements of modern urban practice.

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## References

1. Caetano, I., Santos, L., Leitão, A.: Computational design in architecture: defining parametric, generative, and algorithmic design. Front. Archit. Res. **9**(2), 287–300 (2020). https://doi.org/10.1016/j.foar.2019.12.008
2. Gurcan Bahadir, C.G., Tong, T.: Computational approaches to space planning: a systematic review of enhancing architectural layouts. Int. J. Archit. Comput. 14780771241310215 (2025). https://doi.org/10.1177/14780771241310215
3. Askarizad, R., Garau, C.: Visibility graph analysis vs. human mobility patterns: an empirical validation of simulation-based analysis using space syntax in public squares. In: International Conference on Computational Science and its Applications, pp. 51–68. Springer Nature, Switzerland, Cham (2025). https://doi.org/10.1007/978-3-031-97654-4_4

4. González-Méndez, M., Olaya, C., Fasolino, I., Grimaldi, M., Obregón, N.: Agent-based modeling for urban development planning based on human needs. Conceptual basis and model formulation. Land Use Policy **101**, 105110 (2021). https://doi.org/10.1016/j.landusepol.2020.105110
5. Silva, F., Analide, C.: Computational sustainability and the PHESS platform: using affective computing as social indicators. Futur. Gener. Comput. Syst. **92**, 329–341 (2019). https://doi.org/10.1016/j.future.2018.10.006
6. Karimi, K.: The configurational structures of social spaces: space syntax and urban morphology in the context of analytical, evidence-based design. Land **12**(11), 2084 (2023). https://doi.org/10.3390/land12112084
7. Bibri, S.E.: Data-driven smart sustainable cities of the future: urban computing and intelligence for strategic, short-term, and joined-up planning. Comput. Urban Sci. **1**(1), 8 (2021). https://doi.org/10.1007/s43762-021-00008-9
8. Hillier, B., Leaman, A., Stansall, P., Bedford, M.: Space syntax. Environ. Plan. B Plan. Des. **3**(2), 147–185 (1976). https://doi.org/10.1068/b030147
9. Venkatesh, A., Ma, H.: Tacit knowledge construction in studio-based learning: a conceptual framework. Int. J. Des. Educ. 16(1), 37–53 (2022). http://dx.doi.org/10.18848%2F2325128X%2FCGP%2FV16I01%2F37-53
10. Soliman, A.M.: Appropriate teaching and learning strategies for the architectural design process in pedagogic design studios. Front. Archit. Res. **6**(2), 204–217 (2017). https://doi.org/10.1016/j.foar.2017.03.002
11. Long, J.G.: State of the studio: revisiting the potential of studio pedagogy in US-based planning programs. J. Plan. Educ. Res. **32**(4), 431–448 (2012). https://doi.org/10.1177/0739456X12457685
12. Conole, G., Dyke, M., Oliver, M., Seale, J.: Mapping pedagogy and tools for effective learning design. Comput. Educ. **43**(1–2), 17–33 (2004). https://doi.org/10.1016/j.compedu.2003.12.018
13. Chan, K.K.H., Hume, A.: Towards a consensus model: literature review of how science teachers' pedagogical content knowledge is investigated in empirical studies. In: Hume, A., Cooper, R., Borowski, A. (eds.) Repositioning Pedagogical Content Knowledge in Teachers' Knowledge for Teaching Science, pp. 3–76. Springer, Singapore (2019). https://doi.org/10.1007/978-981-13-5898-2_1
14. Cremin, T., Chappell, K.: Creative pedagogies: a systematic review. Res. Pap. Educ. **36**(3), 299–331 (2021). https://doi.org/10.1080/02671522.2019.1677757
15. Khan, A.R., Thilagam, N.L.: The confluence approach–a theoretical proposition for effective structuring of architecture studio pedagogy in e-learning mode. Open House Int. **46**(4), 510–527 (2021). https://doi.org/10.1108/OHI-11-2020-0158
16. Prakash, P.: Critical learning and reflective practice through studio-based learning in planning and architecture education. Creat. Space **3**(1), 41–54 (2015). https://doi.org/10.15415/cs.2015.31004
17. Torres, J.: Participation as a pedagogy of complexity: lessons from two design projects with children. Urban Des. Int. **17**(1), 62–75 (2012). https://doi.org/10.1057/udi.2011.18
18. Girvan, C., Conneely, C., Tangney, B.: Extending experiential learning in teacher professional development. Teach. Teach. Educ. **58**, 129–139 (2016). https://doi.org/10.1016/j.tate.2016.04.009
19. Cennamo, K., et al.: Managing the complexity of design problems through studio-based learning. Interdiscip. J. Probl.-Based Learn. **5**(2), 5 (2011). https://doi.org/10.7771/1541-5015.1253
20. Alalouch, C.: A pedagogical approach to integrate parametric thinking in early design studios. Archnet-IJAR Int. J. Archit. Res. **12**(2), 162 (2018). https://doi.org/10.26687/archnet-ijar.v12i2.1584

21. Bradecki, T., et al.: Promoting sustainable development of contemporary housing estates. Gamification as an incentive methodology to support urban design. Miscellanea Geogr. Reg. Stud. Dev. **29**(2), 74–80 (2025). https://doi.org/10.2478/mgrsd-2025-0018
22. Poplin, A., et al.: Emotions Geogame: developing a game for mapping emotions and evaluating places. In: International Conference on Computational Science and its Applications, pp. 249–259. Cham, Springer Nature Switzerland (2025)
23. Karadağ, D., Tuker, C.: A proposal for a computational design and ecology based approach to architectural design studio. Int. J. Technol. Des. Educ. **32**(1), 507–532 (2022). https://doi.org/10.1007/s10798-020-09594-x
24. Mohamed, A.A.: Using BERTopic modelling to map the evolution of space syntax research. Land Use Policy **157**, 107639 (2025). https://doi.org/10.1016/j.landusepol.2025.107639
25. Garau, C., Annunziata, A., Yamu, C., D'Orlando, D., Giuman, M.: Investigating the socio-spatial logic of historic urban areas through space syntax: a comparative analysis of the Roman towns Cosa, Nora, Timgad and Thuburbo Majus. TEMA **16**(1), 201–219 (2023)
26. Yamu, C., Van Nes, A., Garau, C.: Bill Hillier's legacy: space syntax-a synopsis of basic concepts, measures, and empirical application. Sustainability **13**(6), 3394 (2021)
27. Russo, A., et al.: Accessibility and mobility in the small mountain municipality of zafferana etnea (Sicily): coupling of walkability assessment and space syntax. In: International Conference on Computational Science and its Applications, pp. 338–352. Springer International Publishing, Cham (2022)
28. Marinelli, L.J., et al.: Accessibility and polarities of pedestrian network in university campuses. A space syntax application. In: International Conference on Computational Science and its Applications, pp. 383–400. Springer Nature Switzerland, Cham (2023)
29. Garau, C., Dastoum, M., Fancello, G.: Developing a methodological framework to assess social equity in regional spaces through the lens of space syntax. In: Gervasi, O., et al. (eds.) Computational Science and its Applications – ICCSA 2025 Workshops. LNCS, vol. 15897, pp. 215–230. Springer, Cham (2025). https://doi.org/10.1007/978-3-031-97660-5_16
30. Karimi, K., Zhand, S., Simons, G., Abdeldayem, W.S., Charalambous, N., Giraud, I.: Framing evidence-based design and planning: an analytical, multi-scalar and iterative framework for Urban Design and planning. Urban Sci. **9**(11), 457 (2025). https://doi.org/10.3390/urbansci9110457
31. Hillier, B.: Space Is the Machine: a Configurational Theory of Architecture. Space Syntax, London (2007)
32. Hillier, B., Hanson, J.: The Social Logic of Space. Cambridge University Press, Cambridge (1984). https://doi.org/10.1017/CBO9780511597237
33. Garau, C., Askarizad, R., Pinna, F.: Urban governance to support adaptable solutions for conversion of residual street spaces into social spaces. Sci. Rep. **15**(1), 32241 (2025). https://doi.org/10.1038/s41598-025-16569-2
34. Dogan, T., Yang, Y.: Computational urban design: a simulation and data-driven approach to designing a sustainable built environment. In: Teaching Carbon Neutral Design in North America, pp. 274–290. Routledge, London (2025)
35. Van Ameijde, J., Cheng, S., Wang, H.: Integrating urban analytics into postgraduate urban design pedagogy: a mixed-methods teaching approach to addressing urban liveability. J. Plan. Educ. Res. **44**(4), 2350–2363 (2024). https://doi.org/10.1177/0739456X231162842
36. Hensel, M.U., Sørensen, S.S.: Intersecting knowledge fields and integrating data-driven computational design en route to performance-oriented and intensely local architectures. Foot **8**(2), 59–74 (2014). https://doi.org/10.7480/footprint.8.2.812

37. Brown, N.C.: Design performance and designer preference in an interactive, data-driven conceptual building design scenario. Des. Stud. **68**, 1–33 (2020). https://doi.org/10.1016/j.destud.2020.01.001
38. Zhang, B., Mo, Y., Li, B.: Web-based computational design tools for architectural design studio: enhancing pedagogical framework. Nexus Netw. J. **27**, 663–680 (2025). https://doi.org/10.1007/s00004-025-00826-y

# Associations and Public Facilities as Infrastructures of Slowness. Proximity and Sociality at Neighbourhood Level

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**Abstract.** In the context of spatial, functional and relational proximity, slowness is a strategy that may enhance the neighbourhood scale. Relational proximity is investigated through social infrastructure, consisting of third sector organisations and public services, which are essential hubs of community connection. The contribution aims to understand the role of these relational actors and their impact on the consolidation of interpersonal relationships, to create a "slow" neighbourhood. The research is part of a collaboration with Cittaslow International, promoter of the slow model, and studies the experiences implemented within the project Cittaslow Metropolis to identify best practices and possible applications for the San Leonardo neighbourhood in Parma. Through spatial analyses and semi-structured interviews with local organisations, relational proximity has been assessed, highlighting how social infrastructure guides the use of public spaces, strengthens proximity networks, and promotes cohesion. In this framework, the social infrastructure emerges as a relevant pillar of slow urban regeneration at the neighbourhood level.

**Keywords:** Slow neighbourhood · proximity · social infrastructure · association · public facilities

## 1 Introduction

In an urban context dominated by speed, productivity, efficiency and global competition, adopting "slowness" as a collective vision of urban regeneration might appear to be a structural paradox or a disciplinary provocation. Traditionally associated with small villages and rural centres, slowness has sometimes been interpreted as a nostalgic desire to slow down the pace of urban life. The globalisation framework, in which people work harder, live faster, produce and consume more, allows speed to shape economic life and the social, cultural and environmental dynamics of the cities [1, 2]. In response to this situation, the concept of urban slowness is investigated.

This contribution engages with this tension through a collaboration between the University of Parma and the Cittaslow International association. Within the framework agreement, the interdisciplinary group, which includes the Urban and regional planning

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unit, is working on two research lines: the identification of action models and good practices at the local level for updating the accreditation criteria for cities with up to 50,000 inhabitants (the network's historical target) and the definition of criteria for the Cittaslow Metropolis project, aimed at accrediting neighbourhoods in medium and large cities. For the second line, a pilot project is underway in the San Leonardo neighbourhood of Parma.

Cittaslow International association promotes slow living as an opportunity to enjoy solutions and services that enhance quality of life. The slow city, formalised in 1999 by Cittaslow, is the "city of good living" where «the best of the past is extrapolated and enjoyed thanks to the best possibilities of the present and the future». This results in a city where «human beings are still the protagonists and enjoy the time they have rediscovered through local products, good food, traditions, landscapes and the joy of a slow and peaceful life» while at the same time leveraging «technological opportunities and modern solutions in communication, transport, incoming tourism, production and sales» [3]. The Cittaslow movement, therefore, aims to promote more liveable environments, preserving local traditions and cultures, and encouraging a slower, more human-centred urban lifestyle [4]. The movement is considered both an urban social movement and a model for local governance [5]. It involves some management goals, including increasing the quality of local life, maintaining the local distinctiveness and supporting sustainable city economies with a focus extending beyond local production and food quality [6]. «First and foremost, a Cittaslow is a community of citizens that looks after and cares for each other...and stimulates social cohesion between the citizens» [7]. The growing diffusion of the network is confirmed by the 308 member cities in 33 countries in 2025 [8–18].

Cittaslow Metropolis aims to extend slow principles to neighbourhoods within medium and large -sized cities to explore new approaches to urban regeneration [19, 20]. The programme addresses global urbanisation trends: by 2030, approximately 70% of the world's population is expected to live in urban areas with significant implications for resource consumption and infrastructural pressure. Metropolitan areas are dealing with challenging issues due to expansion to unprecedented scales and continuous in-migration [21]. In this framework, applying slow principles to metropolitan areas is proposed as a strategy to address challenges related to urban sustainability and quality of life [22]. The programme, launched 15 years ago, has encouraged pilot experiences in the cities of Antalya, Barcelona, Brussels, Busan, Izmir and Taipei [23, 24].

The small city's accreditation consists of 73 criteria based on policies: energy and environment; infrastructure; quality of life; agriculture, tourism and crafts; hospitality, awareness and training; social cohesion; partnerships [25]. The Metropolis programme, however, has no formalised guidelines or a certification system, so pilot neighbourhoods have identified some requirements based on slow principles including evidence-based civic engagement, integration and social benefit through interaction, responsible use and protection of resources and a broader slow philosophy [3, 24].

Beyond adopting the concept promoted by Cittaslow, is the idea of slowness can also be reinterpreted through the lens of proximity. This theme is particularly relevant at the neighbourhood level, since it is precisely at this spatial scale that proximity has the

greatest impact. Moreover, in recent years, the theme of proximity has been at the centre of urban debate due to its applicability within the "15-Minute City" model [26–30].

In Italian cities, the neighbourhood is already traversable within a 15-min walk or bike ride [31]. In this sense, the application of slowness is favoured at this scale by pre-existing forms of spatial, functional and relational proximity that enhance the quality of life in terms of psychological, physical, social and equitable well-being, offering more opportunities for consolidating a slow model. The discussion about proximity requires interpreting the neighbourhood as a place in which effectiveness depends on a multidimensional integration of spatial, functional and relational aspects, instead of a merely administrative unit [32].

Through improved movement quality, spatial proximity can promote active mobility and improve healthy lifestyles and safe conditions for users; it can also reduce car dependency, fast mobility, traffic and environmental and noise pollution [33–37]. Functional proximity, in parallel, can enhance the quality of local spaces through accessibility to public spaces, facilities and economic activities within walking or cycling distance. As reported by literature, these aspects may contribute to reducing stress levels, improving mental and physical health, fostering feelings of happiness and satisfaction, and strengthening local economy [31, 38–42]. Relational proximity based on social infrastructure — mainly consisting of spaces that encourage social ties (e.g., gathering places, places of worship and public spaces) — may create opportunities for social interaction and enhance quality of relations. Interactions, memories and experiences, daily routines, recurring encounters, informal networks and social practices may enable cohesion, cooperation, civic engagement, identity and belonging to the neighbourhood, enhancing well-being and improving quality of life [43–54]. In this sense, the idea of slowness, articulated into three interrelated dimensions — spatial, functional and relational proximity — pursues happy, healthy and safe cities' goals.

Infrastructure and associations can contribute to the production of social capital only if communities actively engage with them; thus, social relations are fundamental to spatial development [55, 56]. From this perspective, slow model should be based on social infrastructure and everyday practice, as these foster accessibility and proximity.

This contribution focuses, in particular, on the relational dimension of proximity and on how to translate relational proximity into operational urban planning criteria based on slowness. The aim is to investigate the role of social infrastructures, such as third sector organisations and public facilities of collective interest, understood as relational anchors within a distributed neighbourhood network.

To this end, the San Leonardo neighbourhood in Parma — selected as a pilot to investigate the slow neighbourhood characteristics within the Cittaslow Metropolis project - is examined in detail. Section 2 therefore introduces the case study of San Leonardo; Sect. 3 describes the materials and methods used in the study and the corresponding results; Sect. 4 develops a discussion of the results obtained; and finally, Sect. 5 presents concluding remarks and possible future developments.

## 2 Case Study: San Leonardo Neighbourhood in Parma

In terms of relational proximity, the San Leonardo neighbourhood, despite its various internal contradictions and vulnerabilities, offers a rich network of third sector organisations and public facilities with significant potential to empower local communities and social interactions. Moreover, this neighbourhood occupies a central role in the urban policies promoted by the Municipality and has been identified as a priority area for research by the University of Parma in light of the neighbourhood's cultural identity, the needs expressed by the local community, social security and urban voids leaved by deindustrialisation [57, 58].

It is a residential neighbourhood of 4 $km^2$ with 20,000 residents and an average age lower than that of the city. It has historically been linked to the productive sector, due to the presence of the railway station, and developed as a working-class area associated with employment in the *Bormioli* glass factory and other industrial activities. In recent years, however, San Leonardo has experienced the settlement of new, younger, and multi-ethnic communities. Regarding open spaces, most parks are equipped with playgrounds, football fields and picnic areas, thus enabling outdoor events during the summer. Schools also provide afternoon and evening activities and host performances and meetings in their spaces. Churches, likewise, support community life by organising scout groups and summer camps.

Furthermore, the social infrastructure consists of organisations, associations, social cooperatives, neighbourhood committees and informal groups that are active in social, cultural, urban and environmental issues and promote initiatives including meetings, open-air cinema and community walks. Several community spaces, among which the *Officine ON/OFF*, the *Lenz* foundation, the *Casa del Quartiere* and *Al-Amal*. Neighbourhood meetings are also held, reflecting a strong propensity for active participation. The former *Bormioli Rocco* factory covers a considerable area; accordingly, the *Amici della Biblioteca San Leonardo* association has proposed transforming it into a cultural centre. In parallel, retired employees of the *Bormioli Rocco* and the *Bormioli Luigi* factories have established the *Medaglie d'Oro Bormioli Rocco* association to preserve the neighbourhood's industrial memory. Currently, the *Green in Parma* desealing project attracted citizen participation which demonstrating civic interest in improving the design [59, 60].

## 3 Materials and Methods

### 3.1 Cittaslow International and Cittaslow Metropolis' Approaches

Initially, the literature on Cittaslow International and Cittaslow Metropolis programme has been analysed to assess whether relational proximity and social policies play a relevant role in neighbourhood implementation.

The following case studies focus on local experiences in Cittaslow International. Mayer & Knox present some European case studies focusing on quality of life, by examining it through attributes of places (housing conditions, morbidity and mortality rates, educational attainment, income levels, the incidence of crime) and community-based services, amenities and opportunities [61]. In Hadong-gun and Busan (South Korea), participation in community life has been assessed through indicators such as

the quality of civil affairs administration services, satisfaction with social services, the perceptions of local politics and autonomy and the satisfaction with opportunities for civic participation [62]. The case of Grumes, Italian Alps, explores how social networks and infrastructure activate interaction. Several initiatives rely on voluntary engagement and the creation of a social centre led to the formation of a theatre association. Such developments highlight how spaces may foster relational dynamics and territorial capital formation [56]. Goolwa's communities (Australia) and the residents of Gökçeada (Turkey) reported a positive impact of Cittaslow principles on collaboration, mutual recognition among actors, active community engagement in local events, community garden projects and the promotion of local identity [63, 64]. Cittaslow towns in the Warmia–Mazury province (Poland) developed new public spaces integrating social and cultural functions into green spaces [65]. In Semarang (Indonesia), Chinatown conservation has been implemented through community events selected through a SWOT analysis. This process has led to regular scheduling, effective event management, strong branding, active community engagement and a collaborative organisational structure [66].

The following analysis examines the experiences of Cittaslow Metropolis. In Seferihisar (Turkey), local associations and the municipality promoted Cittaslow initiatives, such as awareness campaigns and assemblies open to residents, and structured welfare around facilities, number of beneficiaries and allocated staff and budget [67]. Kucukergin & Ozturk show the transformative capacity that social infrastructure possesses but this process appears to resemble gentrification [4]. Cittaslow's involvement in the Perşembe district of Ordu (Turkey) has led to a greater availability of local food, an increased promotion of cycling and a reduction in vehicle noise pollution [68]. In Izmir (Turkey), Pazaryeri and Demirköprü neighbourhoods promoted active resident involvement and rooted interventions in local needs analysis, tried to adapt slow principles to the neighbourhood and improve living conditions [69, 70]. Furthermore, narrated walks explored the sensory dimension related to safety, climatic and acoustic comfort and enhanced interaction [71, 72]. The Cittaslow Metropolis project in Rome's *rione Esquilino* seeks to reshape the neighbourhood's narrative and to improve quality of life by organising events and promoting participatory governance among public and private actors and the territorial DMO [73]. In this context, its location between the historic centre and *stazione Termini* has helped highlight places overlooked by tourist routes.

### 3.2 Social Infrastructure in the San Leonardo Neighbourhood

In a second phase, the methodology (Fig. 1) combines expert and situated knowledge to develop a comprehensive understanding of the neighbourhood. Institutional sources were first consulted, including the Geoportale Emilia-Romagna, the Comune di Parma (SIT Parma) and the RUNTS (Registro Unico Nazionale del Terzo Settore), which provided data forming the technical basis of the analysis [74–76]. These data were integrated with prior knowledge of use, function, mobility and accessibility of San Leonardo and organised within a GIS database. RUNTS data were also cross-checked through site visits, semi-structured interviews with local actors, associations, social cooperatives

and informal groups, as well as a review of their websites and social media. To understand how social infrastructure influences neighbourhood-scale proximity in slow neighbourhoods, a GIS database with georeferenced data was developed. The public facility shapefile includes attributes such as typology, use, accessibility while the shapefile of third-sector organisations includes attributes such as organisational typology, location, opening hours, activities, services, projects and events. This dataset enabled the mapping of social infrastructure and the analysis of relational proximity among services, actors and the community. The approach supports the identification of strategies and best practices for defining a slow neighbourhood model aimed at enhancing social cohesion and local resources.

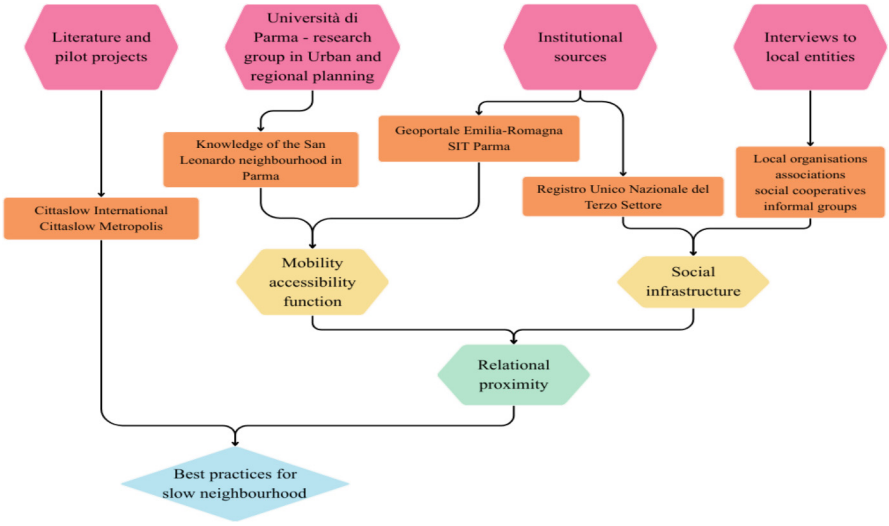


**Fig. 1.** Methodological process (authors' elaboration).

Semi-structured interviews with local actors were conducted following qualitative research practices commonly used in urban regeneration and community-based studies [77–79]. Among the local organisations interviewed were associations, social cooperatives, neighbourhood committees and informal groups, from which qualitative data were collected. The interview protocol included 22 questions organised into 7 thematic areas that enabled an understanding of the opportunities offered by social infrastructure — such as care, educational activities, environmental initiatives and community-building programmes — and their contribution to the San Leonardo neighbourhood (Table 1).

The interviews carried out have enabled a deeper understanding of the social infrastructure. The *ANCeSCAO* association focuses on active ageing and support for the elderly and other vulnerable groups, providing digital helpdesk, free transport, social tourism and prevention initiatives. The *Amici della Biblioteca San Leonardo* association aims to create a cultural centre, with the aim of promoting cultural and historical promotion, science initiatives and collaborations with schools. The *Fiorente* social cooperative provides services for people with disabilities and promotes social inclusion through

**Table 1.** Structure of the interview (authors' elaboration).

| Sections | Questions |
|---|---|
| Role in the neighbourhood | 1. What is the history of your association?<br>2. How many members do you have and what is your organisational structure?<br>3. What is your main mission in relation to the neighbourhood?<br>4. What are the main activities you carry out in the neighbourhood?<br>5. Where do these activities take place?<br>6. What are the main issues you have noticed in the neighbourhood and how can you contribute to resolve them? |
| Citizen participation | 7. How many residents ad citizens participate in the activities?<br>a. How easy or difficult is it to involve the residents of San Leonardo?<br>b. Did participation in the activities meet or fall short of your expectations?<br>c. Were the activities successful?<br>d. What is the impact of your activities on citizens?<br>8. When you involve the local community, what obstacles do you encounter and how do you try to overcome them?<br>a. How do you encourage citizens to participate in your activities?<br>b. How do you deal with the lack of participation or citizens' indifference?<br>c. How do you reach who do not participate in community life? |
| Collab. with organisations | 9. Do you work with other neighbourhood's associations/groups? If so, how?<br>10. Are there any projects underway/planned with other local organisations? |
| Collab. with institutions | 11. What is your relationship with local institutions?<br>a. Have you ever collaborated with them on specific projects?<br>12. Do you receive institutional support for your activities or projects?<br>13. How do participation processes with the institutions take place? |
| Future of the neighbourhood | 14. How do you see the neighbourhood evolving in the coming years?<br>15. What are your hopes or fears regarding future changes?<br>16. What role your organisation will play and what opportunities may arise for it in the future of the neighbourhood? |

(*continued*)

**Table 1.** (*continued*)

| Sections | Questions |
|---|---|
| Urban regeneration | 17. How important physical transformations and social/cultural activities are for the neighbourhood?<br>18. What regeneration strategies are most urgent for the neighbourhood?<br>19. Have you had any direct experience with urban regeneration projects? If so, what were the main challenges and results?<br>20. How do you see your role in urban regeneration processes?<br>21. How might your role evolve in a participatory regeneration process? |
| Conclusion | 22. Is there anything we haven't covered that you think is important to share? |

work, interaction and training activities. It works with associations, schools, businesses and institutions. The *Lenz* foundation is active in contemporary experimental theatre and organises theatre productions, artist residencies, workshops and social inclusion projects. The *Manifesto per San Leonardo* group, although not formally registered, was formed to oppose the opening of *via Ravenna.* The group highlights issues in the neighbourhood and proposes solutions on topics including safety, transport, environment and urban planning. Some group members founded *Urban Trail Parma*, an urban walking initiative to discover the neighbourhood. *Officine ON/OFF* is a space dedicated to social innovation and youth entrepreneurship that hosts co-working spaces, a *Fablab*, courses, workshops, events and activities with educational facilities. The interviews highlighted an active network of organisations promoting social, cultural and community support initiatives. They also reported concerns regarding perceived safety, urban decay, loss of local businesses and social changes due to deindustrialisation. Many interviewees believe that the neighbourhood's future should be built on both spatial transformations, including the regeneration of derelict industrial spaces and the realisation of meeting places, and initiatives to foster citizens' participation and reinforce relationships between associations and institutions. In particular, the former *Bormioli* site could become a new urban node.

To identify the formal and informal meeting places where people may socialise or engage in other activities, spatial data relating to green open spaces and public facilities – such as schools, places of worship, sports facilities, cultural venues and healthcare facilities – have been cross-referenced (Fig. 2).

In the neighbourhood, social infrastructure is well-developed and it consists of organisations, associations, social cooperatives, schools, churches, neighbourhood committees and informal groups. The majority of these actors have their headquarters in *Casa del Quartiere*, located in the north-west of the neighbourhood, but *Officine ON/OFF* also hosts many associations and initiatives (Fig. 3).

Figure 4 shows the opportunities offered by social infrastructure: assistance, consultancy, culture, education, game and sport, identity, neighbourhood projects, politics, religion, safeguarding and sociality. The circles on the map represent the concentration

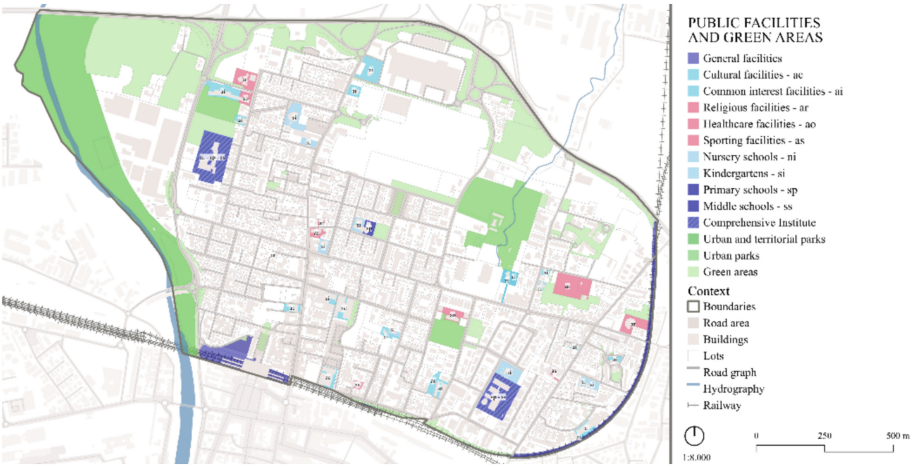


**Fig. 2.** Public facilities and green areas (authors' elaboration).

of activities available at each headquarter without distinguishing between the organisations that provide them. The north-west area is the most well-served area and sociality, culture and assistance are the most common opportunities.

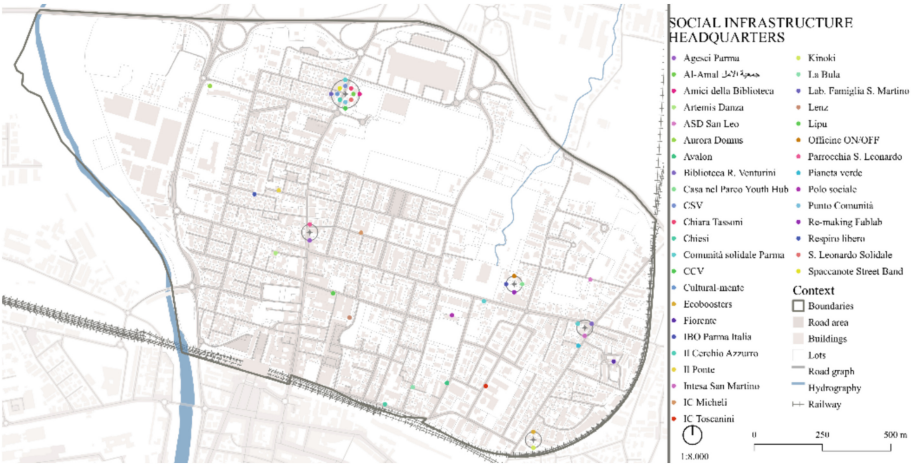


**Fig. 3.** Assessment by location of opportunities offered by social infrastructure (authors' elaboration).

In terms of initiative diversity, Fig. 5 highlights numerous activities targeting different age groups: up to 15 years old, 16–30, 31–50, 51–75 and over 76. Opportunities for users aged 16 to 50 are the most prevalent but, overall, the offering is varied across all age groups and the highest concentration of opportunities is found at *Casa del Quartiere*, *Officine ON/OFF* and *Biblioteca sociale Roberta Venturini.*

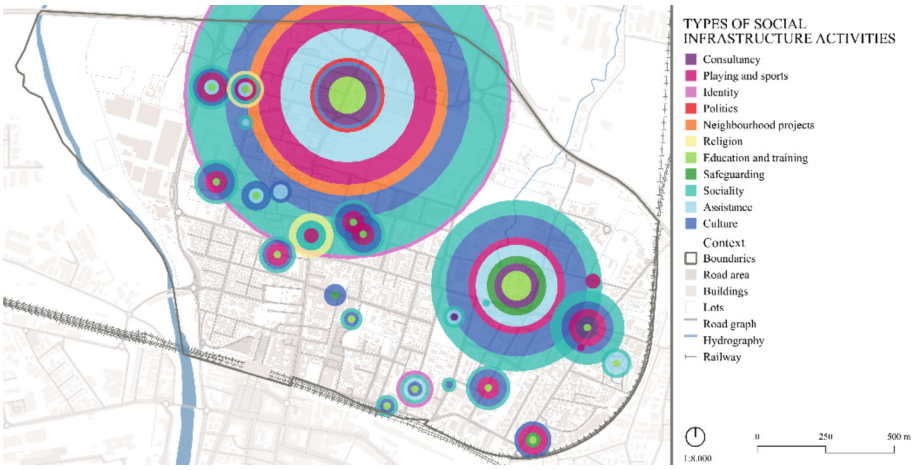


**Fig. 4.** Assessment by type of opportunity offered by social infrastructure (authors' elaboration).

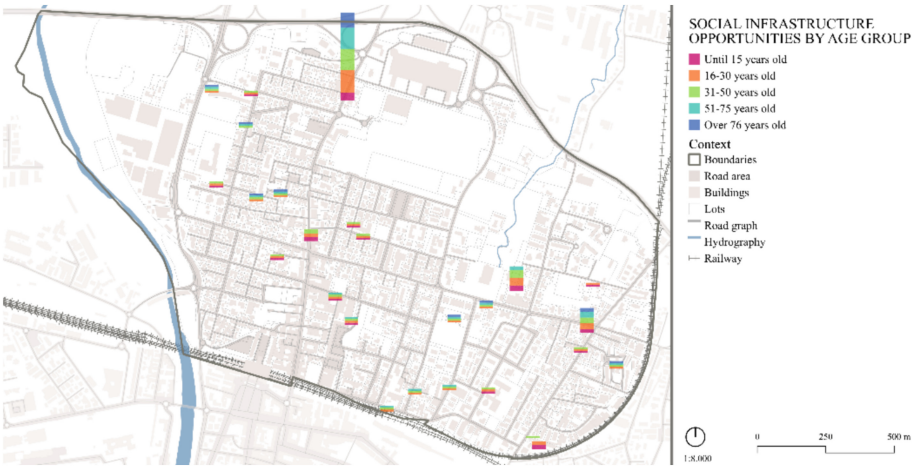


**Fig. 5.** Assessment by age group of the opportunities offered by social infrastructure (authors' elaboration).

## 4 Discussion of the Results

According to the maps, there is a dense network of social infrastructure that is essential for fostering relational proximity and enabling people to spend quality leisure time. The north-western area of San Leonardo is the most accessible due to the concentration of social infrastructure at *Casa del Quartiere* however, interviews revealed that spaces are inadequate to host activities. For this reason, many initiatives have been relocated to school facilities and *Officine ON/OFF*. In this sense, the effectiveness of social infrastructure is constrained when relational demand exceeds the availability of space. This configuration reveals a differentiated geography of relational proximity, characterised

by hybrid spaces where activities converge and urban areas that are less frequented and fewer opportunities for encounter. Regarding inclusion, it is noted a good variety of opportunities aimed at different age groups; however, their higher concentration for people aged 16 to 50 years old highlights the importance of a balanced provision.

It also has been noticed that social infrastructure affects neighbourhood life differently: open public spaces foster informal ways of social interaction, whilst public facilities and local organisations activate more structured forms of participation, gathering citizens together around specific needs or interests. This distinction suggests that relational proximity, rather than as a homogeneous effect of spatial presence, is the result of different forms of social activation. Moreover, social infrastructure is not sufficient to guarantee improvements in quality of life as it depends on both spatial distribution and the capacity of actors to sustain relationships.

The results also suggest that social infrastructure supports participatory processes and helps communities to adapt to changes. In fact, urban transformation processes may lead to exclusion or gentrification rather than regeneration. Moreover, social infrastructure and citizens may help inform planners about neighbourhood needs and propose opportunities [80].

The criticalities highlighted by local stakeholders, including perceived social security, urban decay, loss of commercial activities and socio-economic changes, underscore the limits of an approach based only on physical infrastructure. The case of San Leonardo therefore suggests that relational proximity is a dynamic process and as it depends on interactions between local actors, spatial distribution of opportunities, policy integration and continuity over time. In this context, social infrastructures may foster the consolidation of interpersonal relationships during leisure time, which represents the main sphere in which slow ways of living may be experienced. In fact, from an urban planning perspective, leisure time constitutes the primary field of intervention for promoting slowness, as working time largely falls within the domain of the employer and therefore lies beyond the direct influence of urban planning. In this sense, social infrastructures contribute to the construction of a slow neighbourhood.

In this sense, the neighbourhood confirms that slow should not be reduced to a mere decrease in speed but should be interpreted as a relational and organisational quality of urban life. From this perspective, the neighbourhood provides a fertile context for experimenting with the slow neighbourhood model, which requires the integration of spatial interventions on social infrastructure and intangible measures to foster inclusive and proactive relationships. Within this vision, the former *Bormioli* site emerges as an opportunity to develop a new urban node for connecting social, cultural and territorial dimensions, potentially acting as a new relational centrality. At the same time, the results also call for a more critical reflection on the role of governance. A strong presence of the third sector may lead to fragmentation or overlap with the public agenda. For Cittaslow, delegating or supporting certain initiatives through associations may be productive, since they possess knowledge of the area and may foster initiatives. However, institutional coordination and support are fundamental to avoiding fragmented initiatives or competing priorities. This highlights that, to be effective, a slow strategy depends on governance arrangements that foster connections among local actors.

## 5 Conclusions

The paper explores the role of relational proximity — that supports happy, healthy and safe cities — in shaping a slow neighbourhood. To prove this point, San Leonardo in Parma was selected as a case study for the Cittaslow Metropolis programme. At the neighbourhood level, walkability and accessibility create the conditions for a slow neighbourhood. Moreover, social infrastructure can be leveraged to initiate or support regeneration practices and initiatives that transform spaces into places of interaction and enhance the quality of life [81]. Within this framework, social opportunities embed slowness into daily life, not as a reduction in speed but as a way of experiencing the quality of neighbourhood life. Although relational proximity is not only generated by the social infrastructure, it may also promote active engagement and relationships in slow urban regeneration processes [82, 83].

The case study of San Leonardo allows for the spatial and social definition and evaluation of slow neighbourhoods by combining GIS-based mapping of the opportunities offered by social infrastructure and local actors' insights. This methodology allows to connect spatial analysis with qualitative and situated knowledge. In this case, the effectiveness of social infrastructure depends on its integration with public policies and on its ability to foster collaborative networks. Without institutional support and coordination between stakeholders, may lead to fragmented initiatives or overburden the third sector. Developing governance models to support and systematise these practices may avoid both marginalisation and the substitution of public responsibilities. At the same time, the results highlight an ambivalent condition: a strong associative fabric enhances relational density and compensates for institutional gaps but may also reveal the partial inability of public policies to fully address citizens' needs. The research suggests that the implementation of a slow neighbourhood model should be based on a combination of spatial, social and governance-oriented strategies such as the development of distributed and accessible social infrastructures, the enhancement of hybrid spaces and the collaboration between institutions, associations and local communities.

In conclusion, applying slow principles at the neighbourhood scale is a promising strategy to address contemporary urban challenges as it offers a vision based on proximity, care and everyday lived experience, repositioning the neighbourhood as a key scale for sustainable and inclusive urban transformation. However, this research also presents some limitations, as it presents a single qualitative case study and for the difficulty of measuring relational proximity. Moreover, the empirical analysis focuses exclusively on the San Leonardo neighbourhood, as defined by the framework agreement, which limit the result assessment through comparison. Future research should develop KPIs to assess relational proximity and support the Cittaslow Metropolis programme. Furthermore, in this case the slow strategies for San Leonardo are built on a dense network of social infrastructure, but, following Cittaslow principles, local traditions, heritage, productive identity or place-based products could also be interesting fields of investigation. These elements may be interpreted within the framework of relational proximity, insofar as they generate occasions for sociality and shared belonging. This consideration broadens the goal of the slow neighbourhood model, suggesting that its relational dimension may be supported by different place-based resources depending on the local context. Finally, to verify transferability and scalability of the methodology, it should be tested across

different urban contexts, varying in spatial scale, demographic density and urban morphology. Monitoring tools could also assess how relational proximity evolves over time and how it influences urban regeneration processes.

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This manuscript reflects only the authors' views and opinions, neither the European Union nor the European Commission can be considered responsible for them.

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## References

1. Su, W.S., Huang, C.H., Hsu, C.C., Chang, L.F.: Cıttaslow: a new pattern of sustaınable tourısm development in Taıwan. Int. J. Organ. Innov. **9**(4) (2017)
2. Oztürk, S.: Small Towns Reshaping Their Urban Planning Policies Joining in the Cittaslow International Network: The Case of Seferihisar in Turkey. Master's thesis, Middle East Technical University, Ankara (2012)
3. Cittaslow International.: https://www.cittaslow.org/. Accessed 28 Apr 2026
4. Kucukergin, F.N., Oxturk, Y.: Does slowness bring social change through Cittaslow?. Int. J. Tourism. Cities **6**(4) (2020). https://doi.org/10.1108/IJTC-06-2019-0093
5. Pink, S.: Sense and sustainability: the case of the slow city movement. Local Environ. **13**(2) (2008). https://doi.org/10.1080/13549830701581895
6. Pink, S.: Urban social movements and small places- slow cities as sites of activism. City **13**(4) (2009). https://doi.org/10.1080/13604810903298557
7. Cittaslow International: 2011 - Cittaslow International Network: National Website. http://www.cittaslow.org/. Accessed 28 Apr 2026
8. Cittaslow International: All the Slow Cities https://www.cittaslow.org/citta-slow. Accessed 28 Apr 2026
9. Miele, M.: Città slow: producing slowness against the fast life. Space Polity **12**(1) (2008)
10. Mayer, H., Knox, P.: Small-town sustainability: prospects in the second modernity. Eur. Plan. Stud. **18**(10) (2010). https://doi.org/10.1080/09654313.2010.504336
11. Radstrom, S.: A place sustaining framework for local urban identity: an introduction and history of Cittaslow. Ital. J. Plann. Pract. **1**(1) (2011)
12. Presenza, A., Abbate, T., Micera, R.: The Cittaslow movement: opportunities and challenges for the governance of tourism destinations. Tour. Plan. Dev. **12**(4) (2015). https://doi.org/10.1080/21568316.2015.1037929
13. Zawadzka, A.K.: Making small towns visible in Europe: the case of cittaslow network–the strategy based on sustainable development, Transylvanian review of administrative sciences, 13. Spec. Issue (2017). https://doi.org/10.24193/tras.SI2017.6
14. Clancy, M.: Slow Tourism. Food and Cities. Routledge, New York (2018)
15. Donaldson, R.: Cittaslow: Going Nowhere Slowly, Small Town Tourism in South Africa. Springer International Publishing, Cham (2018). https://doi.org/10.1007/978-3-319-68088-0_5

16. Holland, T.: Navigating slow, 'fast' and crafted knowledges: knowing through Cittaslow, Newcastle University, School of Geography, PhD. Thesis (2018)
17. Özmen, A., Can, M.C.: The urban conservation approach of Cittaslow Yalvaç. Megaron. **13**(1) (2018). https://doi.org/10.5505/megaron.2017.67689
18. Shrivastava, A.R., Ohri, L.: Slow tourısm–an approach, an umbrella or a niche? Universal Review. **7**(11) (2018). https://doi.org/10.1108/IJTC-06-2019-0093
19. Cittaslow International: presentazione in anteprima mondiale del progetto "Cittaslow Metropolis" https://www.cittaslow.it/notizia/it-orvieto-presentazione-anteprima-mondiale-del-progetto-cittaslow-metropolis. Accessed 28 Apr 2026
20. Cittaslow International: Big cities learn something new from small towns. Cittaslow neighbourhoods launched https://www.cittaslow.it/news/orvieto-big-cities-learn-something-new-small-towns-cittaslow-neighbourhoods-launched. Accessed 28 Apr 2026
21. Glaeser, E.: Triumph of the City. Penguin Press HC, MA (2011)
22. Cittaslow International: Cittaslow Brochure https://www.cittaslow.org/_files/ugd/c3e050_a3f866d8d40744aa8d77e7c77f1d5cd2.pdf. Accessed 28 Apr 2026
23. Cittaslow International: Izmir is candidate to become the first Cittaslow Metropolis https://www.cittaslow.it/news/turkish-national-network-izmir-candidate-become-first-cittaslow-metropolis. Accessed 28 Apr 2026
24. Comune di Roma Capitale: Cittaslow Metropolis, Esquilino rione pilota https://www.comune.roma.it/web/it/notizia.page?contentId=NWS1074079. Accessed 28 Apr 2026
25. Cittaslow International: Charter https://www.cittaslow.org/_files/ugd/c3e050_beef918cb3284a6e9fa8f64a6ca31a02.pdf. Accessed 28 Apr 2026
26. Galster, G.: On the nature of neighbourhood. Urban Stud. **38**(12) (2001). https://doi.org/10.1080/00420980120087072
27. Lupton, R.: 'Neighbourhood Effects': Can we measure them and does it matter? Centre for Analysis of social exclusion. In: Neighbourhood Rffects Research: New perspectives, Springer Netherlands, Dordrecht (2003). https://doi.org/10.1007/978-94-007-2309-2_1
28. Schultheiss, M.E., Pattaroni, L., Kaufmann, V.: Planning urban proximities: an empirical analysis of how residential preferences conflict with the urban morphologies and residential practices. Cities. **152**, 105215 (2024). https://doi.org/10.1016/j.cities.2024.105215
29. Alberti, F., Radicchi, A.: From the neighbourhood unit to the 15-minute city. Past and recent urban models for post-COVID cities. In: Urban and Transit Planning: City Planning: Urbanization and Circular Development. Springer International Publishing, Cham (2023). https://doi.org/10.1007/978-3-031-20995-6_15
30. Moreno, C.: The 15-Minute city: a solution to saving our time and our planet. John Wiley & Sons (2024)
31. Olivari, B., Cipriano, P., Napolitano, M., Giovannini, L.: Are Italian cities already 15-minute? Presenting the next proximity index: a novel and scalable way to measure it, based on open data. J. Urban Mobility **4**, 100057 (2023). https://doi.org/10.1016/j.urbmob.2023.100057
32. Brennan, J., Martin, E.: Spatial proximity is more than just a distance measure. Int. J. Hum. Comput. Stud. **70**(1) (2012). https://doi.org/10.1016/j.ijhcs.2011.08.006
33. Busi, R.: For a Safer City. A Friendlier City. And a more Beautiful City. TeMA-J. Land Use, Mobility Environ. **2** (2009). https://doi.org/10.6092/1970-9870/121
34. Pajares, E., Büttner, B., Jehle, U., Nichols, A., Wulfhorst, G.: Accessibility by proximity: addressing the lack of interactive accessibility instruments for active mobility. J. Transp. Geogr. **93**, 103080 (2021). https://doi.org/10.1016/j.jtrangeo.2021.103080
35. Lanza, G., Pucci, P., Carboni, L.: Measuring accessibility by proximity for an inclusive city. Cities **143**, 104581 (2023). https://doi.org/10.1016/j.cities.2023.104581
36. Rashed, R.: From concept to action: active mobility cards for collective spaces in block-system urban neighborhoods. Ain Shams Eng. J. **16**(12), 103771 (2025). https://doi.org/10.1016/j.asej.2025.103771

37. Suslowicz, J., Hillnhütter, H.: From temporariness to mobility futures: a review of progress in tactical urbanism as an active travel planning tool. Transp. Res. Interdisciplinary Perspect. **32**, 101510 (2025). https://doi.org/10.1016/j.trip.2025.101510
38. Ashton, J., Grey, P., Barnard, K.: Healthy cities—WHO's new public health initiative. Health Promot. Int. **1**(3) (1986). https://doi.org/10.1093/heapro/1.3.319
39. Hancock, T.: The evolution, impact and significance of the health cities/healthy communities movement. J. Public Health Policy. **14**(1) (1993). https://doi.org/10.2307/3342823
40. Norris, T., Pittman, M.: The healthy communities movement and the coalition for healthier cities and communities. Public Health Rep. **115**(2–3) (2000). https://pubmed.ncbi.nlm.nih.gov/10968742/
41. Leyden, K.M., Goldberg, A., Michelbach, P.: Understanding the pursuit of happiness in ten major cities. Urban Aff. Rev. **47**(6) (2011). https://doi.org/10.1177/1078087411403120
42. Florida, R., Mellander, C., Rentfrow, P.J.: The happiness of cities. Reg. Stud. **47**, 4 (2013). https://doi.org/10.1080/00343404.2011.589830
43. Kearns, A., Parkinson, M.: The significance of Neighbourhood. Urban Stud. **38**, 12 (2001). https://doi.org/10.1080/00420980120087063
44. Borlini, B.: Il quartiere nella città contemporanea. Come e perché occuparsene. Quad. Sociol. **52** (2010). https://doi.org/10.4000/qds.717
45. O'Sullivan, T.L., Kuziemsky, C.E., Toal-Sullivan, D., Corneil, W.: Unraveling the complexities of disaster management: a framework for critical social infrastructure to promote population health and resilience. Soc. Sci. Med. **93** (2013). https://doi.org/10.1016/j.socscimed.2012.07.040
46. Lo, L., Preston, V., Anisef, P., Basu, R., Shuguang, W.: Social Infrastructure and Vulnerability in the Suburbs. University of Toronto Press, Toronto, CA (2015)
47. Aldrich, D.P., Kiyota, E.: Creating community resilience through elder-led physical and social infrastructure. Disaster Med. Public Health Prep. **11**(1) (2017). https://doi.org/10.1017/dmp.2016.206
48. Davern, M., Gunn, L., Whitzman, C., Higgs, C., Giles-Corti, B., Simons, K., et al.: Using spatial measures to test a conceptual model of social infrastructure that supports health and wellbeing. Cities Health **1**(2) (2017). https://doi.org/10.1080/23748834.2018.1443620
49. Klinenberg, E.: Palaces for the People: how Social Infrastructure Can Help Fight Inequality, Polarization, and the Decline of Civic Life. Crown Publishing, New York (2018)
50. Latham, A., Layton, J.: Social infrastructure and the public life of cities: studying urban sociality and public spaces. Geogr. Compass. **13**(7), e12444 (2019). https://doi.org/10.1111/gec3.12444
51. Pérez, E., et al.: Neighbourhood community life and health: a systematic review of reviews. Health Place. **61**, 102238 (2020). https://doi.org/10.1016/j.healthplace.2019.102238
52. Manzini, E.: Abitare la prossimità: Idee per la città dei 15 minuti. EGEA spa. (2021)
53. Ruonavaara, H.: The anatomy of neighbour relations. Sociol. Res. Online **27**(2) (2022). https://doi.org/10.1177/13607804211012708
54. Fraser, T., et al.: How far I'll go: social infrastructure accessibility and proximity in urban neighborhoods. Landsc. Urban Plan. **241**, 104922 (2024)
55. Blokland, T., Savage, M.: Networked Urbanism: Social Capital in the City. Ashgate, Burlington (2008)
56. Zanon, B.: Local development in fragile areas: re-territorialization processes in an alpine community. Int. Plan. Stud. **19**(3–4) (2014). https://doi.org/10.1080/13563475.2014.965247
57. PR2050: Piano Urbanistico Generale PUG Parma https://www.parma2050.eu. Accessed 28 Apr 2026
58. Caselli, B., Pedilarco, G., Pellicelli, G., Rossetti, S., Zazzi, M.: Enhancing public space accessibility and inclusivity in residential Neighbourhoods: a methodological framework and pilot application. Sustainability **16**(4), 1435 (2024). https://doi.org/10.3390/su16041435

59. Caselli, B., Ceci, M., De Noia, I., Tedeschi, G., Zazzi, M.: La desigillazione del suolo nelle azioni partecipate di resilienza urbana: Il caso “Green in Parma”. URBANISTICA INFORMAZIONI. **306** (2022)
60. Ceci, M., Caselli, B., Zazzi, M.: Soil de-sealing for cities’ adaptation to climate change. Planning of priority interventions in urban public space. TeMA. **16**(1) (2023). https://doi.org/10.6093/1970-9870/9395
61. Mayer, H., Knox, P.L.: Pace of Life and Quality of Life: the Slow City Charter. Community Quality-of-Life Indicators: Best Cases III, 21–40. Springer Netherlands, Dordrecht (2009). https://doi.org/10.1007/978-90-481-2257-8_2
62. Cho, S.-H.: A comparative study of a slow city and an urban region: a deeper look into the quality of life in Hadong-gun and Busan. Korea J. **51**(4) (2011)
63. Park, E., Kim, S.: Enhancing local community’s involvement and empowerment through practicing Cittaslow: experiences from Goolwa, South Australia. In: SHS Web of Conferences, vol. 12, p. 01044. EDP Sciences (2014). https://doi.org/10.1051/shsconf/20141201044
64. Erdogan, M.: Local community perception towards slow city: Gokceada sample. Asian. Soc. Sci. **12**(5) (2016). https://doi.org/10.5539/ass.v12n5p241
65. Jaszczak, A., Kristianova, K.: Social and cultural role of greenery in development of cittaslow towns. In: IOP Conference Series: Materials Science and Engineering, **603**(3), 032028. IOP Publishing (2019). https://doi.org/10.1088/1757-899X/603/3/032028
66. Kurniati, R., Sophianingrum, M., Khadiyanto, P. & Nugraha, M. F.: A model of community events as a cultural heritage conservation effort in Semarang Chinatown. In: IOP Conference Series: Earth and Environmental Science, **409**(1), 012019. IOP Publishing (2020). https://doi.org/10.1088/1755-1315/409/1/012019
67. Salieva, G. R.: Cittàslow: fluctuating between improvement and commodification of quality of life. Two case studies: Abbiategrasso and Seferihisar. Master’s thesis, Scuola di Architettura Urbanistica Ingegneria delle Costruzioni, Politecnico di Milano (2016)
68. Özdemir, H.: Investigation of social change in cities after participation in cittaslow union in Ordu-Perşembe district. J. Des. Resilience Archit. Plann. **5**(1) (2024). https://doi.org/10.47818/DRArch.2024.v5i1121
69. Cittaslow Turkiye - Cittaslow Metropolis Checklist: Slow neighbourhood https://cittaslowturkiye.org/en/csm/checklist/slow-neighborhood/. Accessed 28 Apr 2026
70. Cittaslow International – Cittaslow Metropolis can save the planet https://www.cittaslow.it/news/orvieto-cittaslow-metropolis-can-save-planet. Accessed 28 Apr 2026
71. Sanul, G., Doğu, T.: Towards a sensorial approach to inclusive urban policy making: narrated walks in Izmir’s cittaslow neighbourhood program. Geoforum. **165**, 104388 (2025). https://doi.org/10.1016/j.geoforum.2025.104388
72. Kaynarkaya, S., Cekmis, A., Çetin, İ., Şahin, Y.H., Unal, G.: Assessing walkability with deep Cnns by integrating objective and subjective urban qualities: the case of ‘Cittaslow’ Neighbourhoods. Sustain. Cities Soc. **106863** (2025). https://doi.org/10.1016/j.scs.2025.106863
73. Destination Management Organization quartiere Esquilino DMO ES.CO. https://www.esquilinocomunita.it/it/evento/esquilino-slow/. Accessed 28 Apr 2026
74. Geoportale Emilia-Romagna RER. https://geoportale.regione.emilia-romagna.it/. Accessed 28 Apr 2026
75. SIT Comune di Parma.: https://sit.comune.parma.it/it-IT/home-sit.aspx. Accessed 28 Apr 2026
76. Registro Unico Nazionale del Terzo Settore RUNTS.: https://servizi.lavoro.gov.it/runts/it-it/. Accessed 28 Apr 2026
77. Bianchi, M.: Renewing the city through public participation and cultural activities. The case study of Gillet square, a community-led urban regeneration project. J. Entrepreneurial Organ. Diversity. (2023). https://doi.org/10.5947/jeod.2019.001

78. Heath, S.C., Rabinovich, A., Barreto, M.: Exploring the social dynamics of urban regeneration: a qualitative analysis of community members' experiences. Br. J. Soc. Psychol. **62**(1) (2023). https://doi.org/10.1111/bjso.12578
79. Piperno, A., Iaione, C., Kappler, L.: Institutional collective actions for culture and heritage-led urban regeneration: a qualitative comparative analysis. Sustainability. **15**(11), 8521 (2023). https://doi.org/10.3390/su15118521
80. Méndez, M.L., Otero, G., Link, F., López Morales, E., Gayo, M.: Neighbourhood cohesion as a form of privilege. Urban Stud. **58**(8) (2021). https://doi.org/10.1177/0042098020914549
81. D'Onofrio, R., Trusiani, E.: The future of the City in the name of proximity: a new perspective for the urban regeneration of council housing suburbs in Italy after the pandemic. Sustainability **14**(3), 1252 (2022). https://doi.org/10.3390/su14031252
82. Sepe, M.: Measuring the impact of slow regeneration process: the HLH Pl@ce index. UPLAND **4**(2) (2019a)
83. Sepe, M.: Slow regeneration: liveable places for all. In: Gospodini, A. (ed.) Proceedings of the International Conference on Changing Cities IV: Spatial, Design, Landscape & Socio-Economic Dimensions Chania, Crete Island, Greece, June 24–29, 2019. University of Thessaly, Department of Planning and Regional Development, Laboratory of Urban Morphology & Design (2019b)

# Urban Data-Driven Energy Planning: Insights and Challenges from Italy and Portugal

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**Abstract.** Effective urban planning for sustainable and equitable development requires data-driven support for policymakers to enable context-specific actions. Big and Open Data can serve as valuable resources for technicians and policymakers, transforming scientific knowledge into decision-support tools. However, the complexity and lack of standardisation of such data can create significant gaps. In the energy sector, open data issues are even more complex due to multiple stakeholders, privacy concerns, and varying motivations for collecting energy consumption data, such as municipal taxation versus energy management.

This paper investigates these critical issues, which underpin the development of reliable, data-driven methodologies for understanding urban systems and supporting targeted interventions. Through two comparative case studies in Italy and Portugal, we highlight how data structure and accessibility shape the methodological approach and outcomes. In the Italian case study, conducted in Naples, comprehensive energy consumption data were available through the Siatel platform, including detailed records for individual users across the city. While the richness of the dataset enabled high-resolution analysis, the primary challenge lay in accurately geocoding and spatially integrating user-level data within the urban fabric. In contrast, the Portuguese case study relied on more aggregated energy datasets, where the key methodological challenge was disaggregating and translating large-scale information into finer spatial units suitable for meaningful urban analysis.

The comparison demonstrates that even when adopting replicable methodologies and modelling approaches, valid cross-city comparison depends on explicit harmonization of the target variables produced from distinct data infrastructures, because addressing data-specific constraints is essential for producing effective, context-sensitive planning solutions.

**Keywords:** Energy data · Urban energy planning · Geocoding · Spatial harmonizarion

## 1 Introduction

The disruptions caused by recent global crises have redefined how planners and researchers conceptualise urban quality of life, revealing with unprecedented clarity the profound impact of residential conditions, such as dwelling quality, neighbourhood

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density, access to open space, and the thermal performance of the housing stock, on the health, well-being, and energy vulnerability of urban populations [1–3]. This context makes the goal of building smarter, safer, and healthier cities more important than ever [4]. It also shows what aggregate urban statistics often hide: that there are big differences in how livable different areas are, and that fixing them needs accurate, detailed data at the neighbourhood and building level [5]. The methodological inquiries this paper examines, how to geocode imprecise administrative records and how to disaggregate collective energy statistics into significant spatial units, are not merely technical endeavours. They are necessary steps to identify where residential energy vulnerability is highest, to ensure that retrofit programs reach the people who need them most, and to monitor the long-term effectiveness of planning interventions [6–10].

Energy consumption data has a unique role in the larger open data ecosystem. Energy records are managed by a wide range of actors and groups, such as distribution system operators (DSOs), municipal tax agencies, national grid authorities, and private utilities. This is different from transport flows or land-use classifications. Each of these groups collects data for reasons that do not always fit with what spatial analysis needs. For example, taxation, billing, grid balancing, and regulatory compliance all require different structures, granularities, and levels of spatial attribution on records. Consequently, the analyst aiming to map energy consumption at the neighbourhood or building level often faces a paradox: the data are available, yet their format makes them analytically inaccessible without considerable preprocessing.

This paper offers a dual perspective on this challenge, utilising two ongoing research initiatives in urban settings in Italy and Portugal. The Italian case study focuses on Naples, which is one of the largest and most crowded cities in Southern Europe. The Siatel platform, a municipal fiscal database that connects utility billing records to individual user addresses, was used to get energy consumption data here. The dataset is very detailed; it has records for each user over several years and includes most of the city's residential and commercial buildings. But the addresses in Siatel are based on tax administration rules rather than topographic maps. They are often incomplete, not in the right format, or have systematic typographic noise that makes it impossible for automated systems to work with them. The main methodological issue is how to reliably assign geographic coordinates to hundreds of thousands of noisy administrative address strings. This is a problem of spatial integration.

The case study of Portugal faces a problem that is almost the opposite. The national DSO and regulatory authorities in Portugal make energy consumption data available through national open data portals. These datasets are combined into administrative units. The methodological challenge here is disaggregation: how to turn macro-level energy stats into reasonable estimates for smaller areas that can be used for neighbourhood-level research. Spatial interpolation, dasymetric mapping, and regression-based downscaling techniques need to be carefully adjusted to fit the shape of the city.

The comparison of these two datasets is highly analytically productive, as they represent the diverse challenges of working with real-world urban energy data. By comparing a high-resolution but spatially noisy dataset and a spatially clean but low-resolution dataset, this paper aims to demonstrate how data structure influences the choice of tools and, therefore, the quality and usability of the outputs. The value of this paper is not in

an exclusive technique but in a comparison of how open data constraints affect urban energy analysis. The comparison of these two datasets is analytically productive because they represent two non-equivalent pathways through which urban electricity indicators are constructed from real-world data infrastructures. By comparing a high-resolution but spatially noisy dataset and a spatially cleaner but lower-resolution dataset, this paper shows how data structure influences the choice of tools, the definition of the target variable, and the validity of subsequent comparison. The value of the paper therefore lies not only in the treatment of open data constraints, but also in demonstrating that cross-city urban electricity comparison is defensible only when the target variables are explicitly harmonized across distinct data infrastructures [11–13].

The following section presents a theoretical position on geocoding, spatial disaggregation, and analytical equivalence in the context of urban informatics and open data. Section 3 describes the materials and methods used in both case studies, while Sect. 4 presents results and comparisons between them. Section 5 concludes by dis-cussing the harmonization requirements that still condition robust cross-city analysis.

## 2 Theoretical Framework

Open data in urban governance has evolved over the past two decades. Initially, this topic generated considerable enthusiasm and interest; however, over time, there has been a growing recognition within the scholarly and policy communities that government data are often less readily accessible than previously assumed. This realisation has highlighted the challenges involved in data transparency and availability, indicating the need for more systematic approaches to improve accessibility. In particular, as Janssen et al. [10] showed, open data remains confounding for those who want to make use of it: technical barriers such as formats not compatible with each other, absence of APIs, legal barriers such as license limits or privacy issues, and institutional barriers such as fragmented mandates, competing stakeholder interests. This is particularly relevant to the energy sector, where the interests of distribution networks, regulators, local governments, and open-data users intersect on several issues.

Within this landscape, urban energy data are considered particularly sensitive forms of open data. Unlike land-use or transport records that describe the built environment at a broad scale, energy consumption records contain details about households, the premises they occupy, and citizens' yearly energy use (often seen as a proxy for annual income). However, full disclosure of this information is unlikely due to data protection rules such as the European General Data Protection Regulation (GDPR). In light of this balancing act between analytical usefulness and the protection of privacy, a number of EU member states release individualised data from their smart meters with strict anonymisation, whereas others release only aggregated spatial scales.

Within this regulatory environment, the characteristics of Italian and Portuguese energy data governance reflect wider national institutional contexts. In Italy, without a centralised open data infrastructure for residential energy use, researchers must often use administrative datasets such as tax or cadastral records. The Siatel platform, a shared access system operated by the Italian Revenue Agency (Agenzia delle Entrate), is one example of an open data system that aggregates tax-related utility information per person

but only provides spatial information in the form of free-text administrative addresses. In Portugal, the transition to smart meters and government demands for data transparency have led to more standardised open datasets, but at the cost of spatial resolution, where most publicly available data are collected at the postcode or administrative unit level.

Different dataset designs demand different strategies for managing open energy data and applying it in urban planning. The Italian case involves a detailed geocoding process to convert data collected by various actors (primarily for fiscal reasons) into usable datasets. Conversely, the Portuguese case requires dasymetric and disaggregation techniques. Different dataset designs demand different strategies for managing open energy data and applying it in urban planning. The Italian case involves a geocoding process that converts user-level administrative records into spatially usable observations. Conversely, the Portuguese case requires disaggregation and spatial translation techniques that reconstruct tract-level indicators from aggregated low-voltage records. In both situations, the resulting electricity indicators are constructed analytical objects rather than simple direct observations, and cross-city comparison therefore depends on harmonizing the meaning of both numerators and denominators across the two pipelines [14].

### 2.1 Geocoding

Geocoding addresses is, in practice, far more complicated than it might appear. The task, which consists of matching a piece of text describing a location to a set of geographic coordinates, becomes progressively harder as the quality of the input data deteriorates. When addresses are well formatted and the underlying gazetteer consistently covers civic numbers, automated systems work well. The trouble is that administrative datasets collected for purposes other than spatial analysis (e.g. tax records, utility bills, planning registers, etc.) almost never meet these conditions. Strings riddled with abbreviations, inconsistent street-type prefixes, typos inherited from manual data entry, or informal references to local landmarks that simply do not appear in any national address database may often be found.

Scientific literature and IT tools developed on geocoding quality have long distinguished between two types of error that pull in opposite directions. The first is location accuracy: how far the geocoded point ends up from the actual location. The second is the match rate: what share of records the system manages to geocode at all. What needs to be taken into account is that improving one may lead to worsening the other. In fact, accepting looser, approximate matches to include more records in the geocoded dataset will inevitably result in some locations being assigned to the wrong street or placed at a street centroid rather than the actual building entrance. Conversely, insisting on exact civic-number matches improves accuracy but leaves a nontrivial portion of the dataset unmatched.

Which trade-off makes sense depends heavily on how the data will actually be used. A building-level energy audit cannot tolerate a geocoded point that is two streets away; accuracy has to come first. A citywide map showing consumption patterns in each neighbourhood can accept some positional inaccuracy as long as coverage remains high, because missing entire neighbourhoods from the analysis is probably the most undesirable result.

Open-source geocoding engines, especially Nominatim, have become increasingly popular as cost-effective alternatives to commercial services such as the Google Maps Platform or ArcGIS World Geocoding Service [15, 16]. Nominatim uses the open source OSM database (with global coverage and community maintenance) that is very heterogeneous in terms of civic number completeness across regions and cities. To sum up, when comparing Nominatim to commercial services, while Nominatim performs reasonably well in densely covered urban areas (with OSM coverage), the accuracy of civic numbers has been inconsistently reported or poorly infrequently.

Fuzzy string matching is an approach to bridge the gap between noisy address inputs and reference gazetteers. Approaches such as the Levenshtein distance, Jaro-Winkler similarity, and the Token Sort Ratio from RapidFuzz can calculate the similarity of two strings after they are compared with respect to character additions, word ordering, and abbreviations. The Token Sort Ratio is particularly useful for address matching because it normalises the comparison by first sorting the tokens of each string alphabetically, making the score invariant to word order, an interesting property given the variable nature of Italian administrative addresses for street prefixes: via, viale, corso, piazza, etc.). For the present comparison, geocoding quality is not only a local data-cleaning issue. It also determines the spatial support of the Naples numerator and therefore conditions whether that numerator can later be aligned with indicators produced under a differ-ent infrastructure. In this sense, geocoding uncertainty enters the comparative prob-lem at the level of target construction rather than merely at the level of cartographic representation [17, 18].

### 2.2 Spatial Harmonization

Spatial harmonization poses an inverse but related problem. When electricity data are released for spatial units other than the official, most widely used administrative units, the analyst must infer how much of that demand should be allocated to meaningful spatial entities for urban analysis. The resulting values are not observed directly at the target scale; they require the analyst to produce (if absent, as is usually the case) a translation model whose assumptions become part of the indicator itself. Area weighting, dasymetric allocation, and morphology-based weighting are typical strategies for this purpose, but each one embeds a different account of how demand is distributed across urban space [19, 20].

This distinction is analytically important because a shared label, such as (kWh/year/household), does not, by itself, guarantee equivalence across cities. A tract-level value derived from direct residential user records is not immediately com-mensurate with a tract-level value reconstructed from mixed low-voltage demand and building-based allocation weights. For this reason, valid cross-city comparison requires an explicit harmonization framework that specifies numerator scope, denominator meaning, spatial support, temporal reference, and uncertainty reporting. Rather than treating Naples and Porto as if they supplied the same variable at different resolutions, the two cases must be aligned as members of a harmonized family of target variables, including at least social normalization tracks such as kWh/year/person and kWh/year/household, and a morphological normalization track such as kWh/year/m2.

## 3 Materials and Methods

This study adopts a methodological-comparative design in which the two case studies are first treated according to their own data constraints and are then evaluated against a common harmonization problem. The comparison is organized around five dimensions: source-data structure, target-variable family, denominator meaning, spatial support and translation logic, and uncertainty reporting.

### 3.1 The Italian Case Study: Naples

The Italian case study uses data from the Siatel 2.0 platform (*Sistema di interscambio anagrafico e tributario elettronico*), which is run by the Italian Revenue Agency (*Agenzia delle Entrate*). The 2005 Financial Law (art. 1, commas 332–334, Law 311/2004) gave the Municipality of Naples access to the platform. This law requires all utility suppliers to send annual consumption records to the national tax registry. The dataset for the Municipality of Naples contains 518,177 records for residential electricity users (persone fisiche) for the 2021 fiscal year. These records are divided into two groups: type 1 users who live at the supply address and type 2 users who live somewhere else. Each record has an annual consumption value in kWh, a billing month count, and most importantly, a free-text address string that shows the supply location as the user entered it when they signed up for the contract.

Two additional and ancillary datasets were combined to help with the spatial analysis. The civic address database was downloaded from the National Geoportal (Geoportale Nazionale) of the Ministry of Environment and Energy Security, which works under the INSPIRE Directive (D.Lgs. 32/2010). It has 107,478 georeferenced address points for Naples, based on data from 2011. The official street register (Stradario Ufficiale) from the open data portal of the Municipality of Naples was used as the official source for standardizing street names. It has 3,826 street entries.

The 2021 ISTAT Population and Housing Census provided socioeconomic data, such as the number of families living in the area and the number of homes that were occupied. This data was broken down to the neighbourhood level across the 30 administrative subdivisions of the municipality. The main methodological challenge is that the free-text address strings in Siatel don't match the standardised toponymic entries in the official geographic databases. This is mainly due to the fact that Siatel's address strings are formatted according to tax administration rules and often have typographic noise, non-standard abbreviations, and extra cadastral descriptors. Managing 518,177 records made it impossible to do everything by hand, so automated tools had to be used. The methodological pipeline created to address this issue and described in this section has three main steps, as outlined in Fig. 1 below: automatic string normalisation, fuzzy matching, and human-guided correction, which is performed iteratively.

The first methodological step is noise cleaning, which means removing elements that are not necessary for spatial identification, such as postal codes, floor indicators, staircases and internal unit references (e.g. piano, scala, interno, palazzo), and other cadastral qualifiers that people often include in billing addresses. After cleaning, the street type prefix and toponym are separated from the civic number. Records marked SNC (*senza numero civico*, or without a street number) require special handling. The

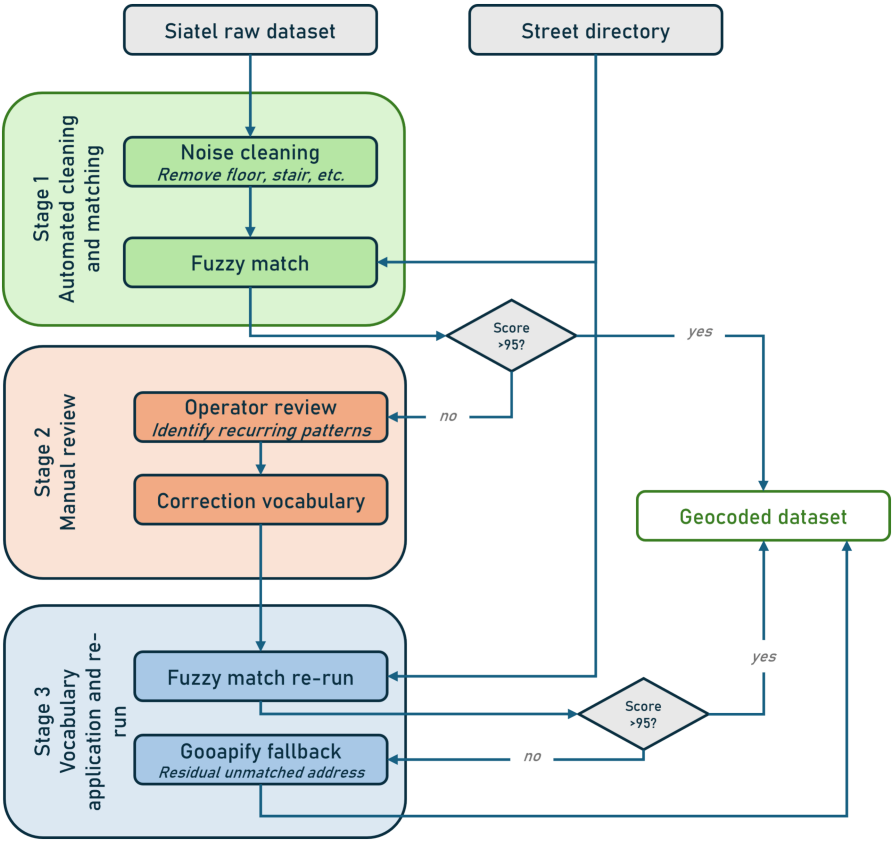


**Fig. 1.** Methodology workflow for Italian-based energy records.

cleaned address is then processed through a fuzzy matching phase that uses the Token Sort Ratio algorithm from the RapidFuzz library. This algorithm normalizes string similarity by sorting component tokens alphabetically before comparing them. This means that the matching score does not depend on the order of the words, which is useful because Italian street type prefixes (via, viale, corso, piazza, and their many shortened forms) can be used in different ways. Addresses that get a match score higher than 95 against the official street register are marked as "valid" and automatically given the right municipality and neighbourhood codes. Addresses that get a score lower than 95 are marked for "revision" and moved to the following methodological step.

The manual review consists of identifying recurrent patterns in the unresolved strings, such as local abbreviations of major thoroughfare names that are not included in the official register, the systematic inclusion of alternative street designations that reflect historical naming conventions, variations in civic number formatting (such as ranges like "15–17" or letter suffixes added to numbers), and strings that refer to buildings or complexes by name. A structured Correction Vocabulary, a mapping table that links problematic input strings to their confirmed equivalents, is used to record identified

corrections. The vocabulary is treated as a cumulative, version-controlled asset; new entries are added with each processing cycle, gradually reducing the amount of manual correction required in later runs.

The methodology has been designed to run iteratively, in order to maximise at each stage the number of strings recorded as "valid". Before the first step is run again, the Correction Vocabulary is applied as a pre-processing step to the complete original dataset. Additionally, a Substitutive Civic Map is created that, after validation against the official register at a 95% threshold, assigns the first valid civic number for a street to all SNC records connected to that street. A cache mechanism was put in place to control the computational cost of repeated fuzzy matching across a dataset this size: string comparisons that have already been calculated in a prior cycle are saved and retrieved directly, preventing redundant computations. After the corrected and re-normalised dataset has been processed through the entire first phase, the remaining "in-revision" records are sent to a final geoprocessing step that uses the Geoapify geocoding service to recover geographic coordinates for addresses that cannot be resolved against the municipal database, while "valid" records are written to the output.

The geocoded consumption data were combined with the civic address shapefile in QGIS after address correction was finished. There should be a clear explanation for the spatial aggregation unit selection. In this context, census tracts, the standard unit for Italian sociodemographic analysis, have two limitations: their geometry has changed over census rounds, making it impossible to compare historical series directly, and their boundaries often include street surfaces, which can result in address points being assigned to adjacent sections rather than the residential block they belong to. A 100-m hexagonal grid was adopted for the spatial aggregation of consumption data in Naples. This choice is justified by the need for spatial stability and time-invariance. Unlike census tracts, whose geometries are frequently modified between census rounds, the hexagonal grid provides a consistent unit for long-term longitudinal observation. Furthermore, this grid diameter minimises the risk of boundary effects where address points are erroneously assigned to adjacent streets, while maintaining a resolution sufficient to capture the block-level heterogeneity of the Neapolitan urban fabric. Spatial join was used to aggregate consumption values to the hexagonal cells by adding up all of the kWh values of address points that fell inside each cell. In order to compare energy behaviour across areas with various socioeconomic and morphological characteristics, a parallel aggregation to the 30 municipal neighbourhoods was also carried out.

The ISTAT census variables PF1 (resident families) and A2 (occupied dwellings) were used as denominators to calculate per-family consumption averages for the neighbourhood-level analysis. This produced a normalised indicator that takes into account variations in residential density across the city's extremely diverse urban fabric.

In the comparative framework developed in this paper, the Naples workflow is interpreted as the construction of an observed residential numerator that can subsequently be normalized using multiple denominator logic. The current Naples-side outputs therefore support at least a social normalization track based on resident families and occupied dwellings, while a person-based track remains contingent on the final alignment between available census denominators and the chosen spatial support.




**Fig. 2.** (a) Portuguese case study (Porto Municipality) – Census Tracts from 2021 census; (b) Buildings footprints and doors numbers (include streets names); (c) Postal codes polygons after combining doors numbers and street names as keys to merge postal codes raw text file; (d) Summary overview of geometric layers overlaps.

### 3.2 The Portuguese Case Study: Porto

The Portuguese case study addresses the inverse condition to Naples.

Porto, the second-largest city in Portugal, presents an urban context as complex as that of Naples but with distinct morphological drivers. With a total area of approximately 41.4 $km^2$ and a hilly topography, the city is characterised by a high-density medieval and 19th-century core surrounded by mid-20th-century expansions and contemporary suburban developments. Its Atlantic climate significantly influences residential heating and cooling demands. Unlike Naples, where user-level records were available, Porto's energy data is primarily governed by a transition toward standardised smart-metering at the postcode level, requiring a top-down spatial translation to identify vulnerable neighbourhoods.

The Porto workflow reconstructs annual low-voltage electricity indicators from observations organized at the CP7 postal-code level and reallocates them to the BGRI2021 census tracts. Because CP7 areas are not available as official analytical polygons, they are first inferred from matched door points and then spatially approximated through tessellation and clipping procedures. The resulting polygons serve as the origin support for allocating annual electricity totals to the target tract geography. Municipal building footprints, roof and ground elevation points, and terrain information are introduced to estimate built form and to derive allocation weights (Fig. 2).

Two allocation strategies are retained in parallel. In the first, electricity is redistributed from CP7 polygons to census tracts according to area-based intersection weights. In the second, the translation uses estimated building volume, derived from footprints and height information, so that the allocation reflects the internal distribution of built mass more directly. Retaining both strategies allows testing the sensitivity of the resulting tract-level indicators to alternative translation logics, rather than masking this uncertainty in a single output.

The Portuguese workflow produces a family of indicators rather than one tract-level metric. Let $((E_j^A)$ denote the annual electricity allocated to tract (j) under the area-weighted procedure and $(E_j^V)$ The annual electricity allocated under the building-volume-weighted procedure. Let $(N_j^{ind})$ denote the number of individuals, $(N_j^{hh})$ the household or family denominator adopted for the tract, and $(GFA_j)$ the estimated gross floor area. The resulting target family is given by

$$I_j^{A,ind} = \frac{E_j^A}{N_j^{ind}}, \quad I_j^{A,hh} = \frac{E_j^A}{N_j^{hh}}, \quad I_j^{A,GFA} = \frac{E_j^A}{GFA_j}$$

and

$$I_j^{V,ind} = \frac{E_j^V}{N_j^{ind}}, \quad I_j^{V,hh} = \frac{E_j^V}{N_j^{hh}}, \quad I_j^{V,GFA} = \frac{E_j^V}{GFA_j}.$$

In this configuration, the Porto-side numerator does not isolate residential demand with the same precision as the Naples dataset. It is better interpreted as mixed low-voltage electricity translated to the tract level under explicit spatial assumptions. For that reason, the Porto indicators are treated in this paper as analytically useful but only partially

commensurate with the Naples residential indicators until a target-level harmonization rule is specified.

### 3.3 Comparative Harmonization Logic

To establish a defensible Porto–Naples comparison, the two workflows are organized into a harmonized family of target variables rather than forced into a single nominal metric. The primary harmonization path is social normalization, which supports indica-tors such as (kWh/year/person) and (kWh/year/household). A complementary morphological path uses (kWh/year/m2) to retain a built-form-sensitive perspective for subsequent analysis. Across both tracks, comparability depends on making explicit five elements: the numerator scope, the denominator meaning, the spatial unit receiving the allocated value, the temporal reference attached to the observation, and the un-certainty introduced by geocoding or spatial translation.

Under this logic, a shared unit label is treated as a necessary but insufficient condition for comparison. A Naples indicator, normalized by resident families and derived from observed residential user records, is not analytically equivalent to a Porto indicator, normalized by family nuclei, if the numerator still includes mixed low-voltage demand or if the household definition differs institutionally. The comparative method, therefore, proceeds by identifying which indicators are already aligned, which are only partially aligned, and which require additional adjustment before any inferential cross-city modeling can be considered.

## 4 Results

### 4.1 The Italian Case Study: Naples

Naples is a densely populated Mediterranean city, with more than 900,000 residents concentrated within just 117 $km^2$, with over 7,700 inhabitants per $km^2$ in the most densely populated areas. Over 2,000 years of history, the city has developed through a long, layered process of urban growth, producing sharp contrasts between its historic core and its peripheral districts. The central areas, characterised by extremely compact medieval and early-modern fabrics, mid-rise buildings, narrow streets, and scarce open spaces, present complex spatial conditions shaped by centuries of densification and are subject to rigid heritage-preservation constraints. In contrast, the peripheral zones, although less dense, are often marked by fragmented urbanisation, larger open spaces, discontinuous building patterns, and, in some cases, major industrial or infrastructural enclaves. The city's overall structure is further conditioned by significant variations in altitude. These combined physical and functional characteristics, topographic fragmentation, limited developable land, heterogeneous settlement structures, and high demographic pressure make Naples a challenging context for urban planning, requiring attention to risk mitigation, mobility, heritage conservation, and equitable service provision. This complexity is also reflected in the city's energy demand: residential electricity consumption is strongly influenced by local urban form, socio-economic composition, and the morphological differences between dense central districts and more dispersed peripheral areas.

Recent studies emphasise the need for fine-scale spatial modelling to support mitigation and adaptation strategies, especially given the structural inefficiencies typical of compact Mediterranean cities and the heightened exposure to climate-related risks. The analysis presented in this study relied on data from the SIATEL 2.0 platform, which provides annual electricity and gas consumption data for all domestic and non-domestic users. Although highly detailed, the dataset contains addresses formatted according to administrative practices rather than cartographic standards, resulting in mismatches, outdated street names, and inconsistent numbering. To reconstruct the city's spatial energy demand, SIATEL data were harmonised and integrated with authoritative geographic information from the National Geoportal, including the municipality's civic-number database and ISTAT census-section boundaries, enabling each consumption record to be associated with a precise spatial entity through an extensive geocoding and preprocessing workflow.

The application of GIS methodology to the city of Naples produced the detailed geolocalization of residential electricity consumption, covering more than 518,000 domestic users. After the iterative correction and validation of addresses and the civic-numbers database, 93% of the SIATEL records were successfully geolocalised.

To represent the spatial distribution of energy data for this application, the census-section boundaries were not used, as they often include street segments and change geometrically over time. The final mapping was performed using a regular hexagonal grid (100 m). Using spatial join operations that accounted for the localisation of residential buildings, all validated consumption records were aggregated into grid cells, producing a detailed and uniform representation of the city's energy demand.

The resulting maps reveal clear spatial relation in the energy residential consumption: high-consumption areas are concentrated in the central and hillside neighbourhoods, particularly San Lorenzo, Pendino, San Giuseppe, Montecalvario, Avvocata, and Vomero. These areas feature dense residential fabrics, mixed land uses, and high occupancy rates, which collectively intensify electricity demand; low-consumption areas are mainly located in peripheral districts such as Chiaiano and San Pietro a Patierno, as well as in major industrial zones (Bagnoli, Zona Industriale), where large open spaces and lower residential densities lead to reduced domestic energy use (Fig. 3).

Additionally, the integration of residential consumption with demographic data from the 2021 ISTAT census enabled a comparative assessment across the city's 30 districts. The distribution of average electricity use per household aligns with expected behavioural and socio-economic patterns. High-consumption clusters in the historic centre (e.g., San Lorenzo, San Giuseppe) do not solely reflect high occupancy, but also the structural inefficiencies of older, uninsulated building stocks. Conversely, the lower consumption observed in peripheral industrial zones and recently developed areas like Chiaiano reflects both lower residential densities and, in some cases, the presence of more modern building materials that reduce the demand for active thermal regulation. Such distribution of average electricity use per household broadly aligns with expected behavioural and socio-economic patterns, reinforcing the reliability of the methodology and highlighting the analytical value of combining real consumption data with socio-demographic indicators.

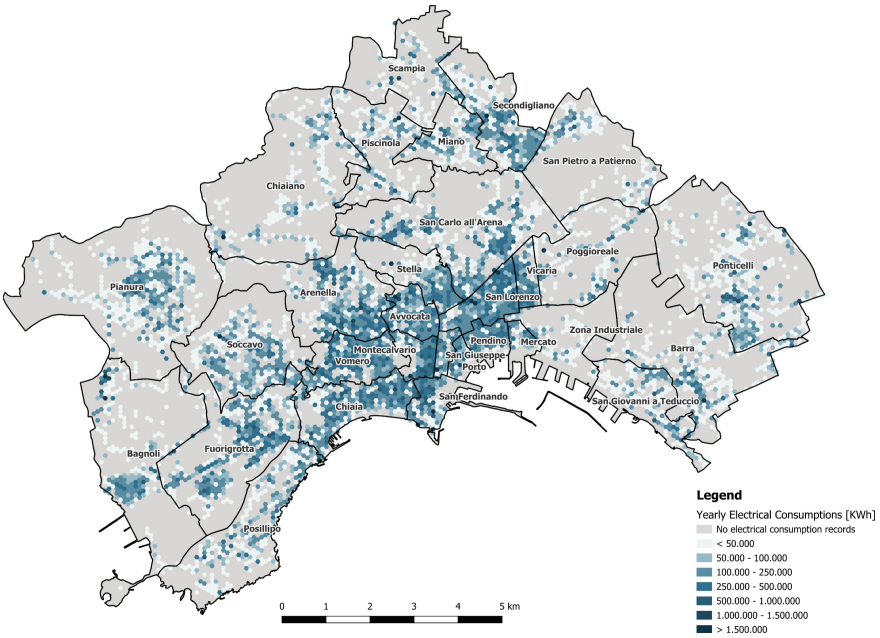


**Fig. 3.** Naples kWh/household distribution.

Overall, the Naples case study demonstrates that detailed user-level datasets, when properly harmonised, cleaned, and integrated within a GIS framework, can provide significant insights into the spatial heterogeneity of urban energy demand. The methodology confirms the importance of addressing data-quality constraints and adopting flexible, high-resolution spatial units to support effective and context-sensitive energy planning.

Overall, the Naples case study demonstrates that detailed user-level datasets, when properly harmonised, cleaned, and integrated within a GIS framework, can provide significant insights into the spatial heterogeneity of urban energy demand. The methodology confirms the importance of addressing data-quality constraints and adopting flexible, high-resolution spatial units to support effective and context-sensitive energy planning. At the same time, the results for the Italian case study clarify that achieving a high geocoding rate locally does not, by itself, solve the comparative problem, because the residential numerator produced here still needs explicit alignment with the numerator scope, denominator logic, and spatial support adopted in Porto.

### 4.2 The Portuguese Case Study: Porto

The Porto workflow yields tract-level electricity indicators via spatial translation rather than by directly geocoding user records. Its first result is therefore methodological: annual low-voltage electricity observed through the postal-code infrastructure can be reassigned to BGRI2021 census tracts using explicit, replicable weighting rules. This produces a sub-municipal analytical surface suitable for urban comparison while also preserving the distinction between the origin and target geographies.

A second result concerns indicator plurality. Because the Porto numerator is translated under both area-based and building-volume-based weights, the workflow produces parallel tract-level values instead of a single definitive allocation. This parallel structure makes the sensitivity of the final indicator to the assumed relationship between electricity demand and urban form visible. The Portuguese case thus yields not a single target variable but a family of plausible targets, bounded by different translation logics.

A third result concerns normalization. By combining translated electricity totals with census counts and estimated gross floor area, the Porto workflow produces socially normalized indicators such as kWh/year/person and kWh/year/household (Fig. 4), together with a morphological normalization track expressed as kWh/year/m2. These outputs make Porto analytically rich for intra-urban assessment, but they also show that the substantive meaning of the indicator depends on whether the analyst is studying demographic burden or built-form intensity.

The Porto-side limitations remain structurally important. The numerator reflects mixed low-voltage demand rather than a purely residential load, the origin polygons are inferred rather than official, and the built-form denominators depend on estimated gross floor area rather than directly observed architectural data. The resulting indica-tors are therefore suitable for comparison only when these constraints are explicitly retained in the interpretation of the target variable.

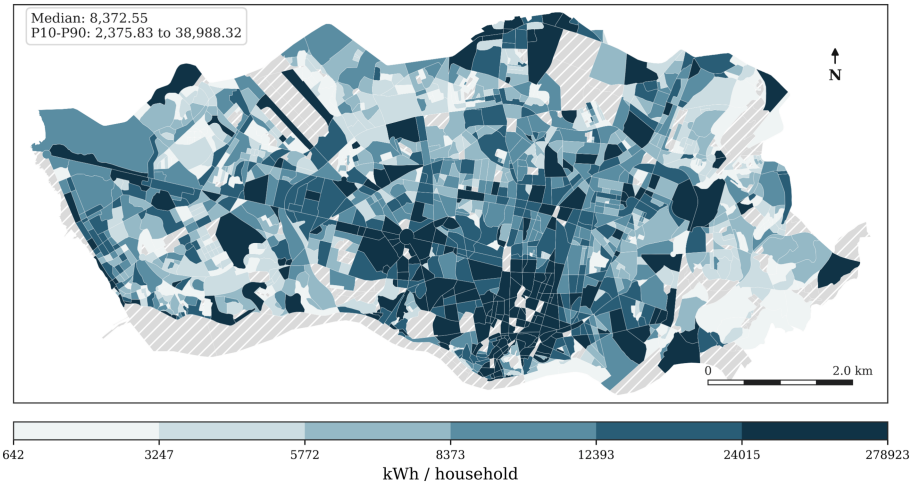


**Fig. 4.** Porto kWh/household distribution.

### 4.3 Comparative Synthesis

Taken together, the two case studies show that both cities can support sub-municipal electricity analysis, but they do so through different data-construction pathways. Naples begins with user-level residential observations and must solve spatial instability in address strings. Porto begins with aggregated low-voltage observations and must solve the translation from one geography to another. The apparent convergence of both

workflows at tract- or neighborhood-scale indicators should therefore not be mistaken for full analytical equivalence.

What is already comparable is the possibility of developing socially normalized indicators to address questions about demographic variation in urban electricity demand. Both cases also confirm strong intra-urban heterogeneity, indicating that city averages conceal relevant differences in morphology, occupancy, and social structure. What remains only partially comparable is the precise meaning of the numerator and, to a lesser extent, the meaning of household-based denominators across the two national statistical systems.

The main methodological result of the merged analysis is therefore not a single common metric, but a harmonized family of target variables. Within that family, some indicators can serve as primary comparison tracks, while others serve as complementary tracks. Socially normalized indicators are the most immediate candidates for cross-city work, provided that the numerator scope and denominator definitions are carefully documented. Morphologically normalized indicators remain valuable, but they should be interpreted as a complementary analytical track because they depend more directly on estimated built-form measures on the Porto side.

## 5 Discussion and Conclusions

The combined evidence from Naples and Porto indicates that open energy data be-comes useful for urban comparison only after a substantial phase of methodological transformation. In Naples, that transformation is dominated by geocoding, address normalization, and record recovery. In Porto, it is dominated by spatial translation, allocation weighting, and denominator construction. These are not peripheral technical adjustments. They define what the electricity indicator means and, therefore, set the conditions under which comparisons are valid.

For this reason, the paper's main conclusion is that cross-city comparisons and modelling of urban electricity are valid only when target variables are explicitly harmonized across distinct data infrastructures. A nominally shared unit such as (kWh/year/household) is insufficient if one city measures residential user-level demand and the other reconstructs mixed low-voltage demand through polygon translation. The comparison becomes defensible only when the analyst specifies the numerator scope, the denominator logic, the receiving spatial unit, the temporal frame, and the uncertainty structure attached to each indicator.

This conclusion does not diminish the value of either dataset. On the contrary, it clarifies how each one should be used. The Naples dataset is strong for recovering the spatial heterogeneity of residential electricity demand once address instability is resolved. The Porto workflow is strong for generating tract-scale indicator families from aggregated infrastructure data and for testing how different translation assumptions affect the resulting urban profile. Their joint value lies in showing that transferability research must begin from analytical equivalence, not from the availability of similarly named variables.

The methodological frameworks presented here offer direct support for municipal Sustainable Energy and Climate Action Plans. For the City of Naples, the 93% geocoding

success rate enables hotspot mapping at the street-segment level, allowing planners to prioritise building-envelope retrofitting subsidies for specific high-consumption blocks. In Porto, the top-down approach provides a sensitivity analysis tool for policy-makers; by comparing area-weighted vs. volume-weighted demand, technicians can more accurately estimate the impact of urban morphology on energy poverty. These data-driven insights transform administrative noise into actionable intelligence, ensuring that interventions are targeted where the intersection of social vulnerability and energy inefficiency is most acute.

Failures persist in both methodologies, which must be considered for sound decision-making. In Naples, the 7% of geocoding-resistant records were randomly spread, indicating no systemic geographic bias in the final spatial indicators. In Porto, sensitivity analysis showed that switching from area-based to building-volume-weighted allocation caused an average variance of 12% in tract-level estimates, emphasizing the need to use morphological proxies when user-level data is unavailable.

Future work should therefore focus on completing the harmonisation process rather than merely extending the modelling stage. On the Naples side, this includes finalising the denominator choice for the primary comparison track and documenting residual geocoding uncertainty at the selected support. On the Porto side, it includes clarifying the extent to which mixed low-voltage demand can be aligned with a residential comparison target and quantifying the sensitivity of the results to the chosen allocation rule. Only after these steps can Porto and Naples sustain a robust comparative modelling framework.

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## References

1. Feitosa, F.O., Batista, P., Marques, J.L.: How to assess spatial injustice: distinguishing housing spatial inequalities through housing choice. Cities **140**, 104422 (2023). https://doi.org/10.1016/j.cities.2023.104422
2. Ascione, L., Gargiulo, C., Guida, C.: Adaptation and energy saving through urban green spaces in climate action plans: the experiences of 20 global cities. TeMA – J. Land Use, Mobility Environ. **2**, 31–46 (2025)
3. Gargiulo, C., Guida, C.: Climate-proofing cities: a focus on vulnerability indices. Int. Planning Stud. 1–19 (2026)
4. Weaver, T.: Urban crisis: the genealogy of a concept. Urban Stud. **54**(9), 2039–2055 (2017)
5. Carpentieri, G., Gargiulo, C., Guida, C., Zucaro, F.: Beyond city average: spatial analysis to support energy-saving interventions in urban planning. In: Gervasi, O., Murgante, B., Garau, C., Taniar, D., Rocha, A.M.A., Faginas Lago, M.N. (eds.) ICCSA 2024 Workshops. LNCS, vol. 14818, pp. 1–13. Springer, Cham (2024)
6. Long, Y., Liu, L.: Transformations of urban studies and planning in the big/open data era: a review. Int. J. Image Data Fusion **7**(4), 295–308 (2016)
7. Wang, C., Yin, L.: Defining urban big data in urban planning: literature review. J. Urban Planning Dev. **149**(1) (2022)

8. Barbosa, L., Pham, K., Silva, C., Vieira, M.R., Freire, J.: Structured open urban data: understanding the landscape. Big Data **2**(3), 144–154 (2014)
9. Östh, J., Nørgaard, N.F., van der Laag-Yamu, C.: The role of delineation for decision making and urban governance. In: Džunić, M., Östh, J., Muratori, S. (eds.) Advancing Urban and Local Governance in Western and Transition Europe. Local and Urban Governance. Springer, Cham (2026)
10. Janssen, M., Charalabidis, Y., Zuiderwijk, A.: Benefits, adoption barriers and myths of open data and open government. Inf. Syst. Manag. **29**(4), 258–268 (2012)
11. Marie, P.: Using geocoded data in maps. In: Modern Web Cartography. Apress, Berkeley, CA (2026)
12. Pérez, V., Aybar, C.: Challenges in geocoding: an analysis of R packages and web scraping approaches. ISPRS Int. J. Geo Inf. **13**(6), 170 (2024)
13. Fichera, A., Frasca, M., Palermo, V., Volpe, R.: An optimization tool for the assessment of urban energy scenarios. Energy **156**, 418–429 (2018). https://doi.org/10.1016/j.energy.2018.05.114
14. Tavakkoli, S., Macknick, J., Heath, G.A., Jordaan, S.M.: Spatiotemporal energy infrastructure datasets for the United States: a review. Renew. Sustain. Energy Rev. **152**, 111616 (2021). https://doi.org/10.1016/j.rser.2021.111616
15. Hong, T., Chen, Y., Luo, X., Luo, N., Lee, S.H.: Ten questions on urban building energy modeling. Build. Environ. **168**, 106508 (2020). https://doi.org/10.1016/j.buildenv.2019.106508
16. HosseiniHaghighi, S., de Uribarri, P., Padsala, R., Eicker, U.: Characterizing and structuring urban GIS data for housing stock energy modelling and retrofitting. Energy Build. **256**, 111706 (2022). https://doi.org/10.1016/j.enbuild.2021.111706
17. Zandbergen, P.A.: Geocoding quality and implications for spatial analysis. Geogr. Compass **3**(2), 647–680 (2009). https://doi.org/10.1111/j.1749-8198.2008.00205.x
18. Helderop, E., Nelson, J.R., Grubesic, T.H.: 'Unmasking'masked address data: a medoid geocoding solution. MethodsX **10**, 102090 (2023). https://doi.org/10.1016/j.mex.2023.102090
19. Geng, G., et al.: Impact of spatial proxies on the representation of bottom-up emission inventories: a satellite-based analysis. Atmos. Chem. Phys. **17**, 4131–4145 (2016). https://doi.org/10.5194/acp-17-4131-2017
20. Zheng, B., et al.: Resolution dependence of uncertainties in gridded emission inventories: a case study in Hebei, China. Atmos. Chem. Phys. **17**, 921–933 (2016). https://doi.org/10.5194/acp-17-921-2017

# Configurational Accessibility and Mobility Patterns in a Port-City Interface: A Space Syntax Analysis of Central Catania

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**Abstract.** Port-city interfaces represent complex urban environments where spatial accessibility, mobility patterns and functional constraints often interact in critical ways. This study investigates the relationship between the spatial configuration of the urban street network and observed movement dynamics within the historical center of Catania, specifically focusing on the port-city interface between Paolo Borsellino Square and Via Dusmet. By proposing an integrated methodology combining Space Syntax and empirical flow analysis, the research explores key configurational measures, i.e. connectivity, integration and choice, computed using an axial map; then, theoretical findings are cross-referenced with empirical data collected through gate counts, distinguishing between pedestrian and vehicular flows.

The results reveal a significant correlation between pedestrian movement and configurational accessibility, suggesting that the spatial structure of the network effectively guides pedestrian flows towards the city's monumental core. In contrast, vehicular traffic shows a weak relationship with the spatial hierarchy, being primarily influenced by external factors, such as port access and traffic regulation. These findings highlight a mismatch between the inherent spatial logic of the area and current traffic conditions, suggesting a high potential for pedestrian-oriented reorganization of the port- city interface.

**Keywords:** Spatial Analysis · Urban Mobility · Space Syntax · Gate counts · Urban Morphology · Accessibility

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## 1 Introduction

In modern urban planning, accessibility has become a key framework for understanding the developing relationship between port infrastructures and the nearby urban fabric. While in the past the port-city interface was identified by a heavy functional synergy, recent changes have progressively turned these areas into zones of friction, producing negative externalities such as physical disintegration and socio-spatial separation. In this context, accessibility plays a key role in determining the barriers that separate the waterfront from the urban fabric, obstructing equitable access to the socio-economic opportunities associated with the maritime-urban interface [1]. Dissimilar generalized urban expansion processes, disconnection in port-city environments often result from a structural imbalance between logistical and urban systems. The expansion of port-related infrastructures regularly reduces the permeability of neighboring urban areas, creating spatial breaks that affect the general quality of urban life [2]. These dynamics provide irregular accessibility conditions, where different parts of the urban system experience considerably different levels of connectivity to services and opportunities [3].

Within this framework, port systems constitute highly strategic and complex nodes in the urban fabric [4]. In this context, the systematic review of transport networks supplies as the fundamental basis for planning processes, since the transport network forms the infrastructural framework through which port functions interface with urban mobility [5]. Maritime transport, despite the evolution of other modes, proceeds to play a central role in global commerce, reinforcing the importance of port infrastructures in urban planning. The presence of port terminals presents additional functional and spatial complexity, needing integrated planning approaches able of managing the interaction between logistics and urban life [6]. Port systems can be understood as dual structures, constituted of seaside (the water area containing basins and water bodies) and landside components (the terrestrial side dedicated to the movement of goods and passengers), whose interaction causes critical spatial interfaces.

In port-city framework, these topics become especially pertinent in areas exposed to freight-related externalities, where the organization of bordering spaces may help moderate the pressure produced by port activities on the urban fabric and improve overall logistics efficiency [7].

The port-city interface is therefore increasingly identified by spatial and functional intersections, where urban activities and logistical operations coexist and often conflict. This coexistence necessitates a critical investigation of these dynamics to mitigate their negative effects [8]. In this point of view, the idea of the waterfront adopts relevance as a transitional space where the urban fabric meets the maritime domain. These areas show key opportunities for sustainable urban regeneration, focusing on balancing port efficiency and functional requirements with urban habitability through aimed redevelopment and revival strategies [9].

Within this wider perspective, the integration of urban planning and mobility strategies becomes essential to guarantee that spatial structure and transport dynamics are addressed logically, particularly in complex urban environments where accessibility, safety, and walkability must be jointly regarded [10].

To deal with such complexity, this study takes on the theoretical and methodological structure of Space Syntax [11], which envisages spatial configuration as a crucial

driver of movement patterns and urban activity. This approach interprets the structure of the street network as an active element enhancing accessibility and flows. Through the analysis of configurational properties, Space Syntax supplies a quantitative basis for understanding movement dynamics within urban systems [12], making it especially pertinent for investigating complex port-city interface areas. Recent studies have proved the utility of Space Syntax for examining port-city environments and waterfront transformations, containing quantitative analysis of port-area morphology and historical analyses of port-city interface evolution [13, 14]. However, these applications have mostly concentrated on morphological and configurational meaning, rather than on the empirical verification of configurational measures through observed movement data.

Although a significant body of literature has examined the relationship between space syntax measures and urban movement, a notable research gap remains concerning the empirical performance of these models in high-friction environments, such as port-city interfaces. While the theoretical framework established by Hillier and Hanson [11] suggests that spatial configuration is a primary driver of *natural movement*, in transitional maritime-urban zones this logic often interacts with and is potentially distorted by strong functional limitations and logistical pressures.

Existing studies on port-city areas, such as the quantitative morphology analysis of the Xiamen port [13] or the historical evolution of the Algiers interface [14], provide valuable insights into the spatial development and configurational meaning of these zones. However, they frequently lack a simultaneous, dual-mode empirical verification (pedestrian vs. vehicular) of how spatial hierarchy operates under the weight of port-related externalities. Empirical studies combining Space Syntax analysis with gate counts to directly compare configurational accessibility with observed pedestrian and vehicular flows in port-city intermediate areas remain limited. This study addresses this discrepancy by examining the relationship between the syntactic attributes of the street network and observed movement patterns in the port-city interface of Catania. The research focuses on a strategic area connecting the historic center with the port, focusing to evaluate whether spatial configuration can describe actual mobility dynamics. An integrated approach is adopted, joining Space Syntax analysis with empirical flow data collected through gate counts, allowing for a direct comparison between configurational accessibility and observed movement. By concerning configurational properties to observed movement, the study supply evidence on how spatial structure influences mobility in port-city transitional areas and provides insights for accessibility-oriented regeneration strategies.

## 2 Methodological Approach

### 2.1 Spatial Configuration Analysis via Space Syntax

The theoretical framework of the research lies in Space Syntax, a methodology that interprets the built environment not as a simple aggregate of individual streets, but as a system of combined spatial relations. According to Space Syntax ideals, the settlement's road network is understood as a collection of interconnected axial lines, which provide as the primary units of the system, defining both its spatial structure and the related accessibility between all its parts. [11, 15].

The approval of this analytical unit derives from the monitoring of navigation behaviors: evidence proposes that those moving through urban space, whether pedestrians or drivers, tend to arrange trajectories that minimize angular differences relative to their destination [16, 17]. Therefore, the axial line is not just a geometric notion; it shows the human tendency to reduce cognitive load during movement by limiting the number of turns necessary to navigate the territory [15, 18].

For the purposes of this analysis, the configuration of the street network is quantified through three main syntactic measures [19]:

- connectivity, a local measure describing the number of direct links of each axial line and, therefore, the immediate permeability of the network.
- integration, a measure of configurational accessibility expressing how central or segregated each axial line is within the overall system.
- choice, a measure of through-movement potential, identifying the routes most likely to be used as paths between different origins and destinations.

In addition, the study considers intelligibility, assessed as the statistical correlation between connectivity and global integration. This parameter expresses the extent to which local spatial properties reflect the global structure of the system and therefore provides an indication of the legibility of the urban environment [20–23].

The spatial modelling process was developed through a sequence of CAD-based and syntactic analysis operations, with axial mapping adopted as the primary tool for investigating the configurational properties of the street network and their relationship with pedestrian and vehicular movement patterns.

First, the technical cartography of the study area was obtained and updated. The cartographic base was then refined in AutoCAD, where the necessary geometric corrections were introduced to guarantee the topological continuity of the network. The resulting drawing was exported in DXF format and imported into DepthmapX. Within this analytical environment, the axial map was produced, permitting the construction of the relational graph required for subsequent configurational analyses. This workflow allowed the extraction and quantification of the main spatial variables, i.e. connectivity, integration, choice, and intelligibility, which give objective numerical values for describing the morphological structure of the urban and port fabric under investigation.

### 2.2 Data Collection Through Gate Counts Technique

To evaluate actual movement dynamics, the research embraces the Gate Counts technique, a combined methodology for measuring traffic density and volumes within urban space [20]. This approach was used to collect empirical data on both pedestrian and vehicular movement, allowing for a direct comparison between observed flows and syntactic properties of the street network. The option of monitoring points (gates) was implemented according to a layered sampling approach, based on the syntactic properties that appeared during the modeling phase. Particularly, the gates were scattered to represent different spatial conditions within the study area, including highly integrated routes, more separated segments, streets close to the port access, and transitional areas between the waterfront and the historic center. This scattering guaranteed adequate coverage of the morphological and functional heterogeneity of the study area.

Field observations were carried out under similar observation conditions, guaranteeing clear visibility of each monitored section and the reliability of the counts. At each gate, pedestrian and vehicular flows were recorded separately, to explore possible variations in the relationship between spatial configuration and movement patterns. Depending on [24], the use of gate counts in this study serves two main purposes: first, to verify the extent to which the syntactic model is consistent with actual movement patterns; and second, to determine whether configurational accessibility impacts pedestrians and vehicles in a different way within the port-city interface.

### 2.3 Syntactic Analysis

The final stage of the methodology consists of statistically comparing the main syntactic measures, connectivity, integration, and choice, with the empirical flow data collected through gate counts. For each monitored gate, observed pedestrian and vehicular volumes were associated with the configurational values of the corresponding axial line. The analysis was performed using Pearson's correlation coefficient and simple linear regression, implemented in an Excel environment.

The methodological approach involves crossing the three analyzed syntactic measures introduced above, i.e. connectivity, integration and choice, with the observed pedestrian and vehicular flows derived from the gate counts.

Separate correlation and regression analyses were performed for pedestrian and vehicular flows to identify possible differences in the way spatial configuration influences the two movement patterns. For each analysis, the coefficient of determination (R2) was extracted and used as an indicator of the model's ability to explain the variance in the observed flows.

Finally, intelligibility was assessed as the statistical correlation between connectivity and integration. This indicator was used to evaluate the legibility of the urban fabric, namely the extent to which local spatial properties reflect the global structure of the system. Higher correlation values indicate a more readable and navigable environment, whereas lower values suggest a more fragmented spatial configuration.

## 3 Case Study

The analysis focuses on a strategic sector of Catania's urban fabric, located in the transition zone between the historic center and the access to the tourist port. Although Catania expands over a complex urban area of about 180 square kilometers, the center of this research lies in this specific area, where metropolitan traffic strains and the mobility demand produced by around 300,000 residents, together with an extensive service area of commuters from the hinterland, converge towards the waterfront [25].

The study area constitutes a critical interface space, where the urban street network accommodates the complex coincidence of urban, tourist, and port-related flows. Within this transitional area, despite the availability of public transport infrastructure and services in the nearby urban area, there is a prevalence of private vehicle use. This condition highlights a structural weakness within the port-city interface, where public transport

alternatives do not constitute a competitive enough option to the flexibility of private vehicles.

As a result, accessibility to the port and waterfront is strongly influenced by road-network saturation and frequent congestion. In this context, the case study gives an appropriate setting for analyzing whether the configurational structure of the street network is consistent with the observed distribution of pedestrian and vehicular flows.

### 3.1 Territorial Framework

Due to daily travel patterns and the strategic attraction of the waterfront, the primary traffic routes in the area correspond with the main access corridors leading to the historic center and the port infrastructures. Indeed, the area is also impacted by its proximity to the central railway station, which behaves as a major regional mobility attractor, focusing a constant mobility demand on the local road network. As shown in Fig. 1, the study area provides as a development and distribution node between the railway infrastructure, the port basin and the historic urban fabric. Key corridors such as Via Dusmet and the roads connecting the waterfront to the historic center play a strategic role in port access, local circulation, and the distribution of incoming and outgoing flows.




**Fig. 1.** Study area and POIs

Despite the significant presence of public transport lines and the proximity to railway system, mobility in the area is still dominated by private vehicles. Traffic volumes are further increased by the presence of points of interest (POIs) related to yachting activities and to the tourist and commercial attractiveness of the historic center.

At the same time, the road configuration has experienced several alterations over time to manage the coexistence of port-related logistic operations and urban mobility in a sector influenced by chronic saturation.

### 3.2 Data Collection

Following the initial observations performed on the study area and the studies of the main flow patterns characterizing the port-city interface, particular monitoring sections were

identified. The choice of these sections was planned to provide direct empirical references within the studied network, thus allowing the syntactic analysis to be compared with the actual dynamics of movement.

Specifically, four crucial sections along Via Dusmet were selected and marketed as Gate Counts (C1, C2, C3, C4), as shown in Fig. 2.

These locations were selected because they catch different movement conditions within the port-city interface, including access-related traffic, urban circulation, and the influence of nearby transport nodes. Their position also reveals the pressure produced by the nearby central railway station and by the bus services operating in the area.

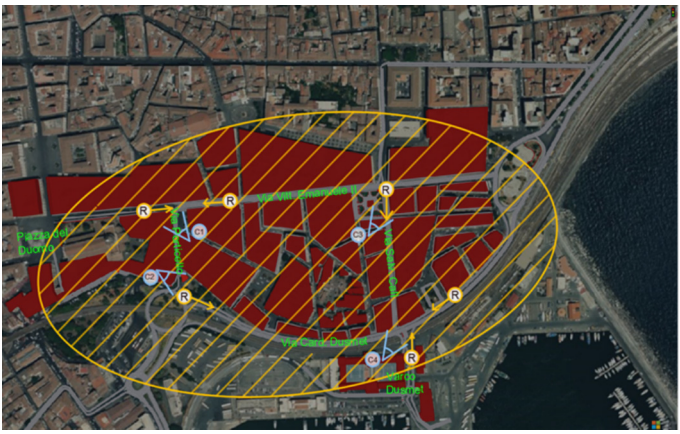


**Fig. 2.** Gate counts

**Intelligibility**

Intelligibility represents the degree when a user can understand the global structure of the city based on local visual cues, such as immediate intersections. Mathematically, it expresses the correlation between Connectivity (local scale) and Integration (global scale).

Figure 3 displays the plot with a positive regression line ($y = 0.0225x + 0.0225$), with a coefficient of determination of $R^2 = 0.25$. In an organic and historical urban fabric context, this value indicates a moderate intelligibility. While the system is not immediately readable as a regular grid, it still displays a detectable configurational logic: the red and orange points (top-right) confirm that streets with higher local connectivity tend also to have more central positions within the overall network.

The dots clustered in the upper part of the graph are associated to the main axis and the Paolo Borsellino Square core. In these areas, intelligibility is higher (i.e. pick values), allowing users to immediately perceive their position within the system. By contrast, the intensity of blue and green dots in the lower-left part of the plot represents the secondary street network, where low connectivity is associated with greater configurational segregation.

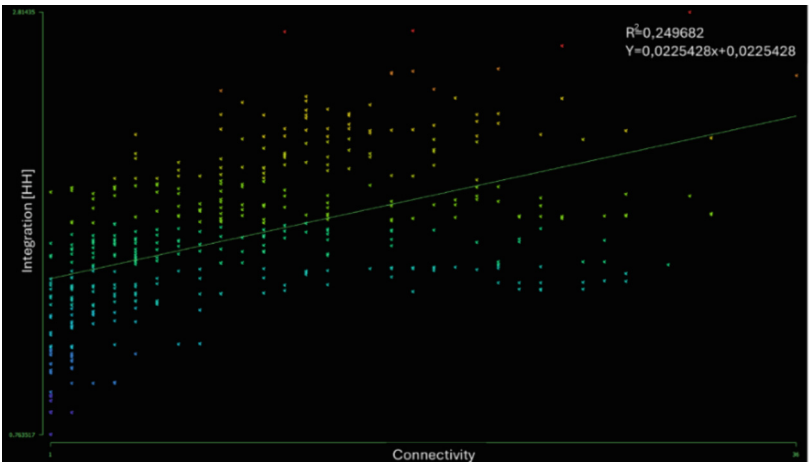


**Fig. 3.** Intelligibility plot

## 4 Results

This section shows the results acquired through the configurational analysis of the network and empirical field observations. First, the spatial structure of the case study is reviewed by processing Connectivity, Choice, and Integration maps to determine the morphological hierarchy and the degree of intelligibility of the urban fabric. Subsequently, the parameters obtained from the syntactic analysis are related to the data collected through Gate Counts to verify the model's stability with the observed real-world flows. The investigation uses the coefficient of determination ($R^2$) as a key statistical indicator to assess the extent to which the spatial configuration describes the distribution of the observed movement. Finally, the comparison between pedestrian and vehicle flows highlights the different movement logics defining the study area.

### 4.1 Space Syntax Analysis

Configurational analysis through Space Syntax permits the complexity of the urban fabric to be understood by transforming street geometry into numerical values that describe its spatial hierarchy. This section analyzes the four fundamental parameters that define the movement potential and legibility of the study area.

**Connectivity**
The connectivity map (Fig. 4), developed through DepthmapX, reveals the local hierarchical structure of the urban fabric. In this representation, the chromatic gradient represents different levels of direct connection among axial lines. The map is controlled by a clear axis colored deep red, equivalent to the main artery of the study area. This segment records the highest number of direct intersections and therefore the highest local connectivity with alleyways and secondary streets. The orange and yellow areas branching out from the main axis symbolize secondary distribution roads, which perform as connectors between the central core and the surrounding streets. By contrast,

the light blue and blue lines determine alleyways and local streets, which exhibit low connectivity because they are connected to a limited number of other lines or are dead ends.

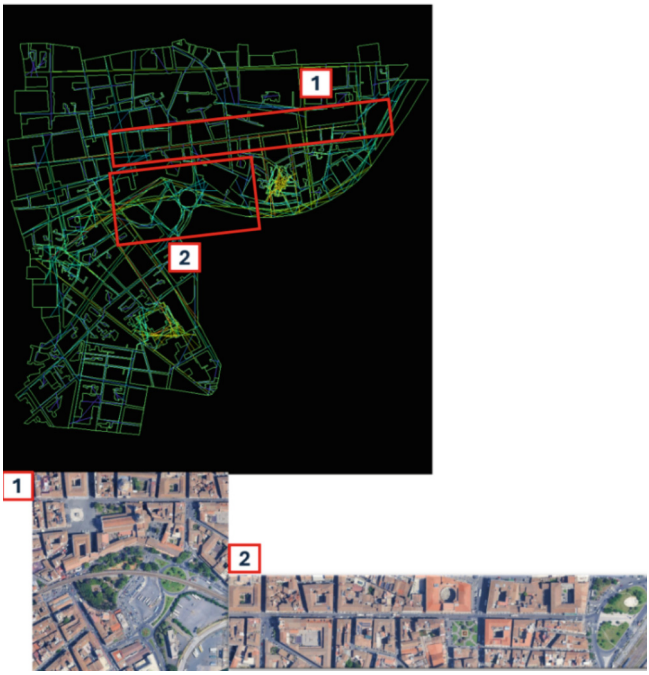


**Fig. 4.** Connectivity attribute: (1) Via Vittorio Emanuele II; (2) Duomo

The connectivity analysis shows significant values along the axis of Via Vittorio Emanuele II (Fig. 4, detail 1), one of the city's most important arteries, can distribute traffic flows between the top part of the city and the waterfront. A second area characterized by high connectivity is Duomo Square (Fig. 4. Detail 2), dominated by Saint Agatha Cathedral. The high connectivity in this area shows the importance of the site and indicates how the street grid converges toward this public space, developing a fundamental pedestrian and vehicular distribution node. The spatial structure thus seems to support the monumental hierarchy: the Saint Agatha Cathedral and the Duomo serve not only as tourist destinations but also as central hubs integrated into the local network, promoting the overall permeability of the historic center.

**Choice**

The Choice attributes measure the through-movement potential of each street within the system. In DepthmapX, this value indicates which streets are most frequently selected as the shortest path between different origins and destinations. Referring to the Choice map (Fig. 4), a single, prominent deep red line is clearly visible.




**Fig. 5.** Choice attribute: (1) Via Vittorio Emanuele II

This indicates that one axis (Fig. 5, detail 1) concentrates most of the through-movement potential within the analyzed network. Due to its strategic position and linearity, this route functions as the main movement corridor. In an urban fabric characterized by numerous secondary streets and alleys (shown in blue), the main axis acts as a primary channel for movement across the system. Consequently, the Choice value is highly concentrated along this axis, while the remaining streets show lower values and play a more local role.

**Integration**

Integration (Fig. 6) measures the global accessibility of urban network. In Space Syntax, it describes how topologically close a street is to all other streets in the system by given the number of directional changes (turns) required to arrive at any point in the network. A highly integrated street therefore symbolizes an accessibility core within the system.

The most noticeable element is the long horizontal axis (Fig. 6, detail 1) shown deep red. This represents the main artery of the area, crossing the urban fabric and guaranteering maximum continuity. In syntactic terms, this road acts as a global collector, concentrating movement from different parts of the system, thereby decreasing the topological effort required to navigate the neighborhood.

Close to this artery, the integration core expands, with peak values, in Paolo Borsellino Square area (see Fig. 6, detail 2). This node is not only a transit point but also a central configurational element within the system. Its importance is related to its strategic position within the Dusmet area, which serves as a transition point between the tourist port and the historic center, including the area of Saint Agatha Cathedral. The

high integration values extending on both sides of the square confirm that this sector represents the main accessibility core for movement between the waterfront and the monumental center.

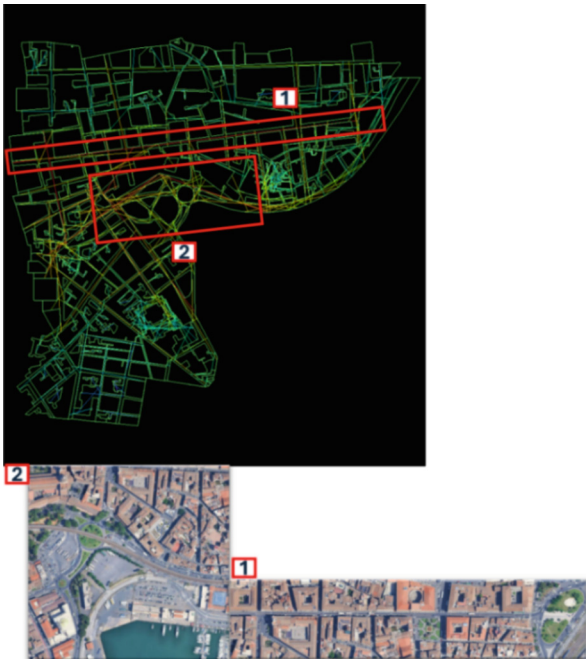


**Fig. 6.** Integration attribute: (1) Via Vittorio Emanuele II; (2) Paolo Borsellino Square

### 4.2 Empirical Observation: Gate Counts Analysis

This section analyzes the total pedestrian and vehicular traffic volumes recorded during the survey (from 4:30 p.m. to 5:30 p.m.). The data were collected at four strategic gates (i.e. C1, C2, C3, C4, as shown in Fig. 2) to outline the observed distribution of movement within the study area.

Table 1 summarizes the hourly totals pedestrian and vehicular flows recorded at the four analyzed gates. The data shows a clear hierarchical variation between the points of the network.

**Table 1.** Pedestrians and vehicular flows.

| Gate count | Pedestrians | Vehicles |
|---|---|---|
| C1 | 171 | 882 |
| C2 | 52 | 2002 |
| C3 | 42 | 589 |
| C4 | 51 | 2130 |

The data show a higher concentration of pedestrian flows toward the northern sector of the area. In more detail, Gate C1 records the highest pedestrian volume, with a total of 171 movements. This value makes the area as the main pedestrian attractor during the investigated period. Gates C2, C4, and C3 show substantially lower and more homogeneous pedestrian volumes. Specifically, Gates C2 and C4 record very similar values (52 and 51 pedestrians, respectively), while Gate C3 shows the lowest value for the area with only 42 pedestrian movements.

The vehicular pattern differs from the pedestrian results, emphasizing the transit role of the perimeter roads. Gates C4 and C2 represent the main transit corridors of the area, with volumes exceeding 2000 units (i.e. 2130 vehicles at gate C4 and 2002 at gate C2). The high traffic intensity recorded at these gates is consistent with their strategic role in traffic distribution, particularly for Gate C4, located near the port entrance. Gate C1, despite its pedestrian prominence, records a lower vehicular volume with 882 vehicles, suggesting a role more closely related to local distribution rather than to major through-traffic. Gate C3 records the lowest vehicular volume, with 589 vehicles, confirming its more marginal role within the traffic hierarchy.

### 4.3 Correlation Between Syntax and Observed Flows

The statistical analysis conducted through the scatter plots suggests a differentiated relationship between syntactic measures and observed movement within the study area.

The three graphs shown in Fig. 7, Fig. 8 and Fig. 9 related to pedestrians show a positive trend, indicating that higher syntactic values are associated with higher pedestrian flows.

The relationship between pedestrian flows and choice yields an $R^2 = 0.995$), indicating an almost perfect linear correspondence between the observed values. Although this result suggests a very strong association between through-movement potential and pedestrian flows, it should be interpreted with caution due to the limited number of monitored gates. The correlation between pedestrian flows and connectivity is also high (R2 = 0.86), indicating that local permeability and direct connections are closely associated with pedestrian presence. The relationship between pedestrian flows and integration, although slightly lower (R2 = 0.72), still indicates a substantial association between global configurational accessibility and pedestrian movement. Overall, these results suggest that pedestrian flows are more consistent with the configurational structure of the street network, particularly in relation to choice and connectivity.

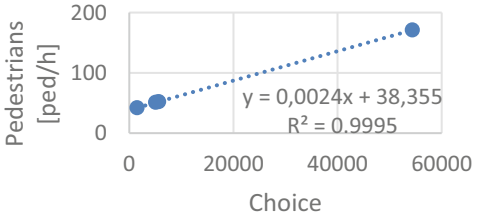


**Fig. 7.** Relationship between pedestrian flows and choice

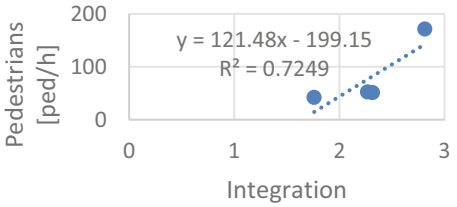


**Fig. 8.** Relationship between pedestrian flows and integration

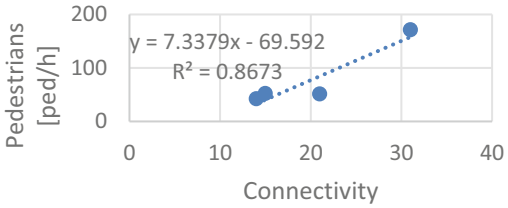


**Fig. 9.** Relationship between pedestrian flows and connectivity

By contrast, the plots related to vehicular flows in Fig. 10, Fig. 11 and Fig. 12 show weaker and less coherent relationships.

The relationship between vehicular flows and integration is extremely weak (R2 = 0.026), as is the relationship with connectivity (R2 = 0.029), indicating that vehicular traffic is only marginally associated with the natural centrality or local permeability of the network. The relationship between vehicular flows and choice is slightly stronger (R2 = 0.14) but still limited. This suggests that vehicular movement is only weakly associated with the through-movement potential identified by the syntactic model. Overall, these results indicate that vehicular flows are influenced less by the configurational structure of the street network and more by external functional factors, such as port-related access, traffic regulation, and the operational role of specific road sections.

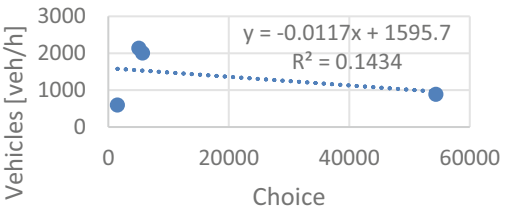


**Fig. 10.** Relationship between vehicular flows and choice

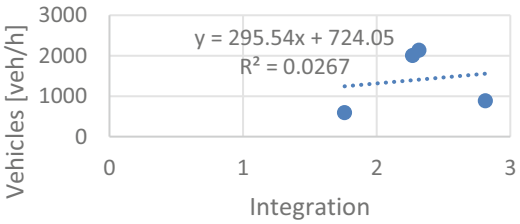


**Fig. 11.** Relationship between vehicular flows and integration

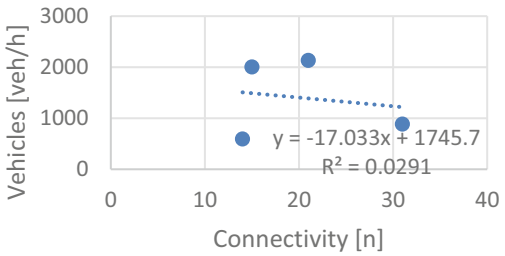


**Fig. 12.** Relationship between vehicular flows and connectivity

### 4.4 Discussion

The results highlight a differentiated relationship between spatial configuration and observed movement within the port-city interface of Catania. On the one hand, pedestrian flows show a relatively strong correspondence with the syntactic structure of the street network, particularly with respect to choice and connectivity. This suggests that pedestrian movement in the study area is closely associated with configurational properties such as route continuity, directness, and local permeability. Streets that are more accessible and more likely to be traversed within the network also tend to attract higher pedestrian volumes.

On the other hand, vehicular flows have weak relationships with the syntactic measures considered. In fact, integration and connectivity do not explain traffic volumes reasonably, while choice shows only a limited association. This result suggests that vehicular movement in the study area is not mainly modelled by the intrinsic configurational logic of the urban grid.

This discrepancy highlights a fundamental challenge in contemporary traffic systems within historical port-city interfaces: the conflict between *natural movement* and *forced movement*. While the historical urban fabric of Catania still dictates legible logic for pedestrians, vehicular traffic is increasingly decoupled from the spatial grid due to rigid traffic management, such as one-way systems and signalization, which override the natural hierarchy of the network.

In the specific context of the port, this mismatch is further exacerbated by the role of the waterfront as a logistical corridor. Road sections like Via Dusmet function as forced channels for heavy-duty vehicles and port-related flows that are not exploring the city, but are being funneled toward specific gateways (i.e., the port entrance). This magnet effect of the port infrastructure creates a high-pressure environment where logistical efficiency

takes precedence over urban accessibility. Consequently, contemporary mobility patterns in this area are driven by external functional demands rather than the inherent properties of the street network, representing a significant barrier to the morphological integration of the waterfront.

This divergence between pedestrian and vehicular patterns is particularly meaningful in a port-city transitional environment, where different mobility logics coexist within a limited space. Pedestrian movement appears to have a more direct correlation with the spatial structure of the urban fabric, whereas vehicular traffic is influenced by infrastructural and functional pressures that partially defy the natural hierarchy of the street network. From this perspective, the study area can be interpreted as a space in which configurational accessibility still supports pedestrian movement, but where vehicular circulation reflects a more externally driven pattern.

As a result, the current mobility structure may reduce the potential of the waterfront as an integrated and accessible urban space. At the same time, the empirical validation is based on a limited number of monitored sections and on observations conducted within a specific time window. Therefore, the statistical relationships identified in this study should be regarded as context-specific and exploratory. Nevertheless, the observed patterns provide a useful indication of how Space Syntax can support the interpretation of movement dynamics in complex port-city environments.

### 4.5 Policy Implications

The relative relationship between configurational accessibility and pedestrian flows indicates that urban design and mobility policies should build upon the existing spatial logic of the street network. In practical terms, to reinforce pedestrian continuity along the most accessible axes some infrastructural interventions can be planned, e.g. improve crossings, sidewalk quality. In addition, introduce wayfinding systems to strengthen the natural walkability of the connection between the waterfront and the historic center. Conversely, the weak relationship between syntactic measures and vehicular flows suggests that road traffic in the area is driven less by urban form than by functional and operational constraints. This implies that traffic management strategies cannot rely only on the existing street configuration but should address port-related access and the regulation of vehicular circulation. Therefore, measures such as selective access control, traffic calming, redistribution of port-related movements, and the reorganization of loading and operational functions may be necessary to reduce pressure on the urban network.

The mismatch between pedestrian-oriented spatial accessibility and vehicle-dominated traffic conditions highlights the need for a more balanced mobility framework in the port-city interface. Some policies could help to increase the coherence between the spatial structure of the area and its actual usage patterns. They can be related to the improvement of intermodality, strengthening the connections with the railway station and public transport services, and limiting avoidable private vehicular traffic.

## 5 Conclusions and Future Research

This study explored the relationship between the configuration of the network and observed movement patterns at port-city interface of Catania, with a focus on the Dusmet-Paolo Borsellino Square area. The findings indicate that pedestrian flows are more closely associated with the configurational properties of the street network respect to vehicular flows. Choice, connectivity, and integration show a meaningful correspondence with pedestrian movement, suggesting that the spatial structure of the area supports pedestrian accessibility towards the historic center and the waterfront interface.

By contrast, vehicular flows exhibit only weak relationships with calculated syntactic measures. This should indicate that vehicular movement in the area is greater shaped by functional and operational constraints, including port access and traffic regulation. Thus, this divergence highlights a mismatch between the inherent spatial logic of the area and its current mobility patterns, especially in the transition between the waterfront and the historic urban fabric.

In this regard, from a methodological point of view, the study confirms its usefulness, combining Space Syntax analysis with empirical gate counts to investigate movement dynamics in complex port-city environments. The proposed approach provides an interpretable framework to correlate configurational accessibility with observed flows, distinguishing between pedestrian and vehicular mobility patterns.

At the same time, the results should be interpreted considering some limitations. The empirical analysis is based on a limited number of monitored sections and on observations conducted within a specific time window. While this basis is sufficient for an exploratory study aimed at testing the methodology in a complex interface, the statistical relationships identified here should be regarded as context-specific rather than a final generalization of urban behavior.

Future research should therefore aim to strengthen the empirical basis of the analysis by expanding the monitoring network (increasing the number of gate counts) and extending the observation campaign to different time periods and urban sectors characterized by different morphological conditions. Furthermore, expanding the spatial boundaries of the configurational model would be essential to verify the stability of the syntactic measures and to mitigate potential edge effects, ensuring that the integration and choice values remain consistent when considering a larger portion of the urban network. In addition, the inclusion of multimodal data, such as public transport and micromobility flows, could provide a more comprehensive understanding of movement dynamics in Catania and support more robust evidence-based planning strategies.

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**Authors Contribution.** This paper is the result of the joint work of the authors. V.T., S.B., R.A., and C.G. contributed to the abstract, Sect. 2.1 (Spatial Configuration Analysis via Space

Syntax), and Sect. 5 (Conclusions and future research). C.G. drafted Sect. 1 (Introduction). V.T. was responsible for Sect. 2.2 (Data collection through Gate Counts technique) and Sect. 3.2 (Data collection), as well as Sects. 4.2 (Empirical observation: Gate counts analysis) and 4.3 (Correlation between Syntax and observed flows). S.B. was responsible for Sect. 2.3 (Syntactic Analysis), Sect. 3.1 (Territorial framework), Sect. 4.1 (Space syntax analysis), and Sect. 4.5 (Policy implications). R.A. was responsible for Sect. 4.4 (Discussion). M.I. contributed to supervision and funding acquisition.

## References

1. Borlini, B., Memo, F.: Ripensare l'accessibilità urbana. Cittalia Fondazione Anci ricerche, 2 (2009)
2. Castrignanò, M., Colleoni, M., Pronello, C.: Muoversi in città. Accessibilità e mobilità nella metropoli contemporanea: Accessibilità e mobilità nella metropoli contemporanea. FrancoAngeli (2012)
3. Pronello, C., Boffi, M.: Muoversi in città: accessibilità e mobilità nella metropoli contemporanea (Vol. 27). FrancoAngeli (2012)
4. Ignaccolo, M., Inturri, G., Giuffrida, N., Torrisi, V., Cocuzza, E.: Sustainability of freight transport through an integrated approach: the case of the eastern sicily port system. Transp. Res. Procedia **45**, 177–184 (2020)
5. Torrisi, V., Leonardi, P., Ignaccolo, M.: Modeling network-based accessibility to analyze the transport network vulnerability: the case study of Catania (Italy). Transp. Res. Procedia **90**, 911–918 (2025)
6. Petrella, B.: Relazione città-porto-waterfront: complessità e complicazioni. Territorio della Ricerca su Insediamenti e Ambiente. Rivista internazionale di cultura urbanistica **11**, 89–102 (2013)
7. Giuffrida, N., Ignaccolo, M., Inturri, G., Torrisi, V.: Port-city shared areas to improve freight transport sustainability. In: International Conference on Computational Science and Its Applications, pp. 67–82. Springer, Cham (2020)
8. Scattaglia, A.: Interazione porto-città: fra pianificazione portuale e novità legislative (2021)
9. Cocuzza, E.: Sostenibilità dei sistemi portuali in ambito urbano–Valutazione dell'accessibilità non motorizzata nelle aree di interfaccia porto/città (2016)
10. Torrisi, V., Leonardi, P., Ignaccolo, M., Inturri, G., Rossetti, S.: Towards safer and more walkable cities: a spatial approach in sustainable urban mobility plans. Eur. Transp.\Trasporti Europei, **105** (2026)
11. Hillier, B., Hanson, J.: The Social Logic of Space. Cambridge University Press, Cambridge (1989)
12. Hillier, B., Vaughan, L.: The city as one thing. Prog. Plan. **67**(3), 205–230 (2007)
13. Yu, X., Zhao, Z.: Quantitative space morphology of Xiamen port area maps based on space syntax analysis. In: 2017 IEEE International Conference on Signal Processing, Communications and Computing (ICSPCC), pp. 1–4. IEEE (2017)
14. Aouissi, K.B., Madani, S., Baptist, V.: Morphological evolution of the port-city interface of Algiers (16th century to the present). Urban Planning **6**(3), 119–135 (2021)
15. Hillier, B.: The hidden geometry of deformed grids: or, why space syntax works, when it looks as though it shouldn't. Environ. Plann. B. Plann. Des. **26**(2), 169–191 (1999)
16. Paul, A.: Reviewing the axial-line approach to capturing vehicular trip-makers' route-choice decisions with ground reality. Transportation **40**(3), 697–711 (2013)

17. Penn, A.: Space syntax and spatial cognition: or why the axial line? Environ. Behav. **35**(1), 30–65 (2003)
18. Hillier, B.: Centrality as a process: accounting for attraction inequalities in deformed grids. Urban Des. Int. **4**(3–4), 107–127 (1999)
19. Al-Sayed, K., Turner, A., Hillier, B., Iida, S., Penn, A.: Space syntax methodology. Bartlett School of Architecture, UCL: London, UK (2014)
20. Hillier, B.: Specifically architectural theory. Harvard Archit. Rev. **9**, 8–27 (1993)
21. Hillier, B., Burdett, R., Peponis, J., Penn, A.: Creating life: or does architecture determine anything? Archit. Comportement/Archit. Behav. **3**(3), 233–250 (1986)
22. Long, Y., Baran, P.K.: Does intelligibility affect place legibility? Understanding the relationship between objective and subjective evaluations of the urban environment. Environ. Behav. **44**(5), 616–640 (2012)
23. Peponis, J., Hadjinikolaou, E., Livieratos, C., Fatouros, D.A.: The spatial core of urban culture. Ekistics, 43–55 (1989)
24. Askarizad, R., Daudén, P.J.L., Garau, C.: Exploring the role of configurational accessibility of alleyways on facilitating wayfinding transportation within the organic street network systems. Transp. Policy **157**, 179–194 (2024)
25. Torrisi, V., Cocuzza, E., Ignaccolo, M.: Simulation model to assess freight flow effects in the urban–port road interface: a practical use-case for the commercial port in Catania (Italy). Transp. Res. Procedia **83**, 236–243 (2025)

# A Digital-Twin-Oriented Monitoring Framework for Traffic-Related Environmental Hotspots and Future Nature-Based Solutions in Catania

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**Abstract.** Urban Digital Twins need integrated observations of different systems to consider complex interactions among mobility patterns, environmental conditions and urban greenery. Within the UISH (Urban Intelligence Science Hub) ecosystem, this work proposes an integrated monitoring framework for the city of Catania (Italy). It combines air-quality sensing, traffic monitoring and selected site characterization relevant for future mitigation-oriented studies. While the wider architecture includes radar-based traffic sensors, environmental multi-sensor platforms and portable devices, this work highlights on the AirQino-based monitoring layer, which acts as the main environmental observational backbone of the proposed framework. It consists of 1 mobile unit installed on a public transport bus and 11 fixed stations deployed across transport and green-infrastructure contexts, such as the Famà parking area and Fontanarossa parking area and the Falcone-Famà traffic-green interface. The framework is supported by a spatial design rationale based on representativeness, multi-criteria prioritization, constrained sensor placement, and deployment feasibility, while also incorporating traffic-data integration, privacy-aware local video analytics, and institutional coordination.

The contribution of the paper lies in the formalization of methodological and operational models for integrated urban monitoring. In this sense, the Catania case provides a real-world example of how a sensing architecture may be designed to support Urban Digital Twin development and to enable future analyses of traffic-related environmental hotspots and Nature-Based Solutions in complex urban settings.

**Keywords:** Urban Digital Twin · multi-sensor monitoring · air quality · traffic monitoring · green infrastructure · Nature-Based Solutions

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## 1 Introduction

Contemporary cities are increasingly exposed to connected pressures related to vehicular traffic, air pollution, urban heat, and the uneven distribution of green infrastructure. These issues are often addressed through sector-specific approaches, with mobility, environmental quality, and urban mitigation strategies being treated separately. However, such fragmentation limits the possibility of understanding how traffic-related pressures interact with local environmental conditions and how urban interventions may be planned and assessed in a more integrated way [1–3].

On the global scale, ongoing urbanization is exerting increasing pressure on environmental systems, natural resources and local biogeochemical cycles, while also intensifying climate and pollution vulnerabilities in metropolitan regions [4].

In this scenario, the management of mobility and air quality is no longer only a logistic challenge, but also a crucial environmental and public-health problem. Vehicular traffic is typically known as one of the main urban causes of damaging pollutants, including nitrogen dioxide ($NO_2$) and fine particulate matter ($PM_{2.5}$ and $PM_{10}$), whose concentration levels are closely linked with respiratory and cardiovascular risks in heavily populated areas [2, 5].

These terms are notably essential in Mediterranean cities, where heavy urban fabrics, restricted ventilation, high solar vulnerability, and the increasing frequency of heatwaves grow both pollutant accumulation and Urban Heat Island impacts. In this respect, Catania symbolizes a highly related case study. Previous studies have demonstrated that its urban microclimate is highly affected by built density, decreased vegetated cover, and local morphological environment, with important effects for heat preservation and environmental quality [6]. Accessibility and mobility issues within the current metropolis further help the need to understand environmental stress not only as a climatic event, but also as a spatial and functional outcome of urban structure [7–9].

In this framework, green infrastructure planning has progressively been recognized as a key strategy to improve urban climate resilience and environmental quality. Such interventions, usually framed as Nature-Based Solutions (NbS), are foreseen to provide pollutant absorption, microclimate management, and heat mitigation, although their current impact is determined by site-specific urban circumstances as well as on the organic status of vegetation [10–13]. Yet, despite the close interrelation between mobility, air quality, thermal stress, and urban ecosystem health, both scientific research and administrative practice have often adopted siloed methods, generating split and partial explanations of urban environmental dynamics.

To overcome these limitations, recent research has moved toward integrated methods able to simultaneously deal with mobility, environmental quality, and green infrastructure within a regular analytical framework. In parallel, the Smart City pattern has advanced the use of Internet of Things (IoT) networks and mixed urban flow data as a basis for real-time monitoring and flexible governance [14, 15]. However, the simple availability of sensors does not certainly cause practical urban understanding. What is progressively required is a structured frame able to join traffic-related pressure, environmental effects, and moderation directed urban elements within a logical operational architecture.

In this regard, Urban Digital Twins have emerged as encouraging frame for integrating different data sources, simulation models and decision-support tools within logical

urban intelligence environments. A Digital Twin of a city should not be realized as a simply virtual description or a static vision system; its real value lies in the possibility of combining real-time sensing, domain-specific models, and compatible data layers to support complex urban decision-making [16–21]. More commonly, the Urban Intelligence paradigm underline the transformation of raw data in multiple domains into operational knowledge, thus supporting evidence-based organization and prospects scenario-oriented governance.

The case of Catania is especially suitable for developing such an approach. Within the Urban Intelligence Science Hub (UISH) framework, the city is treated as a pilot environment in which thematic components devoted to mobility and environmental quality interact with a shared data infrastructure and future decision-support functionalities. In this context, monitoring cannot be conceived as an isolated technical activity. On the contrary, it becomes the observational layer through which traffic conditions, environmental responses, and site-specific urban characteristics can be jointly interpreted.

Despite the growing attention dedicated to Urban Digital Twins, an important methodological gap remains between conceptual system architecture and the operational design of integrated monitoring systems in real urban contexts. Clear frameworks are still needed to define how traffic observation, environmental sensing, and the characterization of urban contexts potentially relevant to mitigation can be jointly organized before the empirical phase.

Against this background, this paper proposes an integrated monitoring framework for the city of Catania, aimed at connecting air-quality and microclimate sensing, traffic observation, and site-specific urban characterization within a unified Digital Twin-oriented architecture, in order to support the identification of traffic-related environmental hotspots and the future assessment of Nature-Based Solutions in traffic-exposed urban contexts.

The paper lies in the formalization of a methodological and operational framework for multi-source urban monitoring, grounded in a real deployment process involving environmental sensors, traffic-related sensing infrastructures, and selected sites characterized by differentiated exposure and mitigation potential. Within the broader sensing ecosystem, the present contribution specifically focuses on the AirQino-based monitoring layer, as it provides the main environmental observational backbone for the selected transport- and green-infrastructure-related case studies.

The conceptual framework of the proposed Digital-Twin-oriented monitoring system, highlighting the transition from multi-domain sensing to future urban assessment, is summarized in Fig. 1.

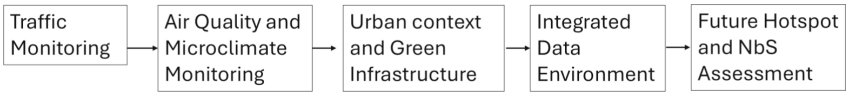


**Fig. 1.** Conceptual Framework

## 2 Background and Project Framework

### 2.1 Urban Intelligence Approach

The proposed framework is developed within the broader Urban Intelligence perspective, which reinterprets the city as a complex system of interacting with subsystems rather than as a set of isolated functional sectors. Within this view, mobility, environmental quality, infrastructure, and urban services are represented through thematic Digital Twins that are designed to operate as interoperable components connected by shared data structures and continuous information flows. Unlike static or sector-specific representations, this approach frames the city as a dynamic and data-driven ecosystem in which heterogeneous observations can be integrated to support joined-up urban analysis and governance [22–25].

In this perspective, the value of monitoring lies not only in the collection of measurements, but in its capacity to enable cross-domain interpretation. Traffic dynamics, environmental conditions, and urban form are not treated as independent layers; rather, they are read as mutually interacting components whose relationships can only be properly understood within an integrated analytical environment. This is one of the main causes why a Digital Twin oriented approach is particularly relevant to complex urban contexts. It allows raw observations to be changed into operational knowledge and supports the transition from siloed data management to more strategic forms of evidence-based planning [14, 19].

The implementation of this approach in Catania is intended to overpass the gap between high-level conceptual architecture and real-world functional needs. The proposed frame is not restricted to the positioning of sensors but is figured as part of a broader methodological structure in which sensing, data integration, and future resolution support are principally linked. Therefore, the consequent system is intended not just to view urban events, but to make the observational foundation for forecasting modelling, combined interpretation and flexible governance.

### 2.2 UISH and the Catania Pilot Architecture

Within this notional setting, the city of Catania constitutes the pilot environment in which the UISH framework is carried out. The developed architecture for this case study is planned as a set of interconnected functional layers that allow monitoring, data storage, modelling, and future decision-support activities to be joined within a single operational sequence. In this perspective, the monitoring system is not thought of as a stand-alone network, but as part of a more extensive urban intelligence ecosystem in which environmental and mobility data are foreseen to interact constantly.

At the base of this architecture there are two thematic modules: the Digital Twin of Mobility (DTMob) and the Digital Twin of Air Quality (DTAir). DTMob is created to support the observation, interpretation, and future simulation of vehicular and pedestrian dynamics, while DTAir is created to describe environmental conditions by integrating atmospheric measurements, traffic-related pressure and urban-context data. A core attribute of the framework is the dealings between these components: the environmental layer is created to profit from mobility-related information to better define pollutant

emission sources and traffic-exposed circumstances. This relationship demonstrates a system-of-systems logic, in which mobility and environmental quality are examined not as separate domains, but as mutal units of the same urban system [14–21].

The link between these analytical modules and the physical city is provided by the sensing infrastructure, which supplies as the observational backbone of the UISH ecosystem. To control the diversity and volume of the consequent data flow, the framework contains a concentrated Data Lake and a combining layer planned to assemble, store, and provide mixed information through compatible interfaces. This architecture is important for changing scattered observations into a collective data environment, facilitating the connection among thematic modules and helping future analytical processes in a scalable and assignable way [15, 19].

The functional series ultimately move toward future Decision Support System (DSS) features; thus, the role of monitoring increases well beyond diagnostics.

By providing structured observational input to DTMob, DTAir and the joint data environment, the monitoring architecture develops the enabling layer for hotspot identification, scenario searches, and future mitigation-oriented investigation. This is notably important in a city such as Catania, where traffic-intensive corridors, transport infrastructures, parking areas, and green spaces correspond within a heavy and environmentally vulnerable urban framework. Here, the integration of environmental and mobility observations gets especially useful for interpreting traffic-related environmental pressure and for planning future evaluation of diminution strategies, containing Nature-Based Solutions.

Within the wider UISH sensing ecosystem, the proposed architecture includes an AirQino-based environmental monitoring layer, radar-based traffic sensors, environmental multi-sensor platforms, and portable E2SENS devices.

The work highlights the AirQino-based layer joint with traffic monitoring, while admitting the wider integrated architecture in which this layer is integrated. This choice is inspired by the fact that the AirQino network makes up the main environmental observational backbone of the selected case studies and the most direct link between traffic-related disclosure, air-quality interpretation, and future mitigation-oriented assessment.

The reason behind the selection of the urban contexts considered in the framework is not based only on accessibility or technical convenience. Rather, it searches for catching differentiated conditions that are pertinent to the interaction between traffic and environmental quality: contexts directly uncovered to vehicular flows, contexts associated with public transport operations, contexts where environmental monitoring can be understood in relation to adjacent green infrastructure and contexts where existing municipal sensing systems can support traffic observation. In this way, the urban context of Catania does not perform as a simple spatial background, but as an active component of the monitoring design itself.

### 2.3 Functional Interaction and Data Interoperability

The interaction among thematic modules of the UISH framework directly shapes the design requirements of the sensing architecture. The monitoring phase is conceived as a structured observational layer able to support cross-domain interpretation. This is particularly relevant in urban interface contexts where traffic pressure, environmental

conditions and mitigation potential of green infrastructures coexist and must be analysed jointly rather than through separate sectoral lenses.

Within this logic, the synergy between DTMob and DTAir becomes especially important. Information associated with mobility is not managed as an external background variable, but as a key input for the environmental assessment of areas revealed to urban traffic. On the other hand, environmental observations provide an empirical basis for understanding how traffic pressure interprets into confined air-quality and microclimatic conditions. This joint relationship braces the idea that the monitoring structure should be planned to capture dynamic interactions rather than isolated variables [14–21].

Therefore, data compatibility is a central necessity of the overall system for hotspot recognition and future scenario-oriented analysis [15, 19]. By counting on a shared Data Lake and an integration layer, the framework enables heterogeneous data streams to be stored, connected, and made accessible within a common environment. This allows fixed and mobile environmental observations, traffic-related sensing outputs and sites' information to converge into an integrated analytical structure.

This aspect is particularly relevant for future Nature-Based Solutions assessment. In urban contexts exposed to high traffic volumes, the possibility of evaluating mitigation-oriented configurations depends on the capacity to relate vehicular pressure, environmental response, and features of nearby green infrastructures within the same observational and analytical environment. Therefore, the role of the monitoring network is foundational because it provides the evidence base required to identify traffic-related environmental hotspots and to support future model-based planning within a coherent Urban Intelligence ecosystem.

## 3 Study Area and Monitoring Design

### 3.1 Site Selection Methodology

The monitoring design is developed within the urban context of Catania, where traffic-intensive corridors, parking facilities, green spaces and a dense historical fabric coexist within a Mediterranean environment characterized by significant environmental vulnerability. These conditions make the city particularly suitable for a spatially differentiated observation strategy aimed at capturing the interaction between mobility-related pressure and local environmental response.

Site selection was based on the availability of locations and at the same time on the need to represent different urban conditions relevant to the framework. The selected contexts include areas directly exposed to heavy vehicular flows, nodes associated with public transport operations, and urban interfaces where environmental monitoring can be interpreted in relation to nearby green infrastructure. In this way, the study area is an active component of monitoring design.

The placement of sensing devices is guided by a planned spatial logic grounded in the discretization of urban space into rationally meaningful units. These units are featured through multiple dimensions, including environmental pressure, urban vulnerability, morphological conditions, and microclimatic conduct. This approach makes it possible to decide on monitoring concerns through a multi-criteria process. In addition, the classification of a set of sites is carried on based on clustering-oriented reasoning

and restricted placement principles assistance. Thus, it is not limited to the most critical sites, but it is also capable of representing the diversity of urban circumstances across the study area. Therefore, sensor location is treated as a design problem in which information coverage, characterization and technical feasibility must be balanced.

This methodological approach is especially pertinent in a Digital Twin frame because the objective is to provide a robust observational basis for wider interpretation, integration, and future scenario studies [19, 21].

### 3.2 The AirQino Network and Monitoring Sites

The environmental element of the proposed frame has its center within the AirQino-based monitoring layer, which includes 11 fixed stations and 1 mobile unit. This element constitutes the main observational backbone of the frame and is planned to catch air-quality and microclimate conditions across selected urban frameworks in Catania. The monitored variables include air temperature, relative humidity, and major atmospheric pollutants, allowing to address both environmental description and the presence of traffic-related pressure in dissimilar settings.

The AirQino layer is placed in a set of infrastructures contexts-related transport- and green chosen for their relevance to the environmental meaning of traffic vulnerability. These include bus-based monitoring, the Famà parking area, the Fontanarossa parking area, and the Falcone-Famà interface. The mobile unit extends the observational logic from fixed-point monitoring to trajectory-based acquisition, thus allowing the frame to capture spatial gradients that would continue in part invisible within only static network. In this sense, bus-based monitoring does not only expand the monitored area, but includes a dynamic dimension to the environmental observation of the city.

The fixed monitoring sites play complementary roles within the overall design. The Famà parking area is notably pertinent because of its nearness to both traffic-exposed spaces and adjacent green elements, making it suitable for examining parking-related vulnerability patterns in a transport-oriented urban context. The Fontanarossa parking area, by contrast, sustains a more specific heat-mitigation-oriented point of view. Here, monitoring architecture is designed to relate environmental conditions to the spatial configuration of green infrastructure and to the potential cooling functions associated with different vegetated settings. In this way, the framework interprets these parking areas not simply as transport nodes, but as functional urban ecosystems in which mobility-related pressure and environmental mitigation opportunities can be jointly observed. Figure 2 illustrates the localization and environmental setting of the Famà and Fontanarossa areas.




**Fig. 2.** Localization of areas. (a) Famà parking lot; (b) Fontanarossa parking lot

Within the broader UISH sensing ecosystem, the framework also includes two radar-based traffic sensors, two environmental multi-sensor platforms, and five portable E2SENS devices. These components contribute to the wider cross-domain logic of the project, but they are only briefly considered in the present contribution, since the focus here is on the AirQino-based environmental layer and on its role in structuring the observational basis for hotspot-oriented analyses.

### 3.3 Integrated Traffic Sensing and Traffic Green Interface

Traffic sensing is a core component of the proposed framework, as environmental observations are explicitly linked to mobility conditions and vehicular pressure. In this perspective, the AirQino-based monitoring layer is combined with a traffic-monitoring system that relies both on dedicated sensing devices and on existing municipal infrastructures. This integrated design allows air-quality and microclimatic observations to be analysed together with traffic dynamics, thereby supporting a more robust interpretation of traffic-exposed urban contexts.

A typical characteristic of the Catania pilot is its ability to build upon pre-existing municipal sensing assets, combining video-surveillance infrastructures and radar-based devices with recently stationed environmental sensors. This approach makes the frame both technologically practical and formally realistic, since it influences actual municipal property to supply the mobility-related information required for environmental interpretation. At the same time, the framework contains privacy-aware local video analytics, in which raw video streams are processed in situ and only joint or anonymized outputs are used for analytical purposes. This strategy avoids the circulation of sensitive visual data while still facilitating the extraction of vehicular flow and other information related to traffic which are needed for Digital Twin applications and integrated hotspot evaluations.

This traffic-monitoring logic is particularly important because it permits the combined observation of vehicular pressure and environmental conditions in the same urban settings. Rather than directing traffic as a separate engineering problem, the frame considers it into the environmental interpretation of urban space. This is notably pertinent in traffic-exposed areas, where pollutant concentrations and microclimatic conditions are firmly affected by the intensity and spatial organization of vehicular flows.

This integrated observation logic is especially evident in the selected pilot areas. The Fontanarossa parking area was selected because of the traffic pressure connected with its proximity to the airport, one of the main intermodal transport hubs in the city, and because of the significant presence of different tree species within the site, which makes it especially suitable for heat and vegetation-related environmental examination. Figure 3 shows the site configuration and the spatial distribution of the mapped tree species.

A consistent reasoning highlights the selection of the Falcone-Famà area, which constitutes a strategic traffic–green interface. The Famà parking lot was selected as a representative transport-related setting distinguished by frequent urban traffic pressure, while the nearby Parco Falcone e Borsellino supplies the corresponding green equivalent. In this case, the monitoring design is meant to catch the environmental gradient between a traffic-exposed area and an adjacent vegetated context, thereby assisting future analyses of how mobility-related pressure communicates with local environmental conditions and green-infrastructure-related diminution potential. Figure 4 illustrates the logic of this traffic-green interface and the relative positioning of the main observational contexts.




**Fig. 3.** Aerial view of the Fontanarossa parking lot with a zoom representing the distribution of different tree species.




**Fig. 4.** Aerial view of the Famà parking lot with a zoom representing Falcone Park

## 4 Sensor Placement

### 4.1 Multi-source Environmental Sensing Architecture

The technical architecture of the proposed frame is a multi-source sensing layer intended to support high-frequency environmental and mobility-related data acquisition within the broader UISH ecosystem. It lies the AirQino-based monitoring network, which forms the main environmental observational backbone of the framework. This layer includes 11 fixed stations and 1 mobile unit, set up to catch both air-quality and microclimatic states across chosen urban contexts in Catania. The observed variables include $O_3$, $NO_2$, CO, $CO_2$, $PM_{2.5}$, $PM_{10}$, air temperature, and relative humidity, thus enabling the combined observation of pollutant dynamics and local atmospheric conditions.

From a technical point of view, the coincidence of stationery and mobile AirQino units permits the framework to address the typical trade-off between temporal continuity and spatial granularity. While the fixed stations guarantee constant observations at representative locations, the unit placement on the bus presents a trajectory-based

monitoring logic able to catch spatial gradients and limited vulnerability patterns that would remain only in part visible within a simple static network. In this sense, the mobile sensor actions as a dynamic observational investigation that enhances the fixed network and expands its interpretative reach. Examples of mobile monitoring unit installation on the public transport bus are shown in Fig. 5.

Within the broader UISH sensing ecosystem, this environmental layer is matched by additional sensing components, including two radar-based traffic sensors, two environmental multi-sensor platforms, and five portable E2SENS devices. These elements contribute to the overall cross-domain architecture by broadening the range of environmental and mobility-related observations.

To complete the environmental observations, the overall architecture also includes a mobility-sensing component based on radar devices and privacy-aware video analytics, as discussed in the next sub-section. This setup allows raw vehicular movement to be transformed into aggregated and obscured traffic metadata, which can then be synchronized with the environmental streams. At the level of the broader digital ecosystem, this integration is necessary for concerning local air-quality patterns to vehicular pressure and for supporting the interaction between the mobility and environmental components of the UISH framework.




**Fig. 5.** Examples of the mobile monitoring unit installation on the public transport bu

### 4.2 Traffic Video Analytics Integration

Traffic-related information is a key component of monitoring architecture, as environmental observations are explicitly linked to vehicular pressure. Within the planned framework, traffic data are expected to be obtained from both dedicated radar sensing devices and existing municipal infrastructures, including radar-based systems and fixed urban surveillance cameras (see Fig. 6). In this point of view, traffic monitoring contributes directly to the identification and interpretation of traffic-related environmental hotspots.

A distinctive element of the framework lies in the use of urban video-surveillance cameras as part of the operational sensing infrastructure of the city. These devices are used as continuous observation sources for critical nodes and corridors. Through an AI-based processing conduit, video streams are locally processed in order to discover, track,

and count vehicles and to restore movement-related information across the observed scene. This permits raw visual data to be progressively transformed into structured traffic variables, such as directional flows and movement patterns, which can then be coordinated and assessed with the environmental observations collected by the AirQino network.

This approach makes it possible to change existing urban video resources into analysis of complete traffic information without depending only on invasive field campaigns. In addition, it allows traffic observations to be related to dynamic vehicular conditions rather than static measurements. In practical terms, radar data and locally processed video flows help reconstruct traffic pressure in selected areas and therefore support the environmental interpretation of the AirQino-based monitoring layer.

At the same time, the use of video-derived information requires privacy-aware processing schemes based on local analysis and on the generation of aggregated or anonymized outputs, so that traffic observation remains compatible with a responsible and operationally realistic data-governance approach. Within the broader UISH ecosystem, the resulting traffic descriptors can support both the environmental reading of sites exposed to high traffic volumes and the future integration of empirical observations into modelling and Digital Twin analytical workflows.

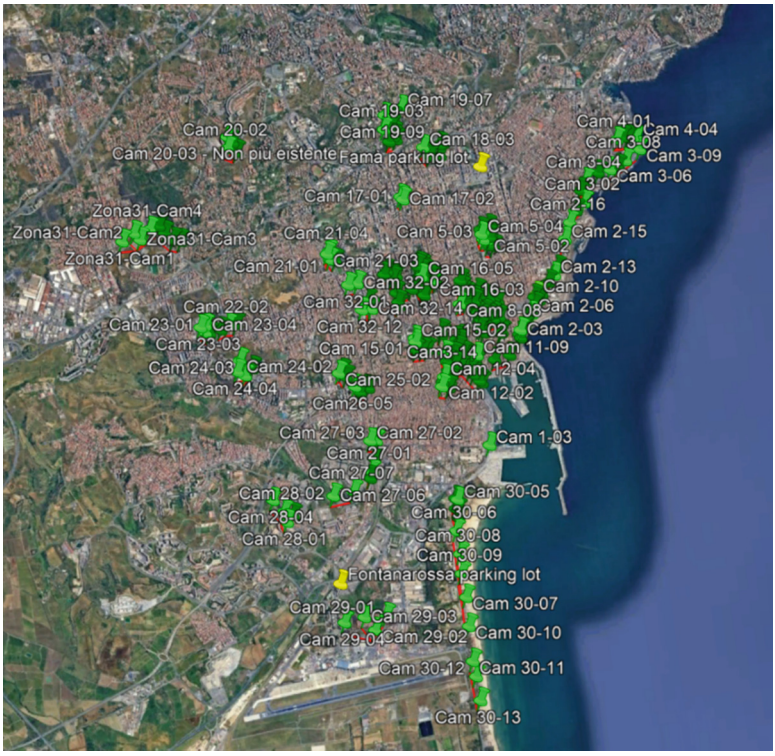


**Fig. 6.** Geolocation of fixed urban surveillance cameras installed in the city of Catania

### 4.3 Hybrid Infrastructure and Mitigation-Oriented Monitoring

To complement traffic and environmental sensing, the broader UISH architecture incorporates a specialized ecological monitoring layer designed to observe the response of green infrastructure to urban stress. This component extends the framework beyond conventional air-quality monitoring by including instruments specifically intended at catching the thermal and physiological behaviour of urban vegetation. In particular, the ecological sensing layer includes thermometric range and plant-level devices, such as Bioristor-based solutions for in vivo monitoring, which provide detailed information on the condition and feedback of vegetation under different environmental pressures. An example of the installation of environmental sensing units for plant-level monitoring is shown in Fig. 7. The use of this layer must satisfy the same feasibility needs that apply to the rest of the monitoring architecture. Power supply, installation height, accessibility for maintenance, protection against vandalism, and compatibility with the physical characteristics of the monitored vegetation all influence the realistic implementation of the system.

Within the overall framework, the role of this layer is to support a broader mitigation-oriented interpretation of urban environments. By combining environmental observations, traffic-related pressure and plant-response indicators within the same analytical ecosystem, the framework establishes a common interpretative basis through which ecological response can be related to mobility-related stress.

This ecological sensing layer is particularly relevant for future Nature-Based Solutions assessment within the UISH urban intelligence ecosystem. The inclusion of plant-level and thermal monitoring devices provides the observational basis needed for future analyses of how urban vegetation responds to localized traffic pressure, heat stress, and environmental exposure.

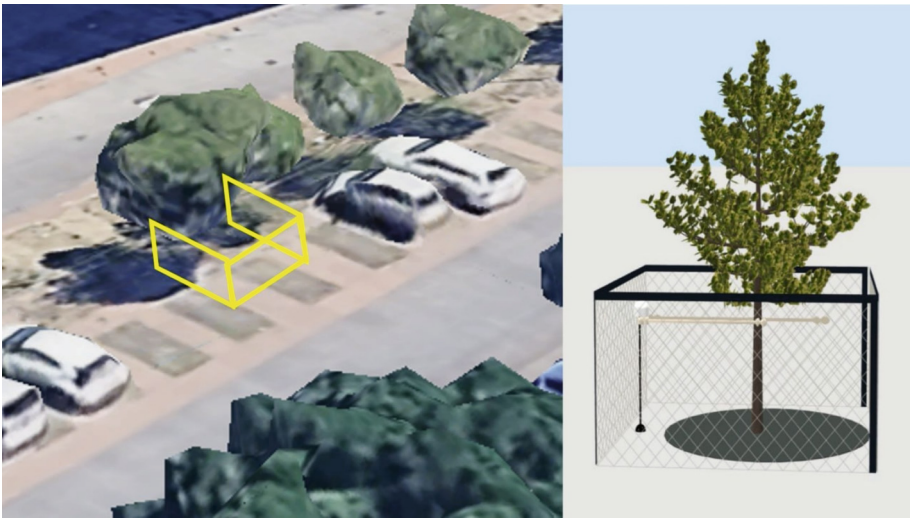

**Fig. 7.** Installation of environmental sensing units for plant-level monitoring

## 5 Environmental Hotspots and Nature-Based Solutions

In the proposed framework, traffic is treated as a major source of environmental pressure able to affect local air quality and, more broadly, the environmental conditions experienced in urban space. The purpose of monitoring expands from the estimation of vehicular counts and flow conditions to the identification of urban situations in which emissions, exposure, urban morphology, and environmental sensitivity interact in especially relevant ways.

Within this perspective, traffic-related environmental hotspots are interpreted as priority urban contexts in which integrated monitoring may provide the observational basis for future mitigation-oriented investigations.

By identifying traffic-exposed contexts and structuring monitoring around air quality, mobility conditions, and features of green infrastructures, the framework enables future analyses of weather and how specific urban configurations may support mitigation. Therefore, the proposed approach turns fragmented observation into a more structured basis for future hotspot-oriented and Nature-Based-Solutions-oriented urban analysis [26–29]. This interpretative logic is particularly relevant in dense urban settings, where the effects of vehicular activity cannot be separated from the characteristics of local morphology, land use, and environmental sensitivity.

The Catania pilot illustrates this logic through the selection of urban contexts in which mobility pressure and mitigation-related urban elements spatially coexist. This perspective is related to the selected case studies. Falcone-Famà provides a representative example of a traffic-green interface suitable for future pollutant-mitigation-oriented analyses, while Fontanarossa offers a context more directly related to heat-mitigation-oriented configurations.

## 6 Discussion and Conclusions

The paper formalizes a coherent sensing architecture within the broader UISH Digital-Twin-oriented environment, providing a methodological and operational reference for integrated urban monitoring in Catania.

The main value of the proposed framework lies in its attempt to bridge the gap between conceptual Urban Digital Twin architecture and the concrete design of real urban monitoring systems. While much of the debate on Digital Twins focuses on modelling environments, simulation, and data integration, the observational layer is often treated as secondary or assumed to be already available. This paper takes the opposite path by placing the monitoring architecture at the center of the discussion. It highlights that the quality of future modelling and decision-support activities relies on how sensing is structured, spatially dispersed and integrated before empirical results become accessible.

A second contribution is the integration of urban domains that are often managed independently. By jointly considering traffic observation, AirQino-based environmental sensing and green-infrastructure urban contexts, the framework helps a more systemic interpretation of traffic-related environmental pressure. This is notably relevant in urban areas where vehicular flows, public-space disclosure, parking-related functions, and

green elements correspond within short spatial ranges. In such situations, isolated observations are often not enough to support meaningful explanation or mitigation-oriented planning.

In addition, the integration of different observational layers within the wider UISH ecosystem makes up an additional value of our planned frame. The interaction between DTMob, DTAir, the shared Data Lake, and future DSS-oriented features gives the monitoring network a role that goes beyond simple diagnostics. Within this architecture, environmental sensing, traffic metadata, and ecological observations are progressively organized into a common interpretative environment, thereby supporting future cross-domain analyses and model-based decision-making.

Nevertheless, the real-world complexity of building integrated monitoring systems may evolve some implementation details according to institutional timing, site accessibility and technical adjustments. In this sense, the framework provides both a concrete basis for the next empirical phase and a transferable reference for forthcoming assessments of urban climate resilience and sustainable mobility in complex urban settings.

Once monitoring data becomes available, next research steps will focus on subsequent phases of data integration, calibration and scenario analysis. It will allow the comparison of traffic-related environmental hotspots, the interpretation of localized environmental responses and the assessment of Nature-Based Solutions in contexts where vehicular pressure and ecological opportunities spatially intersect. In addition, further validation across multiple case studies could be considered as a promising direction for future research, to strengthen the generalizability and robustness of the proposed framework.

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## References

1. Bigazzi, A.Y., Rouleau, M.: Can traffic management strategies improve urban air quality? A review of the evidence. J. Transp. Health **7**, 111–124 (2017). https://doi.org/10.1016/j.jth.2017.08.001
2. Han, X., Naeher, L.P.: A review of traffic-related air pollution exposure assessment studies in the developing world. Environ. Int. **32**(1), 106–120 (2006). https://doi.org/10.1016/j.envint.2005.05.020
3. Kumar, P., et al.: The rise of low-cost sensing for managing air pollution in cities. Environ. Int. **75**, 199–205 (2015). https://doi.org/10.1016/j.envint.2014.11.019
4. Seto, K.C., Güneralp, B., Hutyra, L.R.: Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proc. Natl. Acad. Sci. **109**(40), 16083–16088 (2012). https://doi.org/10.1073/pnas.1211658109

5. Gulia, S., Nagendra, S.S., Khare, M., Khanna, I.: Urban air quality management-A review. Atmos. Pollut. Res. **6**(2), 286–304 (2015). https://doi.org/10.5094/APR.2015.033
6. Mangiameli, M., Mussumeci, G., Gagliano, A.: Evaluation of the urban microclimate in Catania using multispectral remote sensing and GIS technology. Climate **10**(2), 18 (2022). https://doi.org/10.3390/cli10020018
7. Castrignanò, M., Colleoni, M., Pronello, C.: Muoversi in città. Accessibilità e mobilità nella metropoli contemporanea. Franco Angeli, Milano, IT (2012)
8. Vincenza, T., Leonardi, P., Ignaccolo, M., Bellia, S.: Beyond traffic congestion: developing digital twin to enhance accessibility to points of interest. In: International Conference on Computational Science and Its Applications, pp. 123–140. Springer, Cham (2025)
9. Torrisi, V., Rossetti, S., Barbagallo, A., Leonardi, P., Ignaccolo, M.: A digital twin simulation framework to assess the impact of street experiments: transforming urban mobility in Acireale (italy). In: International Conference on Computational Science and Its Applications, pp. 197–210. Springer, Cham (2024). https://doi.org/10.1016/j.trpro.2025.04.065
10. Kabisch, N., et al.: Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. Ecol. Soc. **21**(2) (2016). https://doi.org/10.5751/ES-08373-210239
11. Martinico, F., La Rosa, D., Privitera, R.: Green oriented urban development for urban ecosystem services provision in a medium sized city in southern Italy. iForest-Biogeosci. Forest. **7**(6), 385 (2014). https://doi.org/10.3832/ifor1171-007Ketzler
12. Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L., Logg, A.: Digital twins for cities: a state of the art review. Built Environ. **46**(4), 547–573 (2020)
13. Salmond, J.A., et al.: The influence of vegetation on the horizontal and vertical distribution of pollutants in a street canyon. Sci. Total. Environ. **443**, 287–298 (2013). https://doi.org/10.1016/j.scitotenv.2012.10.101
14. Grasso, C., Leonardi, L., Mertens, J.S., Torrisi, V.: Real-time communication and digital twin modelling towards smart mobility in the samothrace project. In: 2024 IEEE International Symposium on Measurements & Networking (M&N), pp. 1–6. IEEE (2024). https://doi.org/10.1109/MN60932.2024.10615865
15. Hashem, I.A.T., et al.: The role of big data in smart city. Int. J. Inf. Manage. **36**(5), 748–758 (2016). https://doi.org/10.1016/j.ijinfomgt.2016.05.002
16. Zanella, A., Bui, N., Castellani, A., Vangelista, L., Zorzi, M.: Internet of things for smart cities. IEEE Internet Things J. **1**(1), 22–32 (2014). https://doi.org/10.1109/JIOT.2014.2306328
17. Batty, M.: Digital twins. Environ. Planning B: Urban Anal. City Sci. **45**(5), 817–820 (2018). https://doi.org/10.1177/2399808318796416
18. Batty, M.: Digital twins in city planning. Nat. Comput. Sci. **4**(3), 192–199 (2024). https://doi.org/10.1038/s43588-024-00606-7
19. Fuller, A., Fan, Z., Day, C., Barlow, C.: Digital twin: enabling technologies, challenges and open research. IEEE Access **8**, 108952–108971 (2020). https://doi.org/10.1109/ACCESS.2020.2998358
20. Jones, D., Snider, C., Nassehi, A., Yon, J., Hicks, B.: Characterising the Digital Twin: a systematic literature review. CIRP J. Manuf. Sci. Technol. **29**, 36–52 (2020). https://doi.org/10.1016/j.cirpj.2020.02.002
21. Schrotter, G., Hürzeler, C.: The digital twin of the city of Zurich for urban planning. PFG–J. Photogrammetry, Remote Sens. Geoinf. Sci. **88**(1), 99–112 (2020). https://doi.org/10.1007/s41064-020-00092-2
22. Weil, C., Bibri, S.E., Longchamp, R., Golay, F., Alahi, A.: Urban digital twin challenges: a systematic review and perspectives for sustainable smart cities. Sustain. Cities Soc. **99**, 104862 (2023). https://doi.org/10.1016/j.scs.2023.104862

23. Pala, A.L., et al.: Digital Twin for mobility: simulation integrated approach for demand matrices calibration with empirical data. Transp. Res. Procedia **86**, 516–523 (2025). https://doi.org/10.1016/j.trpro.2025.04.065
24. Bibri, S.E.: Data-driven smart sustainable cities of the future: urban computing and intelligence for strategic, short-term, and joined-up planning. Comput. Urban Sci. **1**(1), 8 (2021). https://doi.org/10.1007/s43762-021-00008-9
25. Ketzler, B., Naserentin, V., Latino, F., Zangelidis, C., Thuvander, L., Logg, A.: Digital twins for cities: a state of the art review. Built Environ. **46**(4), 547–573 (2020). https://doi.org/10.2148/benv.46.4.547
26. Shahat, E., Hyun, C.T., Yeom, C.: City digital twin potentials: a review and research agenda. Sustainability **13**(6), 3386 (2021). https://doi.org/10.3390/su13063386
27. Menon, J.S., Sharma, R.: Nature-based solutions for co-mitigation of air pollution and urban heat in Indian cities. Front. Sustain. Cities **3**, 705185 (2021). https://doi.org/10.3389/frsc.2021.705185
28. Baró, F., Gómez-Baggethun, E.: Assessing the potential of regulating ecosystem services as nature-based solutions in urban areas. In: Nature-based solutions to climate change adaptation in urban areas: linkages between science, policy and practice, pp. 139–158. Springer International, Cham (2017)
29. Augusto, B., Roebeling, P., Rafael, S., Ferreira, J., Ascenso, A., Bodilis, C.: Short and medium- to long-term impacts of nature-based solutions on urban heat. Sustain. Cities Soc. **57**, 102122 (2020). https://doi.org/10.1016/j.scs.2020.102122

# Remote Work and Residential Attractiveness Across the Centre–Periphery Gradient

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**Abstract.** Remote work, accelerated by COVID-19, is increasingly understood as a durable shift that can reweight how residential environments are evaluated. Using national survey data from Poland for employed respondents with defined remote-work capability (N = 870), this paper examines perceived change in residential attractiveness during the pandemic, assessed through the lens of the ongoing COVID-19 pandemic, and a two-layer view of residential wellbeing that distinguishes dwelling satisfaction from locality satisfaction across a settlement gradient interpreted in centre–periphery terms. Descriptively, remote-capable workers more often report that their current place of residence became "more attractive" during COVID-19 (38.4% vs 24.0%), and positive revaluation is highest among suburban residents (52.6%) and lowest among large-city residents (14.7%). These patterns are confirmed in binomial-logit and proportional-odds ordinal models, which show that remote-work capability is associated with more positive residential revaluation net of settlement context. A centre–periphery reference specification using large cities as the baseline shows markedly higher odds of positive revaluation outside the core, including suburbs (OR = 7.11), while interaction tests do not support the claim that remote work reshapes the settlement gradient. The wellbeing results reveal a layered split: remote capability predicts higher dwelling satisfaction (OR = 1.51), but not higher locality satisfaction, which remains structured by settlement context. The findings support a post-pandemic interpretation in which remote work reinforces outward revaluation pressures while place-based advantages continue to shape the locality layer of residential wellbeing, highlighting the need for planning strategies that combine housing adequacy with neighbourhood functionality and accessibility.

**Keywords:** Remote Work · Residential Satisfaction · Residential Attractiveness · Centre–Periphery · Suburbanisation · Urban Resilience

## 1 Introduction

The post-pandemic city is not simply a city after a health emergency. It is increasingly a city after a rapid reconfiguration of work geographies, one in which remote and hybrid work have become feasible at scale and, in many sectors, socially and organisationally normalised. Telecommuting has long been understood as loosening the link between

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workplace and residence [1], but the COVID-19 period acted as an unusually powerful coordination shock that accelerated adoption beyond pre-pandemic norms [2]. Evidence from multiple countries further suggests that this shift has persisted in expectations, preferences, and planned working arrangements [3]. In this sense, the pandemic is analytically useful not only as a historical episode, but as a stress-test that made longer-term mechanisms newly visible.

When work becomes less tethered to a fixed office location, a classic metropolitan trade-off is reweighted. Urban theory has long framed residential choice as a tension between accessibility, often associated with central locations, and space or affordability, more often obtained farther from the core [4, 5]. If commuting becomes less frequent, the shadow cost of distance falls and the relative value of space, privacy, and environmental amenities rises [Brueckner et al., 2023]. Post-pandemic evidence from several countries is increasingly read in these terms, with stronger housing-demand growth in suburban and peripheral rings than in dense cores [6, 7]. In Poland, where suburbanisation has long interacted with fragmented spatial planning and governance, remote work has accordingly been discussed as a potential catalyst of renewed outward pressure [8]. This question is especially salient for metropolitan contexts such as Warsaw, where centre–periphery tensions are already central to debates on urban development.

Yet metropolitan restructuring is not driven only by relocation. It is also driven by re-evaluation: how residents reassess the adequacy and attractiveness of their current living environment under changed daily routines. Residential satisfaction research provides an important bridge here. Satisfaction is often interpreted in terms of the relationship between current conditions and desired standards, including the well-known have–want discrepancy perspective [9], and it is widely treated as a multidimensional component of quality of life [10]. Crucially, the literature distinguishes between at least two scales of residential evaluation: satisfaction with the dwelling and satisfaction with the wider place of residence [11, 12]. The first is shaped primarily by internal housing conditions such as space, privacy, comfort, and layout [13, 14]. The second depends more strongly on neighbourhood characteristics, service access, green space, safety, and everyday accessibility [15, 16]. Remote work is likely to intensify this distinction because it increases the functional demands placed on the dwelling while also potentially changing how locality conditions are perceived when more time is spent near home [17, 18].

This distinction matters for post-pandemic urban policy because residential wellbeing is shaped not only by housing conditions, but also by uneven access to services and opportunities across the urban gradient. Accessibility research has shown that service provision, mobility burdens, and transport-related exclusion are distributed unevenly across metropolitan space [19, 20]. Remote work may therefore create differentiated advantages: for some households it increases the ability to optimise location and housing space, while for others it leaves fixed workplace dependence and accessibility constraints largely intact [21, 22]. The question is not simply whether remote work is beneficial, but how it reshapes residential evaluation across different spatial contexts.

Against this background, this paper examines how remote-work capability relates to perceived change in residential attractiveness during the COVID-19 period and to two layers of residential satisfaction, dwelling and locality, across a settlement gradient

interpreted in centre–periphery terms. Settlement context is measured through respondents' classification of their residential setting, which is treated here as substantively meaningful because it captures lived urbanity and metropolitan position rather than only administrative size [23, 24]. The empirical strategy then tests whether this perceptual gradient helps explain how remote work and residential evaluation intersect under post-pandemic conditions.

Accordingly, the paper addresses three linked questions. First, is remote-work capability associated with a more positive perceived shift in residential attractiveness under pandemic stress-test conditions? Second, is remote-work capability associated with dwelling satisfaction and locality satisfaction net of settlement context? Third, do the combined patterns support a two-sided reading of post-pandemic urban dynamics in which dwelling revaluation may strengthen outward pressures while place-based advantages of centrality continue to structure locality-level outcomes?

## 2 Data and Methods

### 2.1 Analytical Sample

The analysis draws on a national online questionnaire survey conducted in Poland in 2020. Data were collected from respondents of productive age (18–64) using a panel sample with quota controls for age, gender, education, and voivodeship to ensure comparability with the national population structure. The questionnaire covered housing conditions, characteristics of the current place of residence, and residential preferences and perceptions related to the living environment. The full survey dataset includes 1,480 respondents.

Because remote-work capability was measured only for employed respondents, the present analysis is restricted to the employed subsample. Respondents with missing or "don't know" answers on remote-work capability were excluded. The final analytical sample comprises 870 employed respondents with defined remote-work capability, including 292 remote-capable respondents (33.6%) and 578 respondents without remote-work capability (66.4%).

### 2.2 Settlement Context

The main contextual variable is perceived settlement type, measured through respondents' classification of their residential setting into one of five categories: open rural area, village or small town, medium-sized city, large city, and suburbs of a large city (Table 1). This measure is treated as substantively meaningful because it captures perceived metropolitan position and lived urbanity rather than only settlement size. In the employed analytical sample, the suburban category is relatively small, accounting for 2.2% of respondents, and is therefore interpreted as an analytically distinctive perception group rather than as a basis for precise population-level inference.

As a robustness specification, settlement context is also operationalised using a self-reported settlement-size category ranging from rural areas to cities with more than 500,000 inhabitants. This alternative measure is more conventional than the perceived settlement-type classification, but it also relies on respondent report rather than external administrative coding.

**Table 1.** Analytical sample by perceived settlement type and remote-work capability

| Perceived settlement type | All (N) | No remote (N) | Remote possible (N) |
|---|---|---|---|
| Open rural area | 40 | 31 | 9 |
| Village / small town | 380 | 255 | 125 |
| Medium-sized city | 214 | 143 | 71 |
| Large city | 217 | 136 | 81 |
| Suburbs of a large city | 19 | 13 | 6 |
| **Total** | **870** | **578** | **292** |

### 2.3 Outcomes

First, perceived residential attractiveness during the COVID-19 period is measured through a three-category question asking whether the respondent's current place of residence appeared more attractive, unchanged, or less attractive than before the pandemic. The main binary specification captures whether the respondent reported "more attractive", while an ordered specification is used as a complement.

Second, residential satisfaction is measured through two five-point questions asking whether the respondent is satisfied with the dwelling currently occupied and with the place of residence in which they live, ranging from very dissatisfied to very satisfied. These two items are treated as distinct layers of residential wellbeing.

Third, secondary attitudinal indicators capture agreement with statements that the pandemic made the respondent appreciate their place of residence more and made the respondent consider changing their place of residence. These variables are treated as supplementary rather than central outcomes.

### 2.4 Analytical Strategy

The empirical analysis combines descriptive comparison with multivariable modelling. All data processing and statistical analyses were conducted using PS IMAGO PRO software, with IBM SPSS Statistics as the analytical engine. At the descriptive level, the paper compares the distribution of perceived attractiveness change and residential satisfaction across settlement categories separately for remote-capable and non-remote respondents, reporting counts and within-group percentages.

For binary outcomes, the analysis applies generalized linear models with binomial distribution and logit link, equivalent to logistic regression, estimated in SPSS using GENLIN. Robust covariance estimates are used, and results are reported as odds ratios alongside Wald $\chi^2$ tests.

For ordered outcomes, the analysis uses cumulative logit ordinal regression, estimated in SPSS using PLUM. These models are reported using log-odds coefficients, odds ratios, likelihood-ratio tests against intercept-only models, and McFadden pseudo-$R^2$. Where available, AIC and BIC are reported as descriptive fit indicators.

Interaction terms between remote-work capability and settlement context are treated as exploratory, because interaction effects represent a higher-order claim and are more sensitive to sparse cells in some settlement categories, especially the suburban category, and to the relatively small number of negative evaluations.

# 3 Results

## 3.1 Stress-Test Revaluation: Perceived Change in Residential Attractiveness

Table 2 reports perceived change in residential attractiveness during the COVID-19 period ("more attractive", "no change", "less attractive") across settlement contexts, shown separately for respondents with and without remote-work capability. The outcome is based on the survey question: *"Considering the ongoing COVID-19 pandemic, does your current place of residence seem less or more attractive than before the pandemic?"* Two patterns are visible. First, there is a clear settlement gradient: non-core contexts show higher shares reporting positive revaluation than large-city contexts. Second, within settlement categories, respondents with remote-work capability display a consistent shift towards the "more attractive" category compared with those without remote-work capability. In the employed sample (N = 870), the share reporting that the current place of residence became more attractive is 38.4% (112/292) among remote-capable respondents, compared with 24.0% (139/578) among non-remote respondents. Aggregated across work regimes, the suburban category shows the highest "more attractive" share (52.6%, 10/19), while large cities show the lowest (14.7%, 32/217).

**Table 2.** Perceived change in residential attractiveness during COVID-19 by settlement context and remote-work capability

| Remote-work capability | Settlement context | More attractive | No change | Less attractive | N |
|---|---|---|---|---|---|
| No remote | Open rural area | 10 (32.3%) | 21 (67.7%) | 0 (0.0%) | 31 |
| No remote | Village / small town | 80 (31.4%) | 169 (66.3%) | 6 (2.4%) | 255 |
| No remote | Medium-sized city | 30 (21.0%) | 105 (73.4%) | 8 (5.6%) | 143 |
| No remote | Large city | 14 (10.3%) | 114 (83.8%) | 8 (5.9%) | 136 |
| No remote | Suburbs of a large city | 5 (38.5%) | 8 (61.5%) | 0 (0.0%) | 13 |
| Remote possible | Open rural area | 6 (66.7%) | 3 (33.3%) | 0 (0.0%) | 9 |
| Remote possible | Village / small town | 62 (49.6%) | 59 (47.2%) | 4 (3.2%) | 125 |
| Remote possible | Medium-sized city | 21 (29.6%) | 44 (62.0%) | 6 (8.5%) | 71 |
| Remote possible | Large city | 18 (22.2%) | 58 (71.6%) | 5 (6.2%) | 81 |
| Remote possible | Suburbs of a large city | 5 (83.3%) | 1 (16.7%) | 0 (0.0%) | 6 |

These patterns are confirmed in multivariable models. Model M1 (Table 4) estimates the probability of reporting "more attractive" versus "no change/less" using a binomial-logit specification with settlement context, remote-work capability, and their interaction. The model is highly significant overall (LR $\chi2(9) = 72.59$, $p = 4.72e-12$; AIC = 60.74; BIC = 108.42). Both settlement context (Wald $\chi2(4) = 46.31$, $p = 2.12e-09$) and remote-work capability (Wald $\chi2(1) = 12.86$, $p = 0.000335$) are significant predictors, while the interaction is not supported (Wald $\chi2(4) = 2.82$, $p = 0.588$). In substantive terms, remote-work capability is associated with a higher probability of reporting improved attractiveness even after accounting for settlement differences, while the data do not support the claim that remote work reshapes the settlement gradient in this sample.

To make the centre–periphery contrast more explicit, Model M1b re-estimates the attractiveness-increase model using large cities as the reference category. This model is again highly significant (LR $\chi2(5) = 69.54$, $p = 1.28e-13$; AIC = 55.79; BIC = 84.40). Net of remote-work capability, the odds of reporting "more attractive" are substantially

higher outside the core: open rural areas (OR = 4.51, p = 5.92e − 05), villages and small towns (OR = 3.70, p = 3.49e − 09), medium-sized cities (OR = 1.90, p = 0.0113), and suburbs of a large city (OR = 7.11, p = 5.44e − 05). Remote-work capability remains independently significant (OR ≈ 2.17, p = 1.41e − 06). This specification makes the centre–periphery contrast explicit: the strongest revaluation signal is observed outside large-city contexts, including the suburban category, even when remote-work capability is held constant, although the suburban estimate should be interpreted cautiously because of the small subgroup size.

To ensure that the finding is not an artefact of dichotomising the outcome, the full three-category attractiveness-change measure is also estimated using a proportional-odds ordinal logit model (Model M2, Table 4). The model is highly significant overall (LR $\chi 2(5) = 66.72$, p = 4.91e − 13; − 2LL 144.50 → 77.78; McFadden R2 = 0.050) and confirms a robust association between remote-work capability and a more positive attractiveness category. The coefficient for "no remote" relative to "remote" is negative (B = − 0.644, p = 2.89e − 05; OR = 0.53), corresponding to approximately 1.90 times higher odds of a more positive category among remote-capable respondents. Taken together, the descriptive evidence and both modelling specifications support the conclusion that remote-work capability is associated with positive residential revaluation under stress-test conditions, while settlement context remains a strong structuring dimension.

### 3.2 Two-Layer Residential Wellbeing: Dwelling Satisfaction Versus Locality Satisfaction

Table 3 presents the two-layer pattern in residential wellbeing by comparing the distribution of dwelling satisfaction and locality satisfaction between respondents with and without remote-work capability, collapsed into dissatisfied (1–2), neutral (3), and satisfied (4–5) categories. The dwelling layer shows a clear remote-work difference: respondents with remote-work capability exhibit a higher satisfied share (80.1%) than respondents without remote-work capability (71.6%). In contrast, locality satisfaction is broadly similar in top-box shares (71.2% satisfied among remote-capable respondents versus 72.7% among non-remote respondents), although remote-capable respondents show a higher dissatisfied share (14.0% versus 8.1%). This split suggests that remote-work capability relates more strongly to the dwelling layer than to uniformly more positive evaluation of the wider residential environment.

**Table 3.** Dwelling satisfaction and locality satisfaction by remote-work capability

| Outcome | Remote-work capability | Dissatisfied (1-2) | Neutral (3) | Satisfied (4-5) |
|---|---|---|---|---|
| Dwelling satisfaction | No remote (N = 578) | 9.2% | 19.2% | 71.6% |
| Dwelling satisfaction | Remote possible (N = 292) | 8.9% | 11.0% | 80.1% |
| Locality satisfaction | No remote (N = 578) | 8.1% | 19.2% | 72.7% |
| Locality satisfaction | Remote possible (N = 292) | 14.0% | 14.7% | 71.2% |

Ordinal logistic regression models corroborate this split. In the dwelling-satisfaction model (Model M3, Table 4), remote-work capability is a statistically significant predictor of higher satisfaction categories (B = − 0.415 for no remote relative to remote, p =

0.00215; OR = 0.66, corresponding to about 1.51 times higher odds of higher dwelling satisfaction among remote-capable respondents). Settlement-context coefficients are not statistically significant in this specification, and overall model fit is borderline (LR $\chi2(5) = 10.46$, $p = 0.063$; − 2LL 176.79 → 166.33).

In the locality-satisfaction model (Model M4, Table 4), the model is significant overall (LR $\chi2(5) = 21.94$, $p = 0.000537$; − 2LL 196.10 → 174.16; McFadden R2 = 0.0096), but remote-work capability is not significant ($p = 0.760$). Settlement context does contribute; in this parameterisation, the large-city category is higher than the suburban reference ($B = 0.946$, $p = 0.031$; OR = 2.58).

Settlement-gradient diagnostics further clarify why the two layers behave differently. For dwelling satisfaction, the association with settlement context is not statistically significant ($\chi2(8) = 10.46$, $p = 0.234$; $N = 870$). Descriptively, the suburban category shows a lower satisfied share (52.6%) than large cities (77.9%), but the overall gradient is not robust. In contrast, locality satisfaction shows a significant settlement gradient ($\chi2(8) = 17.77$, $p = 0.023$; $N = 870$). Large cities report the highest satisfied share (81.1%), while open rural areas report the lowest (55.0%), with suburbs at 63.2%. Notably, this differs from the stress-test revaluation result, where the suburban category shows the highest share reporting that the place of residence became more attractive. Together, these results support a layered interpretation: under home-centred routines, the dwelling becomes a key functional platform and is more sensitive to work regime, whereas locality evaluation is more consistently structured by settlement context.

**Table 4.** Summary of models

| Model | Outcome | Model type and fit | Key results |
|---|---|---|---|
| M1 | Attractiveness increase | Logistic regression (GLM binomial-logit; robust covariance). LR $\chi^2(9) = 72.59$, $p = 4.72e{-12}$; AIC = 60.74; BIC = 108.42 | Settlement context: Wald $\chi^2(4) = 46.31$, $p = 2.12e{-09}$; remote-work capability: Wald $\chi^2(1) = 12.86$, $p = 0.000335$; interaction: Wald $\chi^2(4) = 2.82$, $p = 0.588$ |
| M1b | Attractiveness increase (large city reference) | Logistic regression (GLM binomial-logit; robust covariance). LR $\chi^2(5) = 69.54$, $p = 1.28e{-13}$; AIC = 55.79; BIC = 84.40 | Relative to large city: open rural OR = 4.51 ($p = 5.92e{-05}$); village/small town OR = 3.70 ($p = 3.49e{-09}$); medium-sized city OR = 1.90 ($p = 0.0113$); suburbs OR = 7.11 ($p = 5.44e{-05}$); remote-work capability OR ≈ 2.17 ($p = 1.41e{-06}$) |
| M2 | Attractiveness change (ordered) | Ordinal logistic regression (proportional odds; logit). LR $\chi^2(5) = 66.72$, $p = 4.91e{-13}$; −2LL 144.50 → 77.78; McFadden $R^2 = 0.050$ | No remote relative to remote: $B = -0.644$, $p = 2.89e{-05}$; OR = 0.53 |
| M3 | Dwelling satisfaction | Ordinal logistic regression (proportional odds; logit). LR $\chi^2(5) = 10.46$, $p = 0.063$; −2LL 176.79 → 166.33 | No remote relative to remote: $B = -0.415$, $p = 0.00215$; OR = 0.66 |
| M4 | Locality satisfaction | Ordinal logistic regression (proportional odds; logit). LR $\chi^2(5) = 21.94$, $p = 0.000537$; −2LL 196.10 → 174.16; McFadden $R^2 = 0.0096$ | Remote-work capability: $p = 0.760$; large city relative to suburbs: $B = 0.946$, $p = 0.031$; OR = 2.58 |

### 3.3 Robustness Checks

Sensitivity checks confirm that the main conclusions are not driven by the choice of context operationalisation. When settlement context is represented using a self-reported settlement-size category rather than perceived settlement type, the core finding for locality satisfaction remains unchanged: the settlement-size model is significant overall (LR $\chi2(7) = 22.07$, $p = 0.00247$; $-2LL$ 251.43 $\rightarrow$ 229.36), while remote-work capability remains non-significant ($p = 0.738$). This supports treating settlement self-identification as a substantively meaningful context measure for perception-based outcomes, while showing that the key conclusions do not depend on this choice. A complementary regional check for Mazowieckie points in the same descriptive direction: respondents with remote-work capability more often reported improved residential attractiveness (37.5% versus 15.0%). However, model-based estimates remain underpowered because of sparse cells and smaller sample size, so the regional result is treated as supportive rather than conclusive.

## 4 Discussion

The results suggest that remote work is associated with a durable reweighting of residential evaluation rather than a purely temporary pandemic reaction. Remote-capable respondents are more likely to report that their place of residence became more attractive during the COVID-19 period, even after settlement context is taken into account. At the same time, the positive revaluation outcome is strongly patterned by settlement context, and the large-city reference specification shows substantially higher odds of positive reassessment outside the core. This combination is consistent with the idea that reduced commute frequency lowers the relative penalty of distance and increases the value of space and residential amenities [25]. The results do not demonstrate relocation or market restructuring directly, but they do indicate that post-pandemic residential preferences may generate outward pressure unless they are counterbalanced by housing supply and planning responses.

A central contribution of the paper lies in showing that this revaluation is not uniform across residential scales. Dwelling satisfaction and locality satisfaction do not respond in the same way to remote-work capability. The dwelling layer is positively associated with remote capability, whereas the locality layer is not. This split is theoretically important because it aligns with the long-standing distinction in residential satisfaction research between evaluation of the housing unit and evaluation of the surrounding residential environment [11, 12]. It is also consistent with the have–want discrepancy perspective, since remote work may make needs such as space, privacy, and functional workability more salient without necessarily altering service access, public-space quality, or neighbourhood accessibility [9]. In that sense, remote work appears to improve the fit between household needs and the dwelling more readily than it improves the fit between households and their wider locality.

The settlement-gradient diagnostics sharpen the interpretation of this two-layer finding. Settlement context strongly structures stress-test revaluation, with the highest positive revaluation in the suburban category and the lowest in large cities, yet the same settlement measure does not produce a robust gradient in dwelling satisfaction ($\chi^2$ p =

0.234). This avoids a simplistic conclusion that suburbs are simply "better": revaluation of where one lives under home-centred routines can diverge from satisfaction with the housing unit. By contrast, locality satisfaction shows a statistically significant settlement gradient ($\chi^2$ $p = 0.023$), with the highest satisfied share in large cities and the lowest in open rural areas. This indicates that the two layers are not only conceptually distinct, but empirically structured in different ways.

This difference helps explain why remote work does not dissolve the advantages of more central or better-served environments. Locality satisfaction remains structured by settlement context rather than by remote capability. This points towards place-based determinants that are produced collectively and institutionally, such as accessibility, service provision, public and open space, and perceived safety. Research on accessibility and transport-related exclusion has repeatedly shown that peripheral locations can carry everyday disadvantages when essential destinations are harder to reach [20, 26]. This interpretation is also consistent with local human development research showing that subnational trajectories can become increasingly uneven and polarized over time, even where aggregate development indicators appear more stable [27]. From this perspective, remote work may enable some households to improve their dwelling fit without removing the broader inequalities embedded in the urban system. The implication is not that remote work makes place irrelevant, but that it changes the balance between dwelling-based and locality-based sources of residential wellbeing.

These findings have direct implications for post-pandemic planning. If remote and hybrid work remain structurally present, housing adequacy becomes more than a private matter of comfort; it becomes part of the urban conditions that support everyday functioning, work, and quality of life. At the same time, locality-level satisfaction continues to depend on neighbourhood functionality, including service access, public-space provision, and safe everyday mobility. This matters particularly in contexts such as Poland, where outward growth has often been associated with governance fragmentation, infrastructure strain, and dispersed settlement [28, 29]. Planning responses therefore need to work on both levels at once: improving the adaptability of the housing stock, especially where compact urban dwellings are under pressure, while also strengthening locality conditions in both core and peripheral environments.

These findings point to three linked policy implications. First, housing policy should treat remote and hybrid work not only as a labour-market change, but also as a housing-adequacy issue. If the dwelling becomes a more important site of everyday functioning, then minimum standards, housing adaptability, internal layout, acoustic and visual privacy, thermal comfort, digital connectivity, and the availability of flexible work-capable space become more relevant to residential wellbeing [30–33]. This does not mean that every dwelling should be designed around a separate home office, but it does suggest that housing policy and design guidance should pay greater attention to whether dwellings can absorb changing domestic functions without intensifying crowding or inequality. Second, positive revaluation outside large-city contexts should not be interpreted as evidence that suburban or peripheral environments are sufficient on their own. The results on locality satisfaction indicate that wider place quality remains dependent on services, accessibility, public space, mobility options, and everyday infrastructure. Suburban planning should therefore connect residential growth with proximity-based

service provision, local centres, active mobility, and transport accessibility rather than allowing remote-work-enabled demand to reinforce low-service dispersal [34]. Third, because these pressures operate across functional urban areas rather than within single municipalities, they require metropolitan coordination. Post-pandemic planning needs to link housing supply, land-use control, transport, digital infrastructure, and service location; otherwise, remote-work-related residential revaluation may improve dwelling fit for some households while deepening uneven accessibility and infrastructure burdens across the metropolitan system [35].

The methodological lesson is more limited but still important. Settlement self-classification appears to capture a meaningful dimension of perceived metropolitan position that is not fully reducible to administrative size categories. The sensitivity checks do not overturn the main conclusions, but they suggest that administrative bins alone are a weaker lens for perceptual outcomes when suburban identity and lived urbanity are substantively relevant. For this paper, that is less a claim about measurement superiority in general than a claim about fit between context measure and outcome type.

Several limitations define the scope of this interpretation. The analysis is cross-sectional and therefore identifies patterned differences rather than causal effects or within-person change. Since the survey was conducted in 2020, the observed revaluation of residential attractiveness may partly reflect an acute response to lockdowns, travel restrictions, and intensified home-centred routines rather than a durable shift in preferences under stabilised hybrid-work arrangements. At the same time, this timing is analytically informative: the data record residents' assessments at the moment when the functional meaning of home and locality was being actively renegotiated, rather than reconstructed retrospectively. The findings are also limited to employed respondents with defined remote-work capability, and the small suburban category calls for caution when interpreting the magnitude of suburban-specific estimates, although it does not appear to drive the main results. Finally, the paper identifies outcome patterns rather than mechanisms: future research should test how crowding, dwelling size, private outdoor space, internet quality, and other housing constraints shape the relationship between remote work and residential evaluation. Further analysis of the same dataset could link revaluation to stated relocation intentions, but assessing whether such intentions translated into actual moves would require a separately designed panel study or comparable later cross-sectional surveys.

## 5 Conclusion

What emerges from the analysis is not a simple story of post-pandemic residential dispersal, but a more selective revaluation of residential conditions under altered work routines. Remote-work capability appears to strengthen the importance of the dwelling as a site of everyday functioning, making housing adequacy more consequential for how people judge where they live. At the same time, the wider locality does not become irrelevant. Its evaluation remains tied to settlement context and to place-based conditions that households cannot secure through housing choice alone. This is why the paper argues for a two-layer reading of post-pandemic residential change: one layer centred on the dwelling and its capacity to accommodate work and daily life, and another centred on the locality and its accessibility, services, and environmental quality.

This distinction matters beyond the immediate pandemic context. It suggests that the spread of remote and hybrid work may intensify pressure on urban systems not only through possible relocation, but through a reordering of what residents value in the first place. This interpretation must, however, be read in light of the timing of the evidence. The survey captures residential evaluations in 2020, when lockdowns, mobility restrictions, and intensified home-centred routines were still directly shaping everyday experience. The findings therefore speak most directly to pandemic-period residential revaluation, rather than to confirmed long-term relocation behaviour or fully stabilised hybrid-work preferences. At the same time, this timing is analytically valuable: if COVID-19 is understood as a stress test of residential conditions, then the survey captures evaluations at the moment when the functional adequacy of dwellings and localities became unusually visible in everyday life.

In that sense, the significance of remote work lies less in any single behavioural outcome than in the way it redefines the relationship between home, locality, and metropolitan position. For planning, the implication is straightforward: neither housing policy nor neighbourhood policy is sufficient on its own. The post-pandemic city will be shaped by how successfully both dimensions are addressed together.

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## References

1. Mokhtarian, P.: Telecommuting and travel: state of the practice, state of the art. Transportation **18**(4), 319–342 (1991). https://doi.org/10.1007/BF00186563
2. Barrero, J., Bloom, N., Davis, S.: Why working from home will stick. nber.org (2021)
3. Aksoy, C.G., Barrero, J.M., Bloom, N., Davis, S.J., Dolls, M., Zarate, P.: Working from home around the world. Brook. Pap. Econ. Act. **2022**, 281–360 (2022)
4. Brueckner, J.K.: Lectures on Urban Economics. MIT Press, Cambridge (2011)
5. Angel, S., Blei, A.: The spatial structure of American cities: the great majority of workplaces are no longer in CBDs, employment sub-centers, or live-work communities. Cities (2016)
6. Ahrend, R., et al.: Expanding the doughnut? Spatial changes in housing demand since the rise of remote work. Reg. Stud. **59**, 2503968 (2025). https://doi.org/10.1080/00343404.2025.2503968
7. Bond-Smith, S., McCann, P.: Shadows and donuts: the work-from-home revolution and the performance of cities. J. Reg. Sci. **65**(5), 1401–1422 (2025). https://doi.org/10.1111/jors.70008
8. Kuźmar, S., Woźniak-Jęchorek, B., Bole, D.: Will remote work drive a new wave of suburbanisation in Poland? Analysing the relocation preferences of Polish office employees. Appl. Geogr. **186** (2026). https://doi.org/10.1016/j.apgeog.2025.103848
9. Jansen, S.: The impact of the have–want discrepancy on residential satisfaction. J. Environ. Psychol. (2014)

10. Balestra, C., Sultan, J.: Home sweet home: the determinants of residential satisfaction and its relation with well-being. OECD Statistics Working Papers (2013)
11. Amérigo, M., Aragones, J.: A theoretical and methodological approach to the study of residential satisfaction. J. Environ. Psychol. (1997)
12. Mohit, M., Raja, A.: Residential satisfaction-concept, theories and empirical studies. Planning Malaysia (2014)
13. Phillips, D.R., Siu, O., Yeh, A.G.O., Cheng, K.H.C.: The impacts of dwelling conditions on older persons' psychological well-being in Hong Kong: the mediating role of residential satisfaction. Soc Sci Med **60**, 2785–2797 (2005). https://doi.org/10.1016/j.socscimed.2004.11.027
14. Mridha, M.: Living in an apartment. J. Environ. Psychol. (2015)
15. Parkes, A., Kearns, A., Atkinson, R.: What makes people dissatisfied with their neighbourhoods? Urban Stud. **39**(13), 2413–2438 (2002). https://doi.org/10.1080/0042098022000027031
16. Zenk, S.N., Schulz, A.J., Israel, B.A., James, S.A., Bao, S., Wilson, M.L.: Neighborhood racial composition, neighborhood poverty, and the spatial accessibility of supermarkets in metropolitan Detroit. Am. J. Public Health **95**, 660–667 (2005). https://doi.org/10.2105/AJPH.2004.042150
17. Rappaport, J.: Hybrid Working, Commuting Time, and the Coming Long-Term Boom in Home Construction. ER. (2022). https://doi.org/10.18651/ER/v107n4Rappaport
18. Stanton, C., Tiwari, P.: Housing consumption and the cost of remote work. nber.org (2021)
19. Lucas, K.: A new evolution for transport-related social exclusion research? J. Transp. Geogr. (2019)
20. Hernandez, D., Titheridge, H.: Mobilities of the periphery: Informality, access and social exclusion in the urban fringe in Colombia. J. Transp. Geogr. (2016)
21. Davis, S.: The big shift in working arrangements: Eight ways unusual. nber.org (2024)
22. Ghent, A., Davis, M., Gregory, J.: Winners and Losers from the Work-from-Home Technology Boon (2024). Available at SSRN 4768634
23. Mouratidis, K.: Is compact city livable? The impact of compact versus sprawled neighbourhoods on neighbourhood satisfaction. Urban Stud. **55**(11), 2408–2430 (2018). https://doi.org/10.1177/0042098017729109
24. Eizenberg, E., Jabareen, Y., Zilberman, O.: Planning by scale: the role of perceived scale in determining residential satisfaction. J. Plan. Educ. Res. **43**, 829–840 (2023). https://doi.org/10.1177/0739456X20921431
25. Brueckner, J.K., Kahn, M.E., Lin, G.C.: A new spatial hedonic equilibrium in the emerging work-from-home economy? Am. Econ. J. Appl. Econ. **15**, 285–319 (2023). https://doi.org/10.1257/app.20210190
26. Lucas, K., Philips, I., Mulley, C., Ma, L.: Is transport poverty socially or environmentally driven? Comparing the travel behaviours of two low-income populations living in central and peripheral locations in the same city. Transp. Res. Part A: Policy Pract. **116**, 622–634 (2018). https://doi.org/10.1016/j.tra.2018.07.007
27. Kaleyeva, V., Werner, P.A., Porczek, M.: Assessing local human development in poland: insights from 2010 and 2023. In: Gervasi, O., Murgante, B., Garau, C., Karaca, Y., Faginas Lago, M.N., Scorza, F., and Braga, A.C. (eds.) Computational Science and Its Applications – ICCSA 2025 Workshops, pp. 387–401. Springer, Cham (2026). https://doi.org/10.1007/978-3-031-97606-3_26
28. Lisowski, A., Mantey, D., Wilk, W.: Lessons from Warsaw. In: Confronting Suburbanization, pp. 225–255. Wiley (2014). https://doi.org/10.1002/9781118295861.ch8
29. Majewska, A., Denis, M., Krupowicz, W.: Urbanization chaos of suburban small cities in Poland:'tetris development' (2020). https://www.mdpi.com/2073-445X/9/11/461

30. Cuerdo-Vilches, T., Navas-Martín, M.Á., Oteiza, I.: Working from home: is our housing ready? Int. J. Environ. Res. Public Health. **18** (2021). https://doi.org/10.3390/ijerph18147329
31. Quaglio, C., Todella, E., Lami, I.M.: Adequate housing and COVID-19: assessing the potential for value creation through the project. Sustainability, **13** (2021). https://doi.org/10.3390/su131910563
32. Doling, J., Arundel, R.: The home as workplace: a challenge for housing research. Hous. Theory Soc. (2022). https://doi.org/10.1080/14036096.2020.1846611
33. Holliss, F., Barac, M.: Housing space use in the pandemic and after: the case for new design guidance (2021)
34. Mantey, D.: Planning local centres in outer suburbs – The need for a proactive approach towards planning in post-socialist Poland. Cities. 150, (2024). https://doi.org/10.1016/j.cities.2024.105032
35. OECD: Implications of Remote Working Adoption on Place Based Policies: A Focus on G7 Countries. OECD Publishing (2021). https://doi.org/10.1787/b12f6b85-en

# A Data-Driven Framework for Cycle Path Quality: Integrating User Perception and Sensing

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**Abstract.** This paper presents a comprehensive framework for assessing the quality of cycle path design by integrating subjective and objective measures of user experience. The approach combines static infrastructure attributes, dynamic data from multiple sensors, and user-reported perceptions into synthetic indicators that predict service quality. Unlike traditional infrastructure evaluation methods, this research explicitly considers how users perceive and react to real-world cycling conditions, bridging gaps in current methodologies that often isolate technical measurements from behavioral responses. A segmentation-based graph model of the cycling network, enriched with contextual and environmental features, enables fine-grained data fusion and analysis. On-road trials with different user and vehicle profiles collect multi-source data (accelerometers, GPS, eye-tracking, biometric sensors), aligned in time and space to produce synthetic indicators. Predictive models, developed through both econometric and machine learning approaches, evaluate the relationship between objective indicators and subjective quality ratings. Preliminary results show the feasibility of integrating diverse datasets into a scalable framework capable of informing design, planning, and policy.

**Keywords:** Cycle paths · quality of service · data fusion · synthetic indicators · predictive models · sustainable mobility

## 1 Introduction and State-of-the-Art

Recently, cycling has increasingly become the topic of multidisciplinary research, spanning from transport engineering, urban planning, and medical and human behaviour science. The global emphasis on sustainable urban mobility, climate-neutral cities, and promoting active lifestyles primarily drives this leap of interest.

Within this context, the literature has examined the interaction among three features: the physical characteristics of cycling infrastructure, the type of vehicle used (e.g., bicycle, e-bike, e-kick scooters), and the experience of cyclists, both objective (e.g., physiological or mechanical data) and subjective (e.g., comfort, safety perception). Studies

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have affirmed that the experience of cyclists is shaped by an interplay of factors, including road geometry, pavement quality, type of segregation from vehicular traffic, and environmental (context) conditions. For instance, [1] and [2] emphasised the relevance of vibrations in assessing the comfort of cycle paths, developing quantitative methods to evaluate infrastructure quality from a mechanical standpoint. Studies [3, 4] contributed to understanding how different micromobility devices respond to surface irregularities, using onboard sensors to monitor vibration levels and assess their implications for comfort and user health. However, while the relevance of vibrational feedback has been acknowledged, few studies integrate such data with other sensors or behavioural indicators. For instance, [5] combined subjective surveys with eye-tracking data to study how pavement condition affects perceived safety. Study [6] explored how infrastructure and land use characteristics influence gaze patterns during cycling. These approaches provide understanding of how cycle infrastructure affects attentional dynamics, but remain constrained to specific contexts, typically urban and intersections.

The use of eye-tracking, biometric sensors, and wearable devices is growing, especially in cognitive and health-oriented studies (e.g., [7–10]). These tools are often employed in isolation (i.e., just one device is applied) or under laboratory conditions. Moreover, "on-road" studies are limited and rarely synchronised across multiple sensor sources. This methodological gap reduces the generalisability and validity of findings. Moreover, the potential of integrating spatial network models with user-centred sensing remains largely unexplored, as opposed to the integration of passenger-oriented monitoring approaches with digital and web-based decision-support frameworks to support the assessment and management of transport service quality under real operational conditions [11].

An additional limitation of existing literature is the lack of comprehensive frameworks that relate data on infrastructure typologies, user variability, and trip characteristics [12] (e.g., purpose, frequency, and environment). Studies focus primarily on commuting, overlooking leisure or touristic cycling, which often occurs in peri-urban or rural settings and is influenced by different spatial, perceptual, and ergonomic factors. Other point out how cycling for non-systematic purposes is underrepresented in research, despite its growing relevance in sustainable mobility policies [13, 14]. Additionally, while some studies (e.g., [15, 16]) examine safety concerns, such as conflicts with turning vehicles or signalised intersections, they often isolate such events from broader systemic variables like vehicle type or road environment. Therefore, there is a gap in studies attempting to model related effects: for instance, how user stress responses change when different vehicle types (e.g., e-bike vs e-scooter) are used along varying infrastructure typologies, or how trip purpose influences attention, speed, and physiological state.

Consequently, to the best of the authors' knowledge, no studies in the reviewed literature provide a framework that simultaneously integrates:

- Granular network segmentation based on both geometric and dynamic criteria.
- Multi-source, time- and space-synchronised sensor data (e.g., GPS, accelerometer, biometric).
- User-level variability in terms of physical, cognitive, and experiential traits.

- Link between subjective and objective assessment of cycle path quality service [17]. A similar perspective has also been explored in public transport service quality assessment, where subjective user perceptions and objective performance indicators were jointly integrated within a unified evaluation framework [18].

The few studies related often rely on controlled simulations or virtual reality environments, which, although useful, cannot capture the variability of real-world cycling experiences. The spatial and contextual limitations of these environments make them critical for capturing the full complexity of infrastructure-user interactions. Therefore, this study aims to fill these gaps by proposing a rigorous and replicable framework grounded in real-world data. By constructing a segment-based graph of the road network and aligning it with sensor data collected during cycling trials, the study enables a multi-criteria analysis of service quality. The goal is to understand how the physical infrastructure and the surrounding environment interact with individual users and vehicles under realistic conditions, producing measurable effects on objective and subjective "comfort". Furthermore, by incorporating a range of user, vehicle, and cycle path types, the proposed framework enables for generalisable insights across diverse scenarios and derives guidelines. Lastly, it supports the development of predictive models that not only explain behaviour in retrospect but helps identify where and for whom the infrastructure underperforms. Therefore, it contributes to a more inclusive, data-informed approach to infrastructure evaluation and active mobility planning.

## 2 Methodology

The proposed methodology is structured into five sequential phases (Fig. 1), each of which addresses a key aspect of evaluating cycle infrastructure quality of service (QoS). The process integrates infrastructural attributes, user perceptions, and sensor-based measurements into a coherent framework that allows for both descriptive assessment and predictive modelling.

### 2.1 Phase 1. Preliminary Setup

The first phase establishes the analytical bases by building a graph-based representation of the cycling network and attributing relevant infrastructural and contextual variables. The network is modelled as a directed graph, where nodes correspond to intersections or points of divergence and links to homogeneous segments. Topological corrections, such as snapping and node consolidation, are applied to ensure connectivity, while segmentation rules divide the network according to geometric, functional, and land use discontinuities.

Moreover, each segment is enriched with systematic micro-scale data collection from open datasets, geoportals, and field surveys. These attributes include physical features, functional classifications, and contextual characteristics [e.g., 13]. The result is a fine-grained representation of infrastructure conditions, providing the reference layer for subsequent data integration.

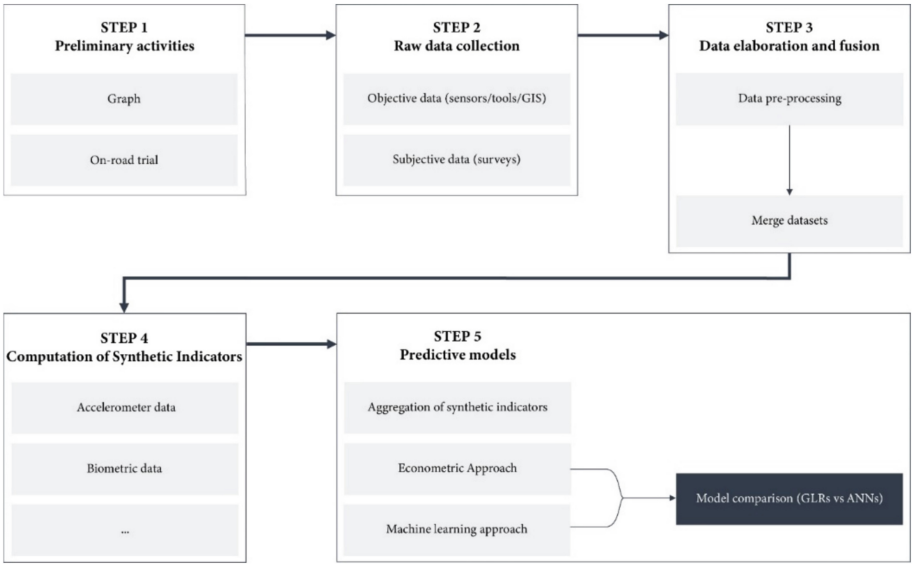


**Fig. 1.** Flowchart of the methodology.

## 2.2 Phase 2. Data Collection

In the second phase, both subjective and objective data are gathered through on-road trials.

Subjective data are obtained through structured questionnaires administered to trial participants. These surveys collect socio-demographic information and mobility habits, while also eliciting perceptions of comfort, safety, fatigue, and environmental quality during the ride. Responses are expressed on a Likert-type scale, providing user-centred evaluations for each segment.

Objective data derive from a set of sensors and devices: accelerometers to capture vibrations, GPS units to trace trajectories and speeds, eye trackers to monitor gaze behaviour, biometric wearables to record physiological responses (e.g., heart rate, electrodermal activity), and meteorological stations to contextualise environmental conditions. These multi-source streams document the physical, cognitive, and physiological dimensions of cycling.

The combination of these two data sources ensures that both experiential perceptions and measurable physical responses are captured for the same routes and conditions.

## 2.3 Phase 3. Data Elaboration and Fusion

Given the heterogeneity of devices, a dedicated pipeline is required to pre-process and integrate data. Outlier removal is performed using statistical thresholds, while temporal alignment harmonises measurements by aggregating high-frequency signals and interpolating low-frequency ones into fixed time windows. Spatial alignment maps each observation to the corresponding network segment using GPS data and proximity rules.

Once cleaned and aligned, datasets from subjective surveys, sensors, and infrastructural attributes are merged into a single analytical framework. This step ensures that for each segment and user, both subjective and objective variables are available, enabling cross-comparison and modelling.

### 2.4 Phase 4. Computation of Synthetic Indicators

Raw sensor data are transformed into synthetic indicators that summarise relevant aspects of the riding experience. Accelerometer signals are processed according to ISO 2631–1 to compute weighted Root Mean Square values representing ride comfort [3]. GPS traces yield average speeds and positional trends, while eye-tracking data produce counts of fixations and saccades that reflect attentional load [e.g., 7,16]. Biometric measures such as heart rate or skin conductance are averaged over time windows, serving as proxies for stress and exertion.

By reducing high-frequency data into interpretable metrics, these indicators allow robust comparisons across users, vehicles, and segments. They serve as objective drivers of quality, complementing the subjective ratings collected in Phase 2.

### 2.5 Phase 5. Predictive Modelling

The final phase develops predictive models that estimate subjective QoS from objective indicators and infrastructural variables. Two complementary approaches are applied.

The statistical approach relies on Generalised Linear Regressions (GLRs), which provide statistical interpretability and enables the identification of significant predictors. Interaction terms and transformations are included to capture non-linear effects.

The machine learning approach employs Artificial Neural Networks (ANNs), which can model complex relationships between indicators and user perceptions.

Networks are trained and validated on partitioned datasets, with model performance assessed through error metrics such as Root Mean Square Error (RMSE) and Mean Absolute Error (MAE). Feature importance is evaluated through permutation methods and sensitivity analyses.

A systematic comparison between GLRs and ANNs highlights trade-offs between interpretability and predictive accuracy. Together, the two approaches provide both explanatory insights and forecasting potential, enabling planners to identify critical factors influencing user satisfaction and to prioritise interventions.

## 3 Results

The methodological framework described above was applied to generate a structured dataset integrating infrastructural, subjective, and objective variables for cycling infrastructure assessment. At this stage, the research primarily focused on the methodological issues rather than exhaustive empirical testing. Therefore, results emerged in relation to theoretical implementation in terms of (i) network representation and segmentation, (ii) computation of synthetic indicators, and (iii) predictive modelling of subjective quality of service (QoS). These results provide the basis for discussing the strengths, limitations,

and implications of the proposed approach, as well as a groundwork for current empirical testing. For the sake of space available in the paper, the list of variables is reported in the Notational Glossary at the end of the paper.

### 3.1 Phase 1. Network Segmentation and Attribute Integration

The graph-based representation of the cycle infrastructure, segmented according to geometric, functional, and contextual discontinuities, provided the analytical foundation for data fusion. The segmentation process ensured homogeneity in both static and dynamic conditions. It is governed by two criteria:

- Statistical consistency in dynamic data distributions, such as those gathered during on-road trials (e.g., acceleration or speed traces).
- Minimum spatial resolution of available static data (e.g., slope, street category), to ensure alignment between infrastructure representation and data granularity.

As formalised in Eq. 1, the variability of dynamic indicators $z$ within a segment was assessed through the standard deviation:

$$\sigma_{\lambda}^{(z)} = \sqrt{\frac{1}{|\Omega_s|}\sum_{\omega\in\Omega}(z_{\omega} - \overline{z_{\lambda}})^2} \tag{1}$$

A segment was considered valid if $\sigma_{\lambda}^{(z)} < \tau_z$, where $\tau$ is a tolerance threshold empirically defined. This ensured that discontinuities aligned with changes perceived by users rather than purely geometric breaks. The segmentation process is performed algorithmically, using a GIS-based procedure that applies "split" rules at each detected discontinuity.

The second preliminary activity enriched each segment with GIS attributes, creating a comprehensive dataset linking:

- Physical features, i.e., slope, width, pavement type (material), route type, dimension (width), pavement maintenance, underpass, direction, traffic volumes, road type, speed limit, bus services, node type.
- Contextual factors, i.e., tree coverage, waterscapes, protected area, landscape peculiarities, shade, historical town unit, manufacturing area, cultural peculiarity, enogastronomic peculiarity, roadside car parking, building height, building density, private vehicular access, green spaces.
- User service availability, i.e., water/drinking points, lighting, accommodation, catering, other generic shops, public transport stops/stations.

Geometries and data sources are retrieved from open and official datasets, ranging from national and regional geoportals to municipal Web Geographic Information System platforms and collaborative mapping projects (e.g., Open Street Maps). These sources often include both spatial and non-spatial components, which are reviewed and, where needed, corrected to ensure consistency with the graph structure adopted.

### 3.2 Phase 2. Network Segmentation and Attribute Integration

**Subjective Quality of Service.** User perceptions were collected through structured questionnaires during the on-road trials I. Ratings referred to multiple components Ξ (comfort, safety, ergonomics, fatigue, environment) and were aggregated into an overall quality score *y(i,λ)*. The questionnaire dataset is filled by the value *c(u)* taken by each characteristic for the user $u \in U$. Moreover, each user $u \in U$ rates the individual components that disaggregate the riding quality based on their experience during the trial. Thus, the rating associated with the overall experience during the trial $i(u,v,p) \in I$ is computed as the arithmetic mean rounded to the nearest integer of the individual components *y(i,λ,ξ)*. Specifically:

$$y(i,\lambda) = Round\left(\frac{1}{|\Xi|}\sum_{\xi\in\Xi} y(i,\lambda,\xi)\right) \forall\ i(u,v,p) \in I;\quad \forall\lambda \in \Lambda(p) \tag{2}$$

**Objective synthetic indicators.** An outcome was the computation of synthetic indicators summarising high-frequency sensor data.

- Accelerometer data were processed according to ISO 2631–1, which prescribes weighted RMS values for vibrations. As it is formalised in Eq. 3, the weighted RMS acceleration along axis r is:

$$m(i,acc,j,\psi) = a_j(i,acc,\psi);\ \forall i(u,v,p) \in I;\ \forall acc \in ACC; \forall j \in J; \forall \psi \in \Psi(i,acc) \tag{3}$$

- GPS data provided spatial and temporal traces (Eq. 4), and the mean speed over a time window was derived from positional differences:

$$m(i,gps,\psi) = \begin{cases} lat(i,gps,\psi)\ if\ \ q = latitude \\ lon(i,gps,\psi)\ if\ \ q = longitude \end{cases} \tag{4}$$

$$\forall i(u,v,p) \in I; \forall gps \in GPS; \forall \psi \in \Psi(i,gps)$$

- Eye-tracking data were translated into counts of fixations and saccades per window. These indicators reflect attentional load and visual scanning behaviour.fixation

$$m(i,eye,\psi) = \begin{cases} \delta_{fix}(i,eye,\psi)\ if\ \ q = state \\ x_{fix}(i,eye,\psi)\ if\ \ q = horiz.fixationcoordinate \\ y_{fix}(i,eye,\psi)\ if\ \ q = vert.fixationcoordinate \\ \delta_{sac}(i,eye,\psi)\ if\ \ q = saccadestate \\ s_{sac}(i,eye,\psi)\ if\ \ q = angularsaccadicspeed \end{cases} \tag{5}$$

$$\forall i(u,v,p) \in I; \forall eye \in EYE; \forall \psi \in \Psi(i,eye)$$

- Biometric data (heart rate, respiratory rate, skin conductance, etc.) were aggregated through mean functions, as in Eq. 6:

$$m(i, bio, q, \psi) = \begin{cases} rain(i, bio, \psi) \ if \ \ q = pulse\ rate \\ prv(i, bio, \psi) \ if \ \ q = pulse\ rate\text{variability} \\ rr(i, bio, \psi) \ if \ q = respiratory\ rate \\ sp(i, bio, \psi) \ if \ \ q = blood\ oxygen\ saturation \\ btemp(i, bio, \psi) \ if \ \ q = body\ temperature \\ eda(i, bio, \psi) \ if \ \ q = electrodermal\ activity \end{cases} \tag{6}$$

$$\forall i(u, v, p) \in I; \forall bio \in BIO; \forall \psi \in \Psi(i, bio, q)$$

These indicators provided a multidimensional and consistent description of the objective quality of service across users and contexts.

- Meteorological data

$$m(i, met, q, \psi) = \begin{cases} rain(i, met, \psi) \, if \ \ q = rain \\ temp(i, met, \psi) \, if \ \ q = temperature \\ rh(i, met, \psi) \, if \ \ q = relativehumidity \\ rad\,(i, met, \psi) \, if \ \ q = globalsolarradiation \\ wspeed\,(i, met, \psi) \, if \ q = windspeed \\ wdir(i, met, \psi) \, if \ \ q = winddirection \end{cases} \tag{7}$$

$$\forall i(u, v, p) \in I; \ \forall met \in GPS; \ \forall \psi \in \Psi(i, met)$$

### 3.3 Phase 3. Data Elaboration and Fusion

Next, sensor data required alignment and cleaning. Outliers were removed using the three-sigma rule (Eq. 8):

$$|m(i, s, q, \psi) - \mu(i, s, q)| > 3\sigma(i, s, q); \forall i(u, v, p) \in I; \forall s \in S; q \in Q(s); \forall \psi \in \Psi(i, s, q) \tag{8}$$

Temporal alignment was then performed by resampling all signals into fixed-duration windows (Eq. 9), applying aggregation functions for high-frequency sensors and interpolation functions for low-frequency ones.

$$syn(i, s, q, \omega) = \begin{cases} agg(\{m(i, s, q, \psi) \in M \,|\, \psi \in \Psi(i, s, q, \omega)\}) \ iff_{samp}(s) \geq 1/\cdot T \\ int(\{m(i, s, q, \psi) \in M \,|\, \psi \in \Psi(i, s, q, \omega)\}) \ iff_{samp}(s) < 1/\cdot T \end{cases};$$

$$\forall i(u, v, p) \in I; \forall s \in \mathrm{S}; \forall q \in \mathrm{Q(s)}; \forall \omega \in \Omega(i) \tag{9}$$

Spatial alignment was carried out by assigning time-window data to the nearest segmt, as formalised in Eq. 10.

$$\breve{\lambda}(i, \omega) = \underset{\lambda \in \Lambda(p)}{\arg\min}\, dist(i, \omega, \lambda); \ \forall \, i(u, v, p) \in I; \ \forall \, \omega \in \Omega(i) \tag{10}$$

This integration ensured that subjective ratings, infrastructural attributes, and synthetic indicators could be consistently merged into a unified dataset.

### 3.4 Phase 4. Computation of Synthetic Indicators

- Meteorological da:

$$syn(i, met, q, \omega) = m\big(i, met, q, \psi_{inf}\big) + \frac{m\big(i, met, q, \psi_{sup}\big) - m\big(i, met, q, \psi_{inf}\big)}{\psi_{sup} - \psi_{inf}} \cdot (midpoint(T(i, \omega)) - T(i, \omega)); \quad (11)$$

$$\forall i(u, v, p) \in I;\ \forall met \in MET;\ \forall q \in Q(met); \forall \omega \in \Omega(i);$$

- Accelerations acting along the three orthogonal axes ($j \in J$) using the multiplying factors $k_j$, as follows:

$$syn(i, acc, \omega) = \left(\sum_{j \in J} k_j^2 \cdot RMS^2_{(i,acc,\omega)}(i, acc, \omega)\right)^{\frac{1}{2}} \left[m/s^2\right] \quad (12)$$

$$\forall i(u, v, p) \in I;\ \forall acc \in ACC;\ \forall \omega \in \Omega(i)$$

- Eye tracking synthetic indicators:

$$syn(i, eye, \omega) = c_{fix}(i, \omega, eye), \boldsymbol{c_{sac}(i, \omega}, eye), \mu\big(x_{fix}(\boldsymbol{i}, \boldsymbol{\omega}, eye)\big), \mu\big(y_{fix}(\boldsymbol{i}, \boldsymbol{\omega}, eye)\big), \mu(s_{sac}(\boldsymbol{i}, \boldsymbol{\omega}, eye)) \quad (13)$$

$$\forall i(u, v, p) \in I;\ \forall eye \in ACC;\ \forall \omega \in \Omega(i)$$

- Biometric data

$$syn(i, bio, \omega) = \{\mu(m(i, bio, q, \omega)) : q \in Q(bio)\}; \quad \forall i(u, v, p) \in I;\ \forall bio \in BIO;\ \forall \omega \in \Omega(i); \quad (14)$$

### 3.5 Phase 5. Predictive Modelling

The central innovation of the framework lies in the modelling of subjective QoS as a function of objective variables. This was implemented through two alternative approaches.

According to a traditional statistical approach, GLR were applied, as formalised in Eq. 15:

$$y(\lambda, i) = GLR(\{x_h(\lambda, i)\} \in X) + \varepsilon(\lambda, i) = \alpha_0 + \sum_{x_h \in X} \sum_{\pi_h \in \Pi_h} \alpha_h \pi_h(x_h(\lambda, i)) + \sum_{(x_{h_1}, x_{h_2}) \in X \times X} \sum_{\pi_{h_1 h_2} \in \Pi_{h_1 h_2}} \alpha_{h_1 h_2} \pi_{h_1 h_2}\big(x_{h_1}(\lambda, i), x_{h_2}(\lambda, i)\big) + \varepsilon(\lambda, i); \forall d \in D; \quad (15)$$

According to an innovative Machine learning approach, As were implemented, following Eq. (16):

$$y(\lambda, i) = ANN(\{x_h(\lambda, i)\} \in X) + \varepsilon(\lambda, i) = \overline{\varphi}\left(\overline{u} + \sum_{\theta \in \Theta} \overline{w}(\theta) \cdot \varphi\left(u(\theta) + \sum_{x_h \in X} w(\theta, x_h) \cdot x_h(\lambda, i)\right)\right) + \varepsilon(\lambda, i); \forall d \in D; \quad (16)$$

The predictive performance of the alternative approaches was compared by Root Mean Squared Error (RMSE) and Mean Absolute Error (MAE), while feature importance analysis was implemented to investigate the contributions of the predictors, such as vibration and slope, user characteristics (e.g., body mass, experience level), and contextual variables (e.g., shade, land use).

## 4 Discussion and Conclusion

The method resulted in a high level of complexity. However, segment-based representation ensures that discontinuities in infrastructure correspond to experiential differences. The combination of subjective and objective measures enhances validity, while synthetic indicators provide a manageable yet meaningful way of summarising complex signals.

From a modelling perspective, the coexistence of GLRs and ANNs offers complementary benefits: GLRs provide interpretable insights for planning and design, whereas ANNs maximise predictive accuracy and capture non-linear relationships. Overall, they establish a robust basis for both explanatory and forecasting purposes.

To conclude, the framework is implemented to supports decision-making by identifying segments with low QoS, guiding maintenance priorities and design improvements [19, 20]. However, limitations remain; the method need to be validated by empirical trial across different urban contexts and user types.

**CRediT Authorship Contribution Statement.** Conceptualization: M.C., R.V.; Methodology: M.C., R.V.; Formal analysis: M.C., R.V., S.R.; Data curation: M.C., R.V., S.R., D.V.; Visualization: All; Validation: M.C., R.V., D.V., M.P.; Writing-Original Draft: M.C., R.V.; Writing-review & editing: All; Supervision: B.B., M.P.

## 5 Notional Glossary

| Variable | Definition |
|---|---|
| U | Set of users involved in the trials |
| u ∈ U | A specific user |
| V | Set of vehicles involved in the trials |
| v ∈ V | A specific vehicle |
| P | Set of paths used in the trials |

(*continued*)

(*continued*)

| Variable | Definition |
|---|---|
| $p \in P$ | A specific path |
| $\Lambda(p)$ | Set of segments along path p |
| $\lambda \in \Lambda(p)$ | A specific segment |
| I | Set of trials |
| $i(u,v,p) \in I$ | A trial *i*, performed by user u with vehicle v on path p |
| $\Xi$ | Set of subjective quality components (comfort, safety, ergonomics, fatigue, environment) |
| $\xi$ | A specific rating component |
| $y(i,\lambda,\xi)$ | Rating for component $\xi$ during trial i on segment $\lambda$ |
| $y(i,\lambda)$ | Overall quality rating for segment $\lambda$ during trial i |
| L | Set of rating levels (e.g., 1–5 or qualitative labels) |
| ACC | Set of accelerometers used in trials |
| J | Set of Cartesian axes (e.g., x, y, z) |
| $a_j(i,acc,\psi)$ | Acceleration along axis j at time $\psi$ during trial i |
| GPS | Set of GPS devices used in trials |
| $lat(i,gps,\psi)$ | Latitude at time $\psi$ during trial i |
| $lon(i,gps,\psi)$ | Longitude at time $\psi$ during trial i |
| EYE | Set of eye-tracking devices used in trials |
| $\delta_fix(i,eye,\psi)$ | Binary indicator of fixation state at time $\psi$ |
| $x_fix(i,eye,\psi)$ | Horizontal fixation coordinate |
| $y_fix(i,eye,\psi)$ | Vertical fixation coordinate |
| $\delta_sac(i,eye,\psi)$ | Binary indicator of saccade state |
| $s_sac(i,eye,\psi)$ | Angular saccadic speed |
| BIO | Set of biometric sensors used in trials |
| $pr(i,bio,\psi)$ | Pulse rate |
| $prv(i,bio,\psi)$ | Pulse rate variability |
| $rr(i,bio,\psi)$ | Respiratory rate |
| $sp(i,bio,\psi)$ | Blood oxygen saturation |
| $btemp(i,bio,\psi)$ | Body temperature |
| $eda(i,bio,\psi)$ | Electrodermal activity |
| MET | Set of meteorological stations |
| $rain(i,met,\psi)$ | Rainfall |
| $temp(i,met,\psi)$ | Temperature |
| $rh(i,met,\psi)$ | Relative humidity |

(*continued*)

(*continued*)

| Variable | Definition |
|---|---|
| rad(i,met,ψ) | Solar radiation |
| wspeed(i,met,ψ) | Wind speed |
| wdir(i,met,ψ) | Wind direction |
| σ_λ(z) | Standard deviation of indicator z within segment λ |
| τ_z | Tolerance threshold for indicator z |
| m(i,s,q,ψ) | Raw measurement of quantity q from sensor s at time ψ |
| μ(i,s,q) | Mean of quantity q from sensor s during trial i |
| σ(i,s,q) | Standard deviation of quantity q from sensor s during trial i |
| syn(i,s,q,ω) | Synthetic indicator for sensor s and quantity q in time window ω |
| ω ∈ Ω(i) | Time window ω in trial i |
| ĉλ(i,ω) | Segment assigned to time window ω |
| x_h(λ,i) | Predictor h for segment λ during trial i |
| y(λ,i) | Predicted subjective quality of service |
| ε(λ,i) | Residual error of prediction |
| GLR(x_h) | Generalised Linear Regression model |
| ANN(x_h) | Artificial Neural Network model |

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## References

1. Gao, J., Sha, A., Huang, Y., Hu, L., Tong, Z., Jiang, W.: Evaluating the cycling comfort on urban roads based on cyclists' perception of vibration. J. Clean. Prod. **192**, 531–541 (2018)
2. Bíl, M., Andrášik, R., Kubeček, J.: How comfortable are your cycling tracks? A new method for objective bicycle vibration measurement. Trans. Res. Part C: Emerging Technol. **56**, 415–425 (2015)
3. Ventura, R., Ghirardi, A., Vetturi, D., Maternini, G., Barabino, B.: Comparing the vibrational behaviour of e-kick scooters and e-bikes: evidence from Italy. In: International Journal of Transportation Science and Technology (2023)

4. Cano-Moreno, J.D., Islán, M.E., Blaya, F., D'Amato, R., Juanes, J.A., Soriano, E.: E-scooter Vibration Impact on Driver Comfort and Health. J. Vibrat. Eng. Technol. **9**, 1023–1037 (2021)
5. Gadsby, A., Tsai, J., Watkins, K.: Understanding the influence of pavement conditions on cyclists' perception of safety and comfort using surveys and eye tracking. Transp. Res. Rec. **2676**(12), 112–126 (2022)
6. Jang, G., Kim, S.: Investigating the effect of a raised cycle track, physical separation, land use and number of pedestrian on cyclists' gaze behavior. J. Archit. Urban. **43**(1), 112–122 (2019)
7. Rupi, F., Krizek, K.J.: Visual eye gaze while cycling: analyzing eye tracking at signalized intersections in Urban conditions. Sustainability **11**, 6089 (2019)
8. Nygårdhs, S., Ahlström, C., Ihlström, J.: Bicyclists' adaptation strategies when interacting with text messages in urban environments. Cogn. Technol. Work **20**, 377–388 (2019)
9. G. Gerboni, G. Comunale, W. Chen, J. Lever Taylor, M. Migliorini, R. Picard, M. Cruz, G. Regalia, "Prospective clinical validation of the Empatica EmbracePlus wristband as a reflective pulse oximeter," Frontiers in Digital Health, 5, 1258915, 2023
10. Vos, G., Trinh, K., Sarnyai, Z., Azghadi, M.R.: Generalizable machine learning for stress monitoring from wearable devices: a systematic literature review. Int. J. Med. Informatics **173**, 105026 (2023)
11. Barabino, B., Lai, C., Casari, C., Demontis, R., Mozzoni, S.: Rethinking transit time reliability by integrating automated vehicle location data, passenger patterns, and web tools. IEEE Trans. Intell. Transp. Syst. **18**(4), 756–766 (2016)
12. Garau, C., Pavan, V.M.: Evaluating urban quality: indicators and assessment tools for smart sustainable cities. Sustainability **10**(3) (2018)
13. Carra, M., Pavesi, F.C., Barabino, B. : Sustainable cycle-tourism for society: Integrating multi-criteria decision-making and land use approaches for route selection. Sustain. Cities Soc. **99** (2023)
14. Rainieri, G., Carra, M., Richiedei, A., Pezzagno, M.: Evaluating active mobility: enhancing the framework for social sustainability. TeMA – J. Land Use, Mobility Environ. **3**, 113–128 (2024)
15. K. Deliali, E. Christofa M. Knodler, "The role of protected intersections in improving bicycle safety and driver right-turning behavior," Accident Analysis & Prevention, 159, 106295, 2021
16. Abadi, M.G., Maloney, P., Hurwitz, D.: Exploring bicyclists' visual attention during conflicts with truck traffic. Transp. Res. Rec. **2676**(11), 137–144 (2022)
17. L. Ferretto, M. Carra, B. Barabino, "Enlarging the concept of quality of service: from a sectoral to a multimodal perspective," Transportation Letters, pp. 1–16, 2026
18. Barabino, B., Deiana, E., Mozzoni, S.: The quality of public transport service: the 13816 standard and a methodological approach to an Italian case. Ingegneria Ferroviaria **68**(5), 475–499 (2013)
19. Rossetti, S., Caselli, B., Stabile, F., Marinelli, L.J., Carra, M.: How do SUMPs consider factors influencing walkability and cyclability? A review of literature and planning tools. European Transport / Trasporti Europei **97**, 1–11 (2024)
20. Ferretto, L., Carra, M., Barabino, B.: Key quality parameters (KQPs) driving the development of sustainable multimodal transport. Transp. Res. Interdiscip. Perspect. **36**, 101924 (2026)

# Transport Infrastructures for Smart Cities (TISC 2026)

# Operationalizing National Road Design Guidelines: A Python Tool for Geometric Design Consistency Assessment

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**Abstract.** Geometric design consistency is a key principle in roadway design, reflecting the degree to which successive geometric elements promote smooth and predictable vehicle operation. Although national road design guidelines typically incorporate qualitative requirements for geometric harmony and operating speed continuity, they rarely provide computational procedures or tools to support systematic consistency evaluation during the design and assessment process. This paper presents a Python-based tool that operationalizes road design guidelines through a speed-based framework for geometric design consistency assessment.

The proposed methodology focuses on horizontal alignment and explicitly computes the 85$^{th}$ percentile operating speed ($V_{85}$) for tangents and circular curves using geometry-based relationships. Design consistency is evaluated by analyzing speed differentials ($\Delta V$) between successive alignment elements and classifying consistency levels based on widely adopted threshold values. The approach enables the construction of continuous operating speed profiles and the automated identification of locations exhibiting potentially inconsistent geometric transitions. An application example is presented to demonstrate the tool's ability to support engineering judgement by highlighting critical locations along a roadway alignment. The approach is readily transferable to different regulatory contexts and provides a foundation for future extensions, including vertical alignment analysis and integration with advanced design and geographic information systems.

**Keywords:** Geometric design consistency · Operating speed ($V_{85}$) · Horizontal alignment · Speed-based assessment · Road design guidelines · Python-based tool

## 1 Introduction

Geometric design consistency is a fundamental principle in roadway design, reflecting the degree to which successive geometric elements support smooth and predictable vehicle operation. Inconsistent horizontal alignment may require abrupt speed adjustments, indicating a mismatch between roadway geometry and expected operating behaviour. As a result, speed-based measures, particularly those based on the 85$^{th}$ percentile operating speed ($V_{85}$), are widely used to quantify geometric design consistency and to identify potentially problematic transitions along road alignments.

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At the same time, national road design guidelines encode valuable but largely qualitative knowledge regarding geometric harmony, continuity, and acceptable speed variation. The absence of computational tools that translate these principles into automated evaluation procedures represents a critical gap between guideline-based design and modern computational practice. This paper addresses this gap by presenting a Python-based tool that operationalises road design guidelines through an explicit, speed-based geometric consistency assessment framework. By computing operating speed (V85) from horizontal alignment geometry and automatically evaluating speed differentials between successive elements, the proposed approach enables transparent, repeatable, and extensible consistency analysis, providing a foundation for integrating geometric design assessment into broader computational science and engineering applications.

The goal of this research is to bridge the gap between qualitative road design guidelines and computational evaluation by developing a Python-based tool for speed-based geometric design consistency assessment. The proposed approach enables automated, transparent, and repeatable evaluation of horizontal road alignment consistency through explicit computation of operating speed and speed differentials.

## 2 Literature Review

The geometric design of rural two-lane highways significantly influences traffic safety and operational efficiency (Gibreel et al., 1999). Engineers face challenges in balancing design criteria with budgetary and environmental factors. A critical aspect of this design is achieving consistency, which aligns roadway features with driver expectations, thereby preventing abrupt maneuvers and mitigating accident risks (Faghri & Harbeson, 1999; Messer, 1980). Geometric design consistency is fundamentally defined as the degree to which a highway's geometric and operational features conform to driver expectancy (Fitzpatrick et al., 2000; Hamilton et al., 2019; Wooldridge et al., 2003). It is generally understood as the alignment of a highway encouraging uniform driving behavior and meeting driver expectations (Messer, 1980). This concept is not limited to a single measure but can be applied across various conditions and measures of effectiveness, including horizontal alignment and intersections (Wooldridge et al., 2003). The underlying principle is that when drivers' expectations align with the actual road conditions, driving is considerably safer (Qin et al., 2020).

Driver expectancy refers to a driver's inclination, based on prior experience, to respond in a predictable manner to a given roadway or traffic situation (Torregrosa, 2015). Expectancies can be categorized as a) a priori - Based on a driver's accumulated long-term experience since obtaining their driving license, or b) ad hoc - Formed from the immediate experience of the road segment the driver is currently traversing (Torregrosa, 2015).

Therefore, a lack of consistency occurs when there are unexpectedly high driver workloads or sudden changes in highway alignment that do not meet these learned expectations (Fitzpatrick et al., 2000; Krammes et al., n.d.; Messer, 1980). Such inconsistencies can surprise drivers, leading to inappropriate speeds, increased workload, delayed responses, incorrect decisions, and ultimately, a higher likelihood of accidents (Messer, 1980; Torregrosa, 2015; Vukoje et al., 2012).

Early research by Messer, emphasizing driver behavior principles and empirical evidence, further developed methodologies for evaluating and improving geometric design consistency on rural non-freeway highways (Messer, 1980). Early research demonstrated that compliance with geometric standards does not necessarily ensure safe operating conditions, as accident occurrence was found to be more closely associated with changes in operating speed than with individual geometric elements [FHWA, 1999;].

The concept continued to gain greater acceptance in North America and globally, with research focusing on its integration into design practices (Gibreel et al., 1999; Hassan et al., 2001). Research commonly categorizes the factors influencing geometric design consistency on two-lane rural highways into speed, safety, and performance considerations (Gibreel et al., 1999).

Operating speed is a primary metric for evaluating design consistency, typically defined by the 85$^{th}$ percentile speed ($V_{85}$), under free-flow conditions (Gibreel et al., 1999). Variations in operating speed that deviate significantly from the design speed ($V_e$), or large differences in operating speeds between successive roadway elements, indicate design inconsistencies (Gibreel et al., 1999; Torregrosa, 2015). Studies have consistently identified the radius of horizontal curves as a dominant factor affecting operating speed prediction and models have been developed to predict operating speeds and assess consistency based on these speed differentials (Gibreel et al., 1999).

Operating speed profiles involve modeling operating speed profiles and comparing the design speed against operating speeds or analyzing the variation in operating speeds between successive highway elements (Gibreel et al., 1999; Torregrosa, 2015). Other methods also use the difference between the 85$^{th}$ percentile operating speed ($V_{85}$) of a road element and the inertial operating speed, defined as the average operating speed on the previous 1 km road segment (Cefalo et al., 2024). Operating speed consistency models can be local, assessing a single element or successive elements, or global, evaluating the entire road segment (Cefalo et al., 2024). The deviation of operating speed from design speed for each vehicle category at specific curve points (entry, mid-point, and exit) is also a criterion (Chaudhari et al., 2022).

Lamm et al. (1988) argued that operating at geometric features on two-lane rural highways with speeds significantly exceeding the allowable or design speed leads to geometric design inconsistencies. To address this issue, Lamm et al. (1988) introduced a consistency evaluation approach, referred to as *Safety Criterion I*, based on the speed differential between the 85$^{th}$ percentile operating speed and the design speed for individual geometric elements. This concept has also been adopted in the Greek road design guidelines as the **first safety criterion**, forming the basis for assessing global geometric harmony through the relationship between operating and design speeds. Within this framework, threshold values are used to classify geometric consistency as good, acceptable, or poor.

Criterion II is also a design consistency criterion, related to operating speed, and considers the differences in operating speeds on successive highway elements (Torregrosa, 2015). Like Criterion I, it is used to categorize the consistency of curves as good, fair, or poor (Chaudhari et al., 2022). The specific details of its calculation are implied to be part of the methodologies developed by Lamm et al. and Fitzpatrick et al. (Chaudhari et al., 2022).

Alignment indices such as the average radius, ratio of maximum to minimum radius, and average rate of vertical curvature, are used to characterize the general geometry of a road section and correlate with collision frequency (Cefalo et al., 2024; Torregrosa, 2015). The idea is that geometric inconsistencies arise when the general character of an alignment change significantly (Cefalo et al., 2024). Comparative analyses of European design standards shows that several countries have moved toward incorporating expected operating speeds and formal consistency rules to better manage driver expectations and improve safety (Brenac 1996). Comprehensive reviews of the literature have since consolidated these findings, consistently identifying operating-speed consistency as a critical prerequisite for safe and efficient traffic operation (Gibreel et al. 1999).

To operationalize these concepts, several models and tools have been developed to evaluate design consistency in practice. Geometric design consistency assessment is commonly supported through a combination of dedicated safety analysis tools, design software environments, and research-oriented computational workflows. Among the most widely used platforms, the Interactive Highway Safety Design Model (IHSDM), developed by the FHWA, incorporates operating speed prediction and consistency evaluation modules within a standardized analytical framework. While such tools are robust and well established, they offer limited flexibility for methodological adaptation and are typically aligned with specific national design practices. Design software environments, such as Autodesk Civil 3D and alignment analysis tools developed by Transoft Solutions, provide detailed geometric modelling capabilities but generally lack built-in, guideline-specific consistency assessment indices tailored to every country roadway design guideline. In several countries, this limitation has been partially addressed through the development of custom add-ins or toolkits integrated into design software platforms. Other tools focus on predicting operating speed levels, performing optical analyses of the road, and determining available sight distance using 3D models (Dell'Acqua et al., 2016). Additionally, advanced techniques like **artificial neural networks** and fuzzy logic are employed in artificial intelligence modeling to analyze the safety impacts of diverse highway geometries on traffic accidents (Garnaik et al., 2023).

However, despite the existence of well-defined national design criteria addressing geometric harmony and speed consistency, such computational tools are not available in the Greek context. As a result, consistency evaluation in practice relies largely on manual checks, spreadsheets, or locally developed scripts, limiting automation, reproducibility, and systematic application during the design process.

## 3 Methodology

### 3.1 Conceptual Framework

The proposed methodology provides a computational framework for assessing geometric design consistency. The approach focuses on horizontal alignment and evaluates consistency through explicit estimation of the operating speed ($V_{85}$) and the analysis of speed differentials between successive geometric elements. The methodology is intended to support automated and repeatable consistency assessment during roadway design and evaluation.

The overall workflow consists of four main stages: (i) representation of roadway geometry, (ii) estimation of operating speed for each alignment element, (iii) computation of geometric consistency metrics, and (iv) classification of consistency levels based on predefined thresholds (Fig. 1).

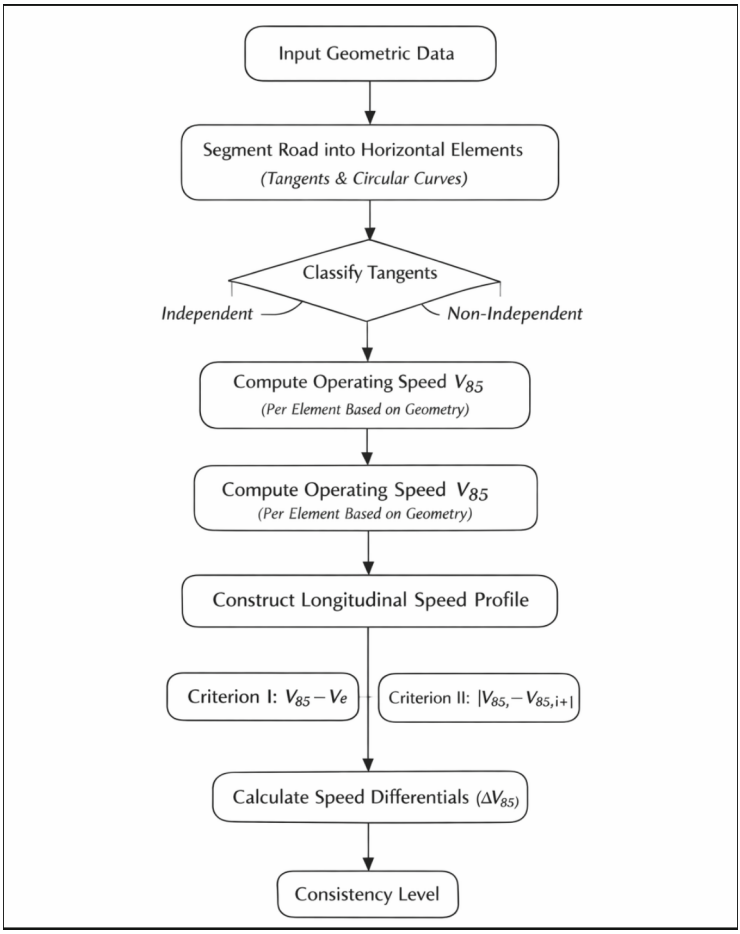


**Fig. 1.** Methodological flow chart of the proposed speed-based geometric design consistency assessment framework.

### 3.2 Input Data and Roadway Representation

The roadway alignment is represented as an ordered sequence of horizontal geometric elements, consisting of tangents and circular curves. Each element is characterized by its length and, where applicable, its radius. The road is assumed to belong to a single functional category, and a corresponding design speed ($V_e$) is assigned based on national

road design guidelines. The analysis assumes homogeneous geometric and operational conditions within the examined segment. Vertical alignment, cross-sectional characteristics, and roadside features are not considered in the present study, in order to isolate the effect of horizontal alignment on geometric consistency.

Each horizontal alignment element (tangent or circular curve) is represented using a set of geometric and operational parameters. The required input data and the corresponding estimated (derived) data used in the consistency assessment are summarized below.

- Total length of horizontal alignment element: Length of the tangent or circular curve.
- Chainage at start/end of design element: Chainage corresponding to the beginning/end of the element.
- Radius of circular curve: Radius of the curve; for tangents, an infinite radius is assumed.
- Lane width: Width of the traffic lane, used as a parameter in operating speed estimation.
- Longitudinal grade in the direction of increasing chainage (s): Average longitudinal slope of the element, expressed as a percentage.
- Deflection angle: Angular change in alignment direction for circular curves; equal to zero for tangents.

Based on the input geometric characteristics, the following quantities are computed:

- **Degree of deflection:** A curvature-related parameter derived from the horizontal geometry, used to characterise the intensity of deflection (gon/km) for each single element.
- **Operating speed ($V_{85}$)** Estimated for each element as a function of geometric characteristics (radius, curvature measure, lane width, and longitudinal grade).

Case 1: Longitudinal grade $s \leq 5\%$, or $s > 5\%$ with element length $L < 250$m

$$V_{85} = \frac{10^6}{10150,10 + 8.529K_E} + [(b - 3.5) \times 20]$$

where:

- $K_E$is the degree of curvature of the alignment element,
- $b$ is the lane width (m).

**Case 2: Longitudinal grade $s > 5\%$ and element length $L \geq 250$m**(independent of lane width)

**For** $5\ \% < s \leq 7\%$**:**

$$V_{85} = 73,260 - 0.015K_E$$

**For** $7\ \% < s < 10\%$**:**

$$V_{85} = 69,456 - 0.0140 \cdot K_E$$

The resulting speed profile represents the expected variation of operating speed due solely to horizontal geometric characteristics and forms the basis for consistency assessment.

In this paper, tangent is a distinct design element influencing operating speed behaviour. Therefore, each tangent is characterized as non-independent or independent tangent. Non-independent tangent are described tangent sections whose length is insufficient to allow drivers to significantly adjust their operating speed between successive horizontal curves. In contrast, this paper adopts the concept of independent tangents to describe tangent sections of sufficient length to permit drivers to accelerate or decelerate and stabilise their operating speed independently of the adjacent horizontal curves.

Thus (Lamm),

- Tangents are regarded as non-independent design elements and the sequence curve-to-curve controls the design process, and
- Tangents are regarded as independent design elements and the sequence tangent-to-curve controls the design process.

### 3.3 Geometric Design Consistency Metrics

Geometric consistency is evaluated using speed-based indicators, consistent with the principles of OMOE-X Safety Criteria I and II. According to the Greek road design guidelines (OMOE-X), Safety Criterion I is concerned with the achievement of overall harmony and continuity in roadway design through the alignment of design speed ($V_e$) and operating speed ($V_{85}$). The criterion establishes that the selected geometric parameters—such as curve radii, tangent lengths, and transition elements—should be compatible with the intended design speed so that the resulting operating speeds do not deviate significantly from it. In this context, consistency is treated as a design-quality requirement, ensuring that successive geometric elements form coherent sequences rather than arbitrary combinations of minimum or maximum values. Criterion I therefore governs the global relationship between geometry and expected operating behaviour, promoting uniformity of design speed over sufficiently long roadway sections and discouraging abrupt changes in geometric standards.

Safety Criterion II focuses more explicitly on the continuity of operating speed (V85) along the alignment and the dynamic interaction between successive horizontal elements. The guideline emphasises that abrupt variations in operating speed between adjacent tangents and curves, or between successive curves, should be avoided, as they may lead to undesirable driving manoeuvres. To this end, OMOE introduces the concept of controlling speed differentials ($\Delta V_{85}$) and prescribes acceptable relationships between successive curve radii through diagrams and qualitative classifications. Criterion II thus addresses local geometric transitions, ensuring that changes in curvature and alignment characteristics lead to gradual and predictable speed adaptation. While the guideline provides graphical and descriptive guidance for assessing these relationships, it does not define a computational procedure, highlighting the need for automated tools capable of translating these principles into quantitative consistency evaluation (Table 1).

These metrics directly quantify the degree of speed adaptation required between elements and provide an objective measure of geometric consistency.

These thresholds are applied consistently across all assessed elements and are considered compatible with the design philosophy of OMOE-X, which emphasizes gradual variation of geometric characteristics and avoidance of abrupt speed changes.

**Table 1.** Quantitative Ranges for Safety Criteria I to III for Good, Fair, and Poor Design Classes

| Consistency level | Good | Acceptable | Poor |
|---|---|---|---|
| Criterion I – Design harmony | $\lvert V_{85i} - V_e \rvert \leq 10$ km/h | 10 km/h $\leq \lvert V_{85i} - V_e \rvert \leq 20$ km/h | $\lvert V_{85i} - V_e \rvert > 20$ |
| Criterion II – Speed continuity | $\lvert V_{85i} - V_{85i+1} \rvert \leq 10$ km/h | 10 km/h $\leq \lvert V_{85i} - V_{85i+1} \rvert \leq 20$ km/h | $\lvert V_{85i} - V_{85i+1} \rvert > 20$ |

### 3.4 Description of the Proposed Tool

The tool will be developed using Python due to its versatility, extensive libraries for data manipulation and numerical computation, and its ability to integrate with other systems. While specific Python libraries for this exact application might need to be custom-developed, existing libraries can aid in data processing and analysis. For instance, Python can interact with geometric data, potentially even through CAD-related Python APIs if detailed geometric models are used (Becker et al., 2022; Heidari & Iosifidis, 2024).

The system is designed around three logical layers:

- **Input layer** – responsible for reading and structuring geometric data.
- **Computation layer** – responsible for operating speed estimation and consistency calculations.
- **Output layer** – responsible for reporting, visualisation, and classification results.
- **(i) Data Processing Module**
  Handles the import of alignment data (e.g., from CSV or Excel format), performs validation checks, and organises the data into element-wise structures (e.g., pandas DataFrames). Each horizontal alignment element is tagged as a tangent or curve and prepared for subsequent analysis.
- **(ii) Tangent Classification Module**
  Implements the logic for distinguishing independent from non-independent tangents based on geometric length criteria. This module determines whether consistency evaluation follows a curve–curve or tangent–curve control sequence.
- **(iii) Operating Speed Computation Module**
  Applies the OMOE-X equations to compute $V_{85}$ for each element, considering curvature, longitudinal grade, and lane width. The module generates the element-based operating speed profile.
- **(iv) Consistency Evaluation Module**
  Computes:
- **(v) Visualisation and Reporting Module**

## 4 Application

The examined roadway section connects the settlements of Fanari and Arogi and serves as a local connector to the primary national road network (EO2 Komotini–Xanthi). The segment from the national road junction to Fanari has a total length of approximately 5.3 km. Due to construction constraints during its development period, primarily related

to land ownership limitations, the alignment followed restrictive geometric conditions. As a result, the roadway exhibits relatively low geometric standards, including successive horizontal curves, short tangent sections, variable superelevation conditions, and constrained cross-sectional characteristics.

The road traverses areas located both outside and partially within settlement boundaries and is bordered by diverse land uses, including tourism-related facilities, recreational areas, coastal bathing areas, residential properties, and entertainment establishments. A primary functional role of the road is to provide access to these adjacent land uses, operating as a collector facility. Accordingly, the roadway is classified as a Category BIII road under the national road classification system, functioning as a collector arterial with a single carriageway.

From a geometric consistency perspective, the alignment presents a suitable test case due to the presence of successive curves, potentially short tangents between curves, and varying geometric parameters along its length. These characteristics allow for the systematic evaluation of operating speed variation and the identification of locations where speed differentials may indicate reduced geometric consistency.

- Speed profile
- Consistency indicators
- Output plots/tables

## 5 Discussion

The proposed Python-based framework demonstrates how qualitative road design guideline principles can be translated into a transparent and repeatable computational process for geometric design consistency assessment. By explicitly computing operating speed and systematically evaluating speed differentials between successive alignment elements, the approach enables a level of automation and consistency that is not achievable through manual checks or spreadsheet-based evaluations commonly used in practice. The case study illustrates that the tool can efficiently identify both global design harmony issues and local speed continuity problems along a roadway alignment.

From a computational perspective, the framework offers a modular and extensible structure that facilitates reproducibility and integration into broader design workflows. The explicit treatment of independent and non-independent tangents allows the assessment logic to adapt to different geometric configurations without introducing subjective judgement during analysis. This feature is particularly relevant for computational applications, as it ensures that consistency evaluation rules are applied systematically across all alignment elements.

Despite these advantages, the proposed approach is subject to certain limitations. The current implementation focuses exclusively on horizontal alignment and relies on geometry-based operating speed models, without accounting for driver behaviour, traffic conditions, or vertical alignment effects. While this scope is intentional and aligned with the objectives of the study, future work could extend the framework to incorporate additional design dimensions or to interface with GIS and CAD environments for seamless data exchange.

Overall, the results indicate that the proposed tool effectively bridges the gap between road design guidelines and computational evaluation, providing a practical foundation

for automated geometric consistency assessment and supporting the integration of design rule verification into computational science and engineering applications.

## 6 Conclusions and Future Work

Despite significant advancements, a standardized and universally adopted procedure for evaluating geometric design consistency in new or existing alignments remains elusive (Hassan et al., 2001). Current design consistency models predominantly focus on two-dimensional horizontal alignments, often neglecting the crucial interaction with vertical alignments and cross-sections in a three-dimensional context (Gibreel et al., 1999). Future research endeavors should prioritize:

- Developing operating speed prediction models based on 3D analysis (Gibreel et al., 1999).
- Establishing novel methodologies for evaluating design consistency that incorporate the effects of 3D sight distance (Gibreel et al., 1999).
- Investigating the impact of design consistency on highway capacity, level of service, and driver comfort (Gibreel et al., 1999).
- Revising and harmonizing existing design guidelines to integrate comprehensive design consistency principles across different countries (Gibreel et al., 1999).

The developed tool will be validated against case studies or existing highway sections with known consistency evaluations. This validation step will ensure the accuracy and reliability of the Python tool. Future enhancements could include incorporating additional consistency criteria (e.g., vehicle stability analysis, alignment indices) (Cefalo et al., 2024), integrating 3D geometric analysis, and linking with crash prediction models to provide a more holistic safety assessment (Chaudhari et al., 2022).

From an engineering perspective, the tool provides a practical and accessible mechanism for evaluating geometric design consistency without requiring advanced programming knowledge. The user supplies standard geometric design parameters for each alignment element, and the tool automatically produces:

- Operating speed estimates per element,
- Speed differential summaries,
- Clear classification of consistency levels (good/acceptable/poor),
- Graphical representation of the longitudinal speed profile,
- Identification of critical geometric transitions.

The automated evaluation reduces reliance on manual spreadsheet calculations and supports objective, repeatable design assessment. Moreover, the tool can be integrated into typical design workflows by importing alignment data exported from CAD environments, thereby enhancing its applicability in practical roadway engineering contexts.

## References


Brenac, T.: Safety at curves and road geometry standards in some European countries. Transp. Res. Rec. J. Transp. Res. Board. **1523**, 99–106 (1996). https://doi.org/10.1177/0361198196152300112

Cefalo, R., Sluga, T., Ossich, G., Roberti, R.: Assessment of design consistency for two-lane rural highways with low tortuosity alignment. Sustainability. **16**(3), 987 (2024a). https://doi.org/10.3390/su16030987

Chaudhari, P., Goyani, J., Arkatkar, S., Joshi, G., Easa, S.M.: Design consistency evaluation of two-lane rural highways in hilly terrains. Transp. Res. Procedia. **62**, 75 (2022). https://doi.org/10.1016/j.trpro.2022.02.010

Dell'Acqua, G., Luca, M. D., Prato, C. G., Prentkovskis, O., & Junevičius, R. (2016). The impact of vehicle movement on exploitation parameters of roads and runways: a short review of the special issue. Transport, 31(2), 127. . doi:https://doi.org/10.3846/16484142.2016.1201912

Faghri, A., Harbeson, M.: A knowledge-based GIS approach to the evaluation of design consistency of horizontal alignments. Transp. Res. Rec. J. Transp. Res. Board. **1658**(1), 1 (1999). https://doi.org/10.3141/1658-01

FHWA: Evaluation of Design Consistency Methods for Two-Lane Rural Highways (1999)

Cefalo, R., Sluga, T., Ossich, G., Roberti, R.: Assessment of design consistency for two-lane rural highways with low tortuosity alignment. Sustainability. **16**, 987 (2024b). https://doi.org/10.3390/su16030987

Fitzpatrick, K.et al.: Alternative design consistency rating methods for two-lane rural highways (2000). https://www.umich.edu/~driving/publications/FHWA-RD-99-172.pdf

Garnaik, M.M., Giri, J.P., Panda, A.: Impact of highway design on traffic safety: how geometric elements affect accident risk. Ecocycles. **9**(1), 83 (2023). https://doi.org/10.19040/ecocycles.v9i1.263

Gibreel, G.M., Easa, S.M., Hassan, Y., El-Dimeery, I.A.: State of the art of highway geometric design consistency. J. Transp. Eng. **125**(4), 305 (1999). https://doi.org/10.1061/(asce)0733-947x(1999)125:4(305)

Hamilton, I., Himes, S., Porter, R.J., Donnell, E.T.: Safety evaluation of horizontal alignment design consistency on rural two-lane highways. Transp. Res. Rec. J. Transp. Res. Board. **2673**(2), 628 (2019). https://doi.org/10.1177/0361198119829414

Hassan, Y., Sayed, T., Tabernero, V.: Establishing practical approach for design consistency evaluation. J. Transp. Eng. **127**(4), 295 (2001). https://doi.org/10.1061/(asce)0733-947x(2001)127:4(295)

Krammes, R.A., Rao, K.S., Oh, H.: Transportation Research Record 1500 19 Highway Geometric Design Consistency Evaluation Software (n.d.)

Lamm, R., Choueiri, E.M., Hayward, J.C., Paluri, A.: Possible design procedures to promote design consistency in highway geometric design on two lane rural roads. Transp. Res. Rec. **1195**, 111–122 (1988)

Messer, C.J.: Methodology for evaluating geometric design consistency. Transp. Res. Rec. J. Transp. Res. Board. **757** (1980) https://trid.trb.org/view/165801

Qin, Y., Chen, Y., Lin, K.: Quantifying the effects of visual road information on drivers' speed choices to promote self-explaining roads. Int. J. Environ. Res. Public Health. **17**(7), 2437 (2020). https://doi.org/10.3390/ijerph17072437

Torregrosa, F.J.C.: Development and calibration of a global geometric design consistency model for two-lane rural highways, based on the use of continuous operating speed profiles (2015). https://doi.org/10.4995/thesis/10251/48543

Vukoje, B., Cvitanić, D., Breški, D.: Methods for ensuring consistency of horizontal alignment elements. J. Croatian Assoc. Civ. Eng. **64**(5), 385 (2012). https://doi.org/10.14256/jce.657.2012

Wooldridge, M.D., Fitzpatrick, K., Harwood, D.W., Potts, I.B., Elefteriadou, L., Torbic, D.J.: Geometric design consistency on high-speed rural two-lane roadways. National Cooperative Highway Research Program Report, 502 (2003). http://trid.trb.org/view.aspx?id=665537

# Circular Management of Tunnel Excavation Materials in Transport Infrastructures: An LCA Approach

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**Abstract.** The construction of a transport infrastructure has significant environmental impacts in terms of overall emissions and resource consumption, making the transition to circular models a priority. This study examines the management of excavated materials (ESR) generated by the Terzo Valico dei Giovi railway project (Italy), assessing their reuse for the renaturalisation of disused quarries.

The analysis, based on the Life Cycle Assessment (LCA) methodology, identifies three indicators – Climate Change, Land Use and Abiotic Resource Depletion–Fossil – to compare traditional and mechanised excavation methods to identify the specific impacts of ESR management.

The results show that mechanised excavation has a greater impact on Climate Change, mainly due to the logistical complexity involved in the proper management of ESR. Overall, their reuse for the morphological restoration of quarries generates benefits in terms of Land Use, contributing to landscape continuity. On the whole, the study highlights how the circular management of ESR represents a key element for the sustainability of major infrastructure projects, transforming excavated materials into resources that benefit the local area.

**Keywords:** LCA · Excavated Waste · Circular Economy · Railway Infrastructures · Post-extraction Land Rehabilitation

## 1 Introduction

European plans for the renovation and upgrading of infrastructure assets also involve substantial investments in the construction of new strategic projects for the transport of people and goods [1]. As supported by the Trans-European Transport Network (TEN-T) policy, this means developing an integrated, sustainable and efficient European transport network in line with the sustainability objectives set for 2050 [2].

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To achieve these goals and build a connected community network, new infrastructure arcs need to be built where they are lacking. However, as highlighted in the literature, the construction sector continues to be a critical in terms of the transition to decarbonisation and resilience objectives [3]. Furthermore, this sector is responsible for over a third of global emissions in terms of CO2 and resource consumption [4].

Part of these impacts can be attributed to the consumption of non-renewable resources necessary for the construction of infrastructure, mainly in terms of land use [5]. Land use is defined as: physical occupation of land [6, 7] and the sourcing and use of soil and its derivatives as construction materials. This condition makes the construction sector one of the most suitable for a transition to a circular economy [8], as approximately one third of the total waste produced in the European Union consists of construction and demolition (C&D) waste, with a reuse rate of less than 50% [3].

Consequently, the issue of resource efficiency, including reuse purposes, is rapidly gaining interest, but the response remains vague, as the current regulatory framework leaves it up to construction companies to assess the use of the material they produce during excavation operations, resulting in a complex management process [9]. Therefore, the construction of new infrastructure, especially when it involves underground sections, constitutes an essential part of total C&D waste, but is rarely treated or described in an independent framework [10].

The literature highlights a gap in the reuse of excavated soil and rock (ESR) from underground construction projects [11] and, as also noted in Italian regulations, its treatment depends on whether it is classified as a byproduct or waste based on its chemical composition or environmental compatibility with final disposal sites [9]. Furthermore, its management and the capitalisation of the impacts generated are delegated to the builder and other stakeholders in the construction chain with whom it interfaces – subcontractors, transporters and owners of the destination sites.

As evidenced by literature and key operational experience, ESR are deposited in abandoned quarries in the area to restore their original morphology for the purpose of renaturalising the area or providing the territory with new agricultural production facilities [12, 13]. This activity is part of the construction site operations that are regulated and controlled on the basis of the Soil Use Plan - *Piano di Utilizzo* (PdU) that the builder is required to draw up, summarising the entire logistics chain and assessment of the quantities of ESR produced and the sites identified for its disposal [9].

This article aims to focus attention on the circular use of resources during the construction process, going beyond the standard view of the construction sector, which applies the principles of the circular economy to properties as a source from which to draw new resources during demolition [11, 14]. For large-scale linear infrastructure, managing on-site materials offers significant economic benefits for supply chain stakeholders and environmental advantages through their reuse or disposal.

However, the excavation techniques adopted for infrastructure construction entail different management approaches for ESR. Two main methods are distinguished: traditional excavation and mechanized excavation, which—regarding the classification of ESR as a by-product—require different treatments. Material excavated by traditional methods (i.e., explosives and equipment such as backhoes, excavators, and bulldozers) is classified on site and transferred directly to the final disposal facility defined in the

PdU. Mechanized excavation uses a Tunnel Boring Machine (TBM), which employs conditioning additives to facilitate advance. As a result, the excavated material is chemically altered and must undergo an intermediate storage phase at a designated facility to allow evapotranspiration of these additives before final disposal [15, 16].

This management approach extends the value chain of sustainable infrastructure by assigning additional costs to the construction phase to ensure project sustainability. This bias can be mitigated through the application and modelling of measurement tools and methodologies capable of quantifying the effects of sustainable solutions from the construction stage onward. Life Cycle Assessment (LCA) models are being developed to address this structural gap in the infrastructure construction sector [14, 17, 18]. Although LCA is recognised for assessing the benefits of responsible construction material use, its application to evaluate impacts from materials generated during infrastructure construction—i.e., ESR—remains limited.

Building on these points, this study addresses the following research questions.

RQ1: What are the environmental costs of reusing ESR for the renaturalisation of quarries? Are these costs balanced by the benefits produced by this action?

RQ2: To what extent do the technologies employed in infrastructure construction influence the environmental impacts associated with the proper management of ESR?

RQ3: In what terms is it possible to quantify the commitment to the management of ESR and its effects?

## 2 Case Study

This section examines Terzo Valico dei Giovi (TV), a new railway link of the TEN-T Rhine–Alps corridor currently in its final construction stages. As the project is largely underground, the management of excavated materials is a key issue. Particular attention is given to excavation methods and their role in identifying strategies for reusing extracted materials as by-products.

The case study was selected because of the infrastructure's strategic relevance and the large volumes of material generated during construction. In addition, publicly available documentation and data from Italian *Ministero dei Trasporti* and *Ministero dell'Ambiente e della Sicurezza Energetica*, enable detailed modelling of extraction, transport and disposal processes.

### 2.1 Terzo Valico Dei Giovi, Italy

TV railway project is a major infrastructure currently under construction (2012-on going) in Northern Italy connecting the port of Genoa with the Po Valley. The new line extends for approximately 53 km, largely developed underground through a complex tunnel system crossing the Ligurian Apennines between Liguria and Piedmont and the use of twin-bore tunnels results in nearly 90 km of total tunnelling, generating large volumes of excavated rock and soil. Excavation is carried out using both conventional methods: traditional and usage of TBM.

From an organisational perspective, construction activities are divided into six construction lots and distributed across 15 main operational construction sites along the

alignment, supported by 6 base camps and additional service facilities: such as quarries or deposit sites. This articulated construction system reflects the territorial scale of the project and the logistical complexity associated with underground infrastructure works.

The tunnelling activities produce approximately 15 million m3 of ESR. Rather than being entirely disposed of as waste, a significant share is managed within circular reuse strategies, including environmental restoration interventions such as the renaturalisation of exhausted quarry sites. In this framework, excavation material management represents a key factor in assessing the environmental performance of the project during the construction phase.

### 2.2 Management of Excavated Soil and Rock

This section analyses the ESR management system implemented during the construction of the TV, with particular focus on the Piedmont section, which provides a more comprehensive view of the material reuse cycle. To this end, the TV's PdU is reviewed and supplemented with the EMAS Environmental Statement, which is used to provide additional data and identify the main strategies adopted in ESR management [19–21].

In Piedmont, 9.4 million m3 of ESR are generated by 11 active construction sites employing both excavation methods. Of this volume, 22% are reused on site for other construction activities, while the remaining 78%constitutes surplus material requiring classification. Over the past five years, approximately 10% of this portion has been classified as waste and disposed of [19, 21]. The remainder has been transferred to a network of designated storage facilities located across Liguria and Piedmont.

ESR destination sites are identified within the PdU based on several criteria, including distance from active construction sites, storage capacity and type of material accepted, site condition, and potential future land use. In Piedmont, these sites are classified as hillside quarries when located in mountainous areas or as lowland quarries in flat terrain. Only inactive quarries are selected, as material deposition enables morphological recontouring for renaturalisation or the restoration of agricultural land continuity. Through this process, 37 quarries have been identified as capable of accommodating the entire volume of material excavated from the TV; transport plans further define mandatory road routes from the construction sites to the final destinations [22].

Mechanized excavation, however, requires a different ESR management approach. Additives used for TBM operation may compromise the environmental compatibility of the material with the destination sites. For this reason, the PdU includes an intermediate storage facility, DP22 – Cascina Romanellotta (DP22), intended for the temporary stockpiling of material in low-height heaps over a large surface area to promote the evaporation of conditioning agents and restore suitability for reuse.

To ground the LCA modelling in a real-world case study, this article focuses on the DP07 – Cascina Bolla quarry (Alessandria, Italy). The project aims to restore the site's original morphology to ensure continuity with the surrounding agricultural landscape. DP07 was selected primarily due to its advanced ESR deposition stage. The site treats materials from four construction areas: COP5 and COP11 (traditional excavation) and COP7 and COP20 (TBM). As shown in Fig. 1, TBM materials are first stockpiled at DP22 before being transported to DP07 or, if unsuitable, sent to landfill.

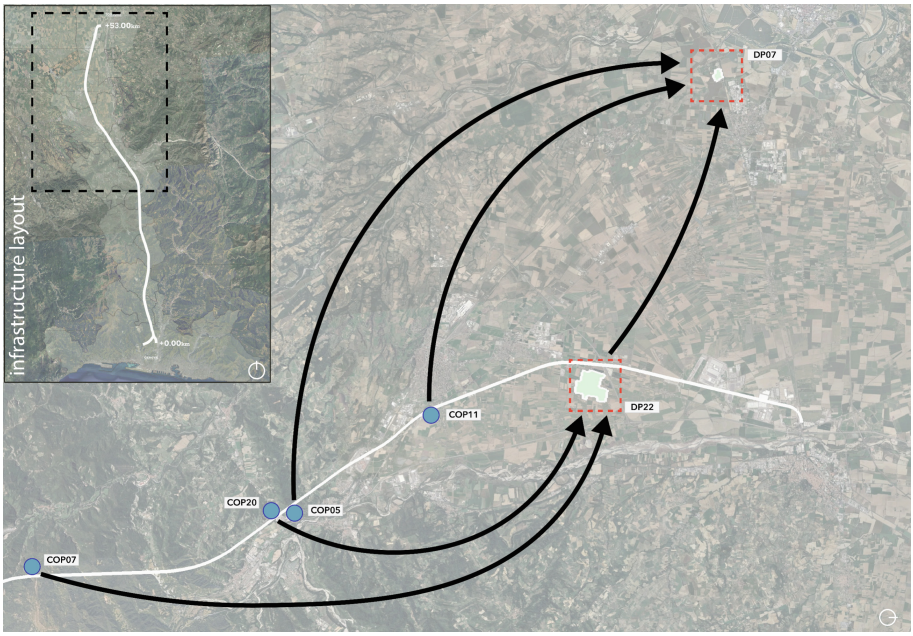


**Fig. 1.** Planimetric overview of the ESR management process from the operational construction sites to DP22 and DP07, including the corresponding transport routes. The upper-left inset shows a schematic representation of the TV project with the study area highlighted.

## 3 Methodology

### 3.1 The LCA Methodology

The analysis has been performed adopting the LCA methodology, consistently with international standards [23, 24] that define it as the *compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle*. According to the standards, the analysis is articulated into four main steps: *Goal definition*, *Scope definition*, *Inventory analysis* (LCI) and *Impact assessment* (LCIA). Moreover, *Interpretation* of interim and final results throughout the methodology is required to refine the analysis, given the iterative nature of LCA.

The current standard for the Sustainability Assessment of Civil Engineering Works, EN 17472:2022 [25], divides the life cycle of a civil engineering work into modules grouped into three main categories: Category A (A1–A5) covers pre-construction, product, and construction process stages; Category B (B1–B8) addresses the use stage; and Category C (C1–C4) encompasses end-of-life management stages.

As the material which is the core of the present study is the waste generated during the excavation activity performed as part of the realisation process of a railway infrastructure, the analysis here reported is meant to be interpreted as a focus on the module A5 described by the above mentioned standard (A5 – Construction and Installation processes). In fact, the standard specifies that the waste-management processes for all waste materials generated on the construction site shall be included within the boundaries of Module A5.

### 3.2 Goal Definition

The objective of the analysis was to estimate the potential environmental impacts associated with the waste management system of the material generated by tunnel excavation, representing a real-world construction scenario. Thus, the TV project was reviewed and it was decided to focus on the waste management chain in Piedmont.

The system under investigation manages waste produced by both conventional and mechanized tunnelling methods and considers the possibility that the material may be used for the recultivation of a decommissioned limestone quarry. Given this context, the research group initially sought to adopt a material-specific perspective, separately assessing the impacts arising from the activities inherent to the processing required for each type of waste. Accordingly, the analysis was initially intended to highlight the effects of the excavation technique on the overall impacts, as well as the role of the material environmental compatibility, which is expressed by the fraction of waste destined for landfill.

Subsequently, the aim was to adopt the perspective of the real-world waste managing system (system-level perspective), taking into account the actual origin and proportions of the treated waste materials. Considering environmental aspects of common concern, the impact evaluation focused on quantifying the potential effects on climate, resulting from greenhouse gas (GHG) emissions; the potential impacts derived from the exploitation of the land resource; and the consumption of energy fossil sources.

### 3.3 Scope Definition

**System Description.** From a material-specific perspective, the analysed waste management chain begins when excavated material from either traditional or mechanised tunnelling reaches the construction site gate after removal from the excavation face. At this stage, the fraction suitable for internal recycling as a substitute for virgin aggregates (VA) in earthworks (*IR*) is separated based on its mechanical properties, while the remaining waste follows different pathways depending on the excavation method.

Two main material flows are identified: from traditional tunnelling (material type M-A) and from mechanized tunnelling (material type M-B). While M-A is directly transported to destination, M-B requires an intermediate storage stage at a Temporary Deposit (TD) for additive evapotranspiration. M-A is characterised based on its environmental compatibility and divided into a fraction that can be effectively used for limestone quarry recultivation and a fraction destined for landfill disposal (*W*).

After evapotranspiration, the M-B material is separated into the *ER* and *W* fractions and subsequently hauled to the final disposal.

From a system-level perspective, the waste chains are integrated into a broader waste management framework involving two mechanized tunnelling sites (COP20 and COP7) and two traditional tunnelling sites (COP5 and COP11). The recyclable fraction is directed to the recultivation of the DP07 quarry and M-B material is first transported to the DP22 temporary deposit.

**Declared Unit.** When a material-specific perspective is adopted, the analysis is conducted with reference to 1 t of excavated material that has been transported to the construction-site gate and it is ready to be processed according to its origin. Subsequently,

when a system-level perspective is adopted, the declared unit is identified with 1 t of material that has reached the decommissioned quarry for recultivation.

**System Boundaries.** The potential environmental impacts addressed by the present study are part of those that can be assigned to Module A5 (Construction and Installation processes), as described by the standard EN 17472:2022. More specifically, only a subset of Module A5 is here analyzed; in fact, the activities that fall within the boundaries of the investigated system are exclusively those related to waste management. Consequently, impacts associated with the excavation activity itself are not of interest in the framework of the present analysis. For clarity reasons, this subset will be here named Module A5 – Waste management Fig. 2.

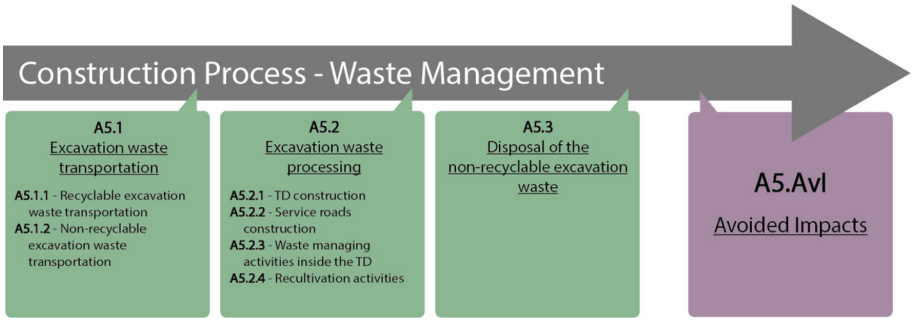


**Fig. 2.** Flowchart of the waste management subset of Module A5 of EN 17472:2022 to define avoided impacts and the system boundaries of the methodology.

As illustrated in Fig. 2, Module A5 is divided into three main submodules: excavation waste transportation (A5.1), excavation waste processing (A5.2), and disposal of non-recyclable excavation waste (A5.3). A5.1 includes the transport of both recyclable material to the temporary deposit or decommissioned quarry and non-recyclable material to landfill. A5.2 covers the main processing activities within the temporary deposit, including infrastructure works, internal handling operations, and recultivation activities. Finally, A5.3 refers to the landfill disposal of the non-recyclable fraction.

The internal use of excavated waste in substitution of VA may be considered in terms of avoided production of primary materials, which results in a negative impact. For this reason, an additional sub-module was introduced (AvI – Avoided Impacts).

To keep the results as general as possible, transportation-related impacts were excluded when adopting a material-specific perspective.

**LCIA Methodology.** In accordance with the objectives defined in the Goal Definition, the Life Cycle Impact Assessment (LCIA) methodology adopted in the present study is the one prescribed by the EN 15804 standard [26], as implemented in SimaPro v.10.2.0.2. This methodology encompasses a total of 16 impact categories and specifically addresses those relevant to the objectives of the study: Climate Change – Total (CC-Total), Abiotic

Depletion of Resources – Fossil fuels (AD-Fossil), and Land Use (LU). The impact category indicators, their unit of measurement, and the respective models used for impact quantification are shown in Table 1.

**Table 1.** Details of the adopted LCIA methodology.

| Impact category | Indicator | Unit | Model |
|---|---|---|---|
| CC-Total | Global Warming Potential (GWP-total) | Kg $CO_2$ eq | Baseline model of 100 years of the IPCC based on IPCC 2013 |
| AD-Fossil | AD Potential for fossil resources (ADP-fossil) | MJ | CML 2002, Guinée et al., 2002, and van Oers et al. 2002 |
| LU | Potential Soil quality index (SQP) | Pt | Soil quality index based on LANCA |

**Working Hypothesis.** This study relied on several working assumptions due to the lack of primary data. For transparency, the main hypotheses are summarised below.

From the technical documentation available on the website of the italian *Ministero dell'Ambiente e della Sicurezza Energetica* [19, 20], it is known that the overall quantity of excavated material originating from construction yards placed in Piedmont region is approximately equal to 9.4E + 06 $m^3$. It is also known that around 2.1E + 06 $m^3$ on average are immediately recycled inside the construction sites in substitution of VA. However, no site-specific data is publicly accessible to our best knowledge. For this reason, it is assumed a constant rate of internal recycling equal to $IR = 22\%$, , derived from the available averages. Regarding the remaining part (78%), it is known that between 0% and 12% of the material is not suitable for limestone quarry recultivation and it is then destined to landfill. For this reason, the waste rate $W$ is made variable and it ranges from 0% to 12% (scenarios W0 and W12). For completeness, it is also considered the hypothetical scenario were the whole mass of excavated material (apart from the fraction internally recycled) is destined to landfilling (scenario W78).

As no site-specific data is available about the quantity of material exiting from each construction site, it is assumed that the overall value is equally distributed among the sites located in Piedmont region (about 6.7E + 05 $m^3$ each, after internal recycling). Considering that the whole mass of excavated waste originated from the four analysed construction yards is entirely disposed either in a landfill (according to $W$) or at the decommissioned quarry ($ER = 100 - IR - W$), the origin of the material being delivered to the quarry is homogeneously distributed.

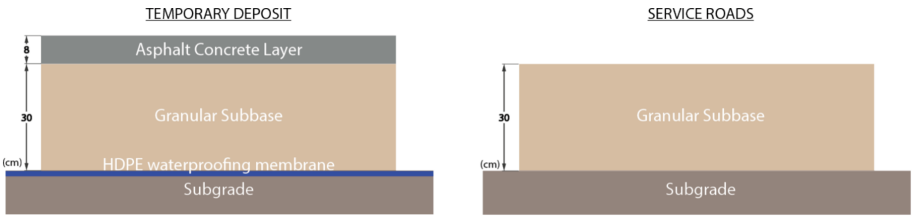


**Fig. 3.** Stratigraphic layout of the Temporary Deposit and the Service Roads, showing the layer thicknesses and the constituent materials as specified in the design sections.

Accessory facilities include the temporary deposit (1.68E + 05 m2) and service roads (1.85E + 04 m2), both built at the start of excavation. For each one, an operative life of 14 years and full end-of-life recycling were assumed. Structural details for the TD and service roads follow standard construction practices and the stratigraphy shown in Fig. 3. The asphalt mix was hypothesised to be a conventional hot mix asphalt, commonly adopted in binder courses (bitumen content, $p_b$, of 4.5% with respect to the aggregates weight, in situ density, $MV_{AM}$, of 2.3 t/m$^3$), whereas the in situ density of the subbase was set at 1.9 t/m$^3$.

The relative positions of the construction sites, the decommissioned quarry and the temporary deposit are known and are reported in Table 2. A transportation distance within the temporary deposit of 1.6 km is accounted for. Additionally, other distances have been assumed. External transport distances are set and supposed as follows: 100 km to the landfill from both construction sites and the TD; 15 km from the aggregate quarry to the TD; and 35 km from the quarry to the asphalt plant. Additionally, the asphalt plant and the waterproofing membrane retailer are located 20 km and 50 km from the TD, respectively.

**Table 2.** Excavated material transportation distances.

| Origin | Distance to D22 (km) | Distance to quarry (km) | Total (km) |
|---|---|---|---|
| COP5 (traditional) | - | 33.4 | 33.4 |
| COP11 (traditional) | - | 28.1 | 28.1 |
| COP20 (mechanized) | 18.05 | 21.8 | 43.0* |
| COP7 (mechanized) | 7.35 | 21.8 | 32.3* |

* the distance comprises the hauling activity which is carried out inside the TD.

Finally, the hourly productivity of the equipment used within the system boundaries was assumed and is reported in Table 3.

**Table 3.** Equipment hourly production.

| Equipment | Hourly production (-) |
|---|---|
| Roller (for subgrade compaction) | 380 $m^3$/h |
| Roller (for subbase compaction) | 200 $m^3$/h |
| Roller (for asphalt course compaction) | 60 $m^3$/h |
| Grader (for subbase formation) | 3780 $m^2$/h |
| Paver (for asphalt course formation) | 220 t/h |

**Allocation.** The impacts of the construction and the demolition activities, at the end of the excavation process, of the temporary deposit and the service roads need to be allocated to 1 t of waste material which is transported to the deposit and stored. Regarding the total volume of M-B exiting from the gates of the construction sites (i.e., 1.3E + 06 $m^3$), an average volumetric mass can be set at 1.7 t/$m^3$, resulting in an overall transported mass of 2.28E + 06 t. Then, the allocation factor ($A$):

$$A = \frac{1}{M_{TD}} = \frac{1}{M_{tot} \cdot Ex} = 4.4E - 07 \quad (1)$$

where $M_{TD}$ is the total mass of excavated waste which is stored in D22 and $M_{tot}$ is equal to the overall mass which is excavated in the construction sites.

### 3.4 Inventory Analysis

The inventory analysis involves the collection of data which is required to model the system under investigation. Since no primary data about the elementary flows exchanged with the Ecosphere by the unit processes involved was collected during this research activity, all the unit processes were modelled according to data available in Ecoinvent v3.11 database [27]. A comprehensive list of the selected items and datasets for each sub-module is provided in the Appendix section. (Tables 6, 7, 8, 9 and 10).

## 4 Results and Discussion

This section presents and discusses the results of the LCIA conducted on the management of ESR. To ensure a clear reading of the following sections and to clarify the technical terminology, acronyms, and scenario parameters adopted, Table 4 provides a summary glossary for reference.

**Table 4.** Summary glossary of technical terminology and scenario parameters adopted.

| Category | Term | Description |
|---|---|---|
| Materials | M-A | Material from traditional excavation |
| | M-B | Material from mechanised excavation |
| Waste Scenarios | W0, W12, W78 | Waste rates: percentage of material deemed unsuitable for recovery (0%, 12%, and 78%) |
| | IR | Internal Recycling ESR, fixed rate (22%) |
| LCA indicators | CC-Total | Total greenhouse gas emissions |
| | LU | Impact on land use resources |
| | AD-Fossil | Consumption of fossil energy resources |
| Waste Management | A5.1.1/A5.1.2 | Impacts related to the transportation of ESR |
| | A5.2.1/A5.2.2 | Impacts from the construction and demolition of the TD and internal service roads |
| | A5.2.4 | Recultivation activities for quarry restoration |
| | A5.3 | Landfill activities impacts |

### 4.1 Material-Specific Perspective

Accordingly to the goals, first, the quantification of the impact indicators is performed adopting a material-specific perspective. Hence, the results are computed considering 1 t of material to be processed according to its origin (M-A or M-B). No impacts from transportation were considered at this stage of the analysis. As mentioned before, three scenarios of waste rate have been considered, to assess the influence of the environmental compatibility of the material on the impacts of the waste management chain. In the following Table 5 the results are reported.

**Table 5.** Impact scores from LCIA for 1 t of waste material (A&B).

| Material | W0 | W12 | W78 | Avoided impacts |
|---|---|---|---|---|
| *Climate Change – total (CC-total) (kgCO2eq/t)* | | | | |
| M-A | 1.68E-02 | 1.09E + 00 | 7.17E + 00 | –8.01E-01 |
| M-B | 2.31E + 00 | 3.38E + 00 | 9.46E + 00 | –8.01E-01 |
| *Land Use (LU) impact category (Pt/t)* | | | | |
| M-A | –1.01E + 02 | –1.54E + 01 | 4.69E + 02 | –2.36E + 01 |
| M-B | 3.54E + 02 | 4.39E + 02 | 9.24E + 02 | –2.36E + 01 |
| *Depletion of Abiotic Resources – Fossil fuels (AD-fossil) (MJ/t)* | | | | |
| M-A | 2.19E-01 | 1.80E + 01 | 1.19E + 02 | –1.17E + 01 |
| M-B | 5.24E + 01 | 7.02E + 01 | 1.71E + 02 | –1.17E + 01 |

The figures in columns W0 to W78 represent the impacts associated with the waste management chain, while the column Avoided impacts describes the effect of recycling a portion of the waste (*IR*) as a substitute for VA. The negative values in the last column result from the comparison between a hypothetical scenario (where the same quantity of material originates from a quarry) and the current alternative. Due to the omission of transportation, the processing of M-A includes only recultivation and landfilling, whereas processing M-B also comprises the construction and demolition of the temporary deposit (allocated) and the placement of material within it.

Limiting the analysis to the largest observed waste rate scenario (W12) and considering the contribution of individual activities to the overall impact, the recultivation process accounts for 1.2% of the total Global Warming Potential and 1.0% of the Abiotic Depletion Potential of fossil resources for material M-A. These results highlight the dominant influence of the landfilling activity on the total impact score. This outcome is not unexpected, as the literature consistently attributes a significant environmental burden to the landfilling of civil works and construction wastes [13, 18, 28]. With regard to the Land Use impact category, recultivation generates a negative impact because land previously allocated to quarrying is restored to an uncontaminated condition. This outcome is in line with the current research on the topic [29]. The positive effect of recultivation on this impact category is visible in scenarios W0 and W12, where the environmental gain is not yet completely counterbalanced by the impact deriving from landfilling. This effect is gradually lost at higher waste rate values.

For M-B (W12), the most impactful activity for Climate Change is the construction and demolition of the temporary deposit (allocated), accounting for approximately 59% of the total impact, followed by the landfilling of the non-recyclable fraction (32%) and the placement of material within the temporary deposit (8%). This trend is consistent with the results of the Depletion of Abiotic Resources – Fossil fuels impact category. For Land Use, however, the construction and demolition of the internal service roads become the third most impactful activity.

Analysis of the results reported in column W12 demonstrates a clear influence of the material's origin on the impacts associated with the waste-management chain. The increase induced by the activities associated with waste material originating from mechanized tunneling reaches 310% for Climate Change and 390% for the Abiotic Depletion of Resources. The influence of the material's origin becomes even more pronounced when examining the Land Use impact indicator. In this case, the benefit (expressed as a negative impact value) associated with quarry re-naturalization is completely offset by the impact generated by the construction and demolition of the temporary storage area and the service roads within the construction site.

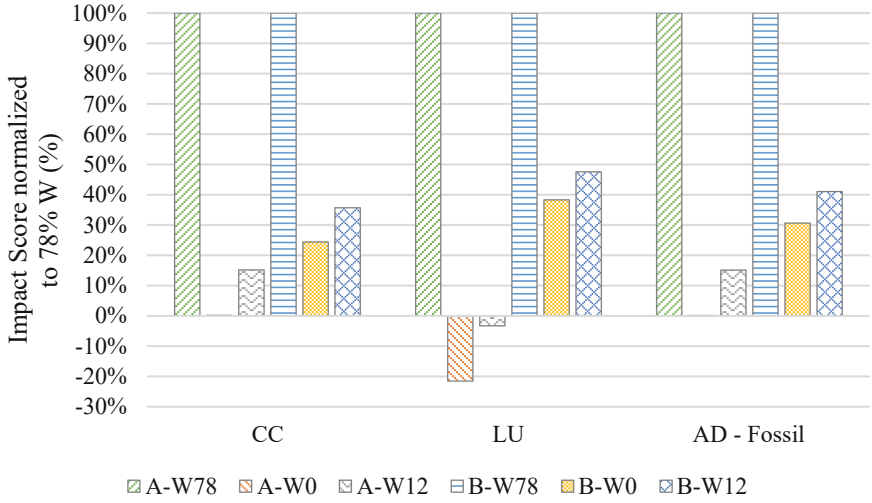


**Fig. 4.** Environmental impact of 1 t of excavated materials A and B, by origin and waste ratio.

In Fig. 4 the impact scores (excluding the benefits deriving from avoided impacts) for the two analyzed material (M-A and M-B) are shown, each normalized to the most impactful waste rate scenario (W78). In this graphical representation, W78 is always assigned 100% of the impact score. The bar graph effectively illustrates the influence of the environmental compatibility on the impact results; for instance, for material M-A, a reduction of the waste rate from 78% to 12% leads to an approximately 85% decrease in both CC-Total and AD-Fossil, while the LU category indicator shows negative values of impact. A smaller reduction is observed in case of M-B, due to the non-negligible impacts associated with the construction and the demolition of the temporary deposit and service roads. In this case, the mitigation ranges from roughly 50% (LU) to about 65% for the Climate Change category.

### 4.2 System-Level Perspective

The results obtained for individual materials are used to compute the overall impact for 1 t of material disposed at DP07, assuming that the waste originates from 4 distinct construction sites (COP5, COP11, COP20, COP7), located in the vicinity of the decommissioned quarry. The origin of the waste is evenly distributed among the sites (25% each). Figure 5 reports the results of W12, disaggregated by sub-submodule and normalized with respect to the total impact score.

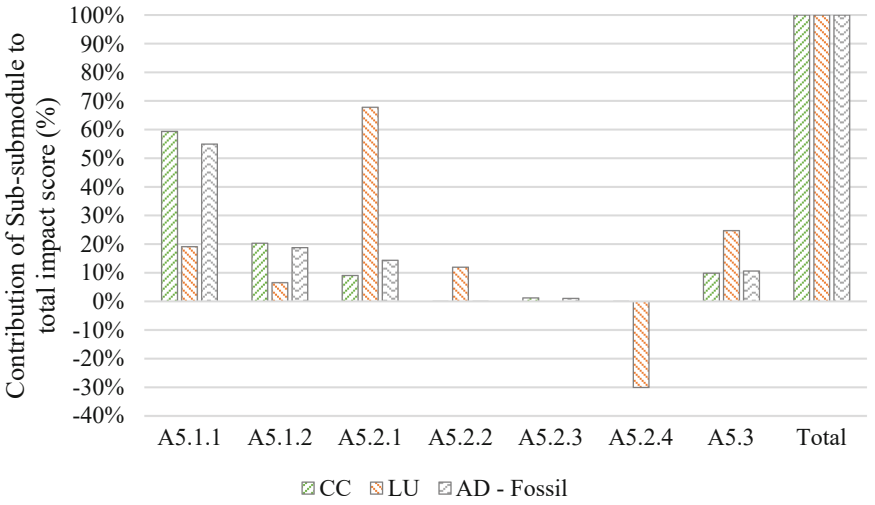


**Fig. 5.** Environmental impacts of 1t of material disposed at DP07 (excluding avoided impacts).

Overall, the potential contribution of 1 t of material to Climate Change is equal to 1.66E + 01 $kgCO_2eq$, while the potential benefit derived from the avoided products accounts for –1.21E + 00 $kgCO_2eq$. Regarding the Land Use, the total impact of Module A5 – Waste chain reaches 4.30E + 02 Pt, which incorporates the beneficial outcomes of recultivation (negative contribution), but does not include the avoided impacts from internal recycling (–3.56E + 01 Pt). Finally, the potential depletion of fossil resources reaches 2.54E + 02 MJ (–1.76E + 01 MJ).

The results presented in Fig. 5 allows the identification of the critical stages of the system for each impact category. For CC-Total and AD-Fossil, the largest contribution to the total impact originates from transportation of recyclable fraction of the excavation waste (A5.1.1), followed by the transportation of the non-recyclable portion (A5.1.2). Regarding the Land Use impact category, as predictable, the most impactful life-cycle stage is the construction and demolition of the temporary deposit (A5.2.1), followed by the transportation of the recyclable waste (A5.1.1) and the construction and demolition of service roads (A5.2.2). The positive contribution of the recultivation activity (A5.2.4) is represented by the negative bar and reflects the restoration of the original landscape.

## 5 Conclusions

In the present research activity, the impacts of different waste-management chains resulting from distinct excavation techniques were investigated. Specifically, ESR from traditional excavation technique and mechanised approaches were compared in terms of Climate Change, Land Use and Abiotic Resource Depletion – Fossil adopting a LCA methodology.

This activity has proved that the use of ESR for the renaturalisation of decommissioned quarries has positive effects on the Land Use impact category, resulting in a reduction of the impact score. Anyway, this activity has a cost in terms of Climate

Change and Abiotic Depletion – Fossil, although almost negligible if compared to the one related to transportation.

Moreover, although mechanised excavation techniques allow for faster construction timelines, the management of ESR involves a more complex logistic system, requiring the construction of temporary storage areas and service roads, ultimately leading to a higher impact value per ton of input waste.

Although the LCA model presented in this paper was developed on a specific case study, it provides a useful reference for developing site-specific models to assess the potential impacts of ESR in other contexts. Therefore, the results of this research may help raise awareness among general contractors of the benefits of excavation-waste management models, promoting circular resource-management practices such as the renaturalisation of decommissioned quarries.

Indeed, this study demonstrates how the adoption of a circular approach in the construction of transport infrastructure can offer significant opportunities for the development of sustainable solutions. However, it should be emphasised that the present analysis is based on several methodological assumptions made necessary by limited data availability and the strong site-specific nature of the case study, such as: a fixed internal recycling rate, a uniform distribution of ESR among the different production sites, and the estimation of transport distances. These assumptions inevitably introduce margins of uncertainty, which could be reduced through multi-scenario assessments and further research developments, both from a methodological perspective—through sensitivity and uncertainty analyses using Monte Carlo simulations—and by addressing existing data gaps through a multiple case-study approach that groups comparable ESR management scenarios by analogy.

In conclusion, this research has proved that adopting a circular approach in the construction of transport infrastructure offers an opportunity to develop sustainable solutions that contribute to the enhancement and value creation in the local environment.

## Appendix

**Table 6.** Activities comprised in A5.1 sub-submodulus and adopted models.

| A5.1 – Excavation Waste Transportation | |
|---|---|
| *A5.1.1 – Recyclable excavation waste transportation* | |
| M-A/M-B transportation from construction sites to decommissioned quarry (possibly via TD) | **(A)** Transport, freight, lorry, 16–32 metric ton, diesel, EURO 5 {RER}\| market for transport, freight, lorry, 16–32 metric ton, diesel, EURO 5 \| Cut-off, U |
| *A5.1.2 – Non-recyclable excavation waste transportation* | |
| M-A/M-B transportation from COP/TD to landfill | See **(A)** |

**Table 7.** Activities comprised in A5.2 sub-submodulus and adopted models (part 1).

| A5.2.1 – Infrastructure: temporary deposit | |
|---|---|
| *A5.2.1.1 – Land transformation and occupation* | |
| Transformation | Transformation, from annual crop, IT Transformation, to dump site, inert material landfill |
| Occupation | Occupation, dump site, inert material landfill |
| *A5.2.1.2 – Raw materials extraction and processing for construction materials* | |
| Production of virgin aggregates | **(B)** Gravel, crushed {CH}\| gravel production, crushed \| Cut-off, U |
| Transportation of virgin aggregates | See **(A)** |
| Production and transportation of bitumen | Bitumen adhesive compound, hot {GLO}\| market for bitumen adhesive compound, hot \| Cut-off, U |
| Raw materials extraction and transportation of the HDPE w.p.m | Adapted from EPD |
| *A5.2.1.3 – Construction materials manufacturing* | |
| Asphalt concrete production | Adapted from [30] |
| Manufacturing of the HDPE w.p.m | Adapted from EPD |
| *A5.2.1.4 – Construction materials transportation* | |
| Aggregates, asphalt concrete and HDPE w.p.m. transportation | See **(A)** |
| *A5.2.1.5 – Construction activities* | |
| Topsoil removal | Excavation, skid-steer loader {RER}\| excavation, skid-steer loader \| Cut-off, U |
| Subgrade compaction, laying and compaction of subbase and asphalt layer | **(C)** Machine operation, diesel, > = 74.57 kW, steady-state {GLO}\| machine operation, diesel, > = 74.57 kW, steady-state \| Cut-off, U |
| *A5.2.1.6 – Demolition activities* | |
| Demolition of the asphalt course | Adapted from [17] |
| Demolition of the subbase course | **(D)** Excavation, hydraulic digger {RER}\| excavation, hydraulic digger \| Cut-off, U |
| *A5.2.1.7 – Landfilling of demolition waste* | |
| HDPE w.p.m | Adapted from EPD |

**Table 8.** Activities comprised in A5.2 sub-submodulus and adopted models (part 2).

| A5.2.2 – Infrastructure: service roads | |
|---|---|
| *A5.2.2.1 – Land transformation and occupation* | |
| Transformation | Transformation, from annual crop, IT<br>Transformation, to traffic area, road network |
| Occupation | Occupation, traffic area, road network |
| *A5.2.2.2 – Raw materials extraction and processing for construction materials* | |
| Production of virgin aggregates | See **(B)** |
| *A5.2.2.4 – Construction materials transportation* | |
| Aggregates transportation | See **(A)** |
| *A5.2.2.5 – Construction activities* | |
| Subgrade compaction, laying and compaction of subbase course | See **(C)** |
| *A5.2.2.6 – Demolition activities* | |
| Demolition of the subbase course | See **(D)** |

**Table 9.** Activities comprised in A5.2 sub-submodulus and adopted models (part 3).

| A5.2 – Excavation waste processing | |
|---|---|
| *A5.2.3 – Waste managing activities inside the temporary deposit* | |
| Laying of the excavated material | See **(D)** |
| *A5.2.3 – Recultivation activities* | |
| Limestone quarry recultivation | Recultivation, limestone mine - COPIA {CH}\| recultivation, limestone mine \| Cut-off, S |

**Table 10.** Activities comprised in A5 modulus and adopted models.

| Module A5 – Waste chain | |
|---|---|
| **A5.3 – Disposal of the non-recyclable excavation waste** | |
| M-A/M-B landfilling activity | Adapted from [31] |
| **A5.B – Avoided products** | |
| Avoided impacts from substitution of VA | See **(B)** |

## References


1. European Court of Auditors (ECA): Special report 02/2026: EU transport infrastructure (2026)
2. European Commission: Regulation of the European Parliament and of the Council on Union Guidelines for the Development of the Trans-European Transport Network, Amending Regulation (EU) 2021/1153 and Regulation (EU) No 913/2010 and Repealing Regulation (EU) No 1315/2013. European Commission, Brussels (2021)
3. United Nations Environment Programme: Not just another brick in the wall: The solutions exist - Scaling them will build on progress and cut emissions fast. Global Status Report for Buildings and Construction 2024/2025. United Nations Environment Programme (2025). https://doi.org/10.59117/20.500.11822/47214
4. International Energy Agency: World Energy Outlook 2024 (2024)
5. Benedetto, A.: Strade, Ferrovie. UTET Università, Aeroporti (2019)
6. Nedd, R., Light, K., Owens, M., James, N., Johnson, E., Anandhi, A.: A synthesis of land use/land cover studies: definitions, classification systems, meta-studies, challenges and knowledge gaps on a global landscape. Land **10**, 994 (2021). https://doi.org/10.3390/land10090994
7. Häkkinen, T., Helin, T., Antuña, C., Supper, S., Schiopu, N., Nibel, S.: Land use as an aspect of sustainable building. Int. J. Sustain. Land Use Urban Plan **1** (2013). https://doi.org/10.24102/ijslup.v1i1.202
8. United Nations Environment Programme: Building Materials and the Climate: Constructing a New Future. United Nations, Erscheinungsort nicht ermittelbar (2023)
9. Felice, P., Zortea, M.: Riqualificare le cave dismesse in Italia. Wolters Kluwer Italia S.r.l., Milano (2019)
10. Whittaker, M.J., et al.: Novel construction and demolition waste (CDW) treatment and uses to maximize reuse and recycling. Adv. Build. Energy Res. **15**, 253–269 (2021). https://doi.org/10.1080/17512549.2019.1702586
11. Associazione Infrastrutture Sostenibili: Position Paper 2025 n.10 - Il recupero delle terre e rocce da scavo: soluzioni per una maggiore sostenibilità economica e ambientale, (2025)
12. Larondelle, N., Haase, D.: Valuing post-mining landscapes using an ecosystem services approach—an example from Germany. Ecol. Ind. **18**, 567–574 (2012). https://doi.org/10.1016/j.ecolind.2012.01.008
13. Rugani, B., Petucco, C.: Environmental benefits of re-using excavated soil flows: the case of Luxembourg. Sci. Total. Environ. **958**, 177867 (2025). https://doi.org/10.1016/j.scitotenv.2024.177867
14. Associazione Infrastrutture Sostenibili: Position paper 2024 n.7 - Life Cycle Assessment e la catena del valore delle infrastrutture sostenibili (2024)
15. Sebastiani, D., et al.: Circular economy and reuse of excavated materials from TBM excavations. In: Expanding Underground - Knowledge and Passion to Make a Positive Impact on the World, pp. 904–912. CRC Press, London (2023). https://doi.org/10.1201/9781003348030-109
16. Voit, K., Kuschel, E.: Rock material recycling in tunnel engineering. Appl. Sci. **10**, 2722 (2020). https://doi.org/10.3390/app10082722
17. Gruber, M.R., Hofko, B.: Life cycle assessment of greenhouse gas emissions from recycled asphalt pavement production. Sustainability. **15** (2023). https://doi.org/10.3390/su15054629
18. Blay-Armah, A., Bahadori-Jahromi, A., Mylona, A., Barthorpe, M.: A life cycle assessment of building demolition waste: a comparison study. Proc. Inst. Civ. Eng. Waste Resour. Manage. **177**, 100–113 (2024). https://doi.org/10.1680/jwarm.22.00012
19. COCIV: Piano di utilizzo dei materiali di scavo - Decreto n. 161/2012, Aggiornamento PdU ex art. 8 del D.M. n. 161/2012 - Relazione Generale (2012). https://va.mite.gov.it/it-IT/Oggetti/MetadatoDocumento/190286

20. COCIV: Piano di utilizzo dei materiali di scavo - Decreto n. 161/2012, Aggiornamento PdU ex art. 8 del D.M. n. 161/2012 - Descrizione dei siti di riqualificazione ambientale (2012). https://va.mite.gov.it/it-IT/Oggetti/MetadatoDocumento/190287
21. COCIV: Dichiarazione Ambientale EMAS (2025)
22. COCIV: Piano delle percorrenze Regione Piemonte (2012)
23. BSI: BS EN ISO 14040:2006+A1:2020: Environmental management, Life cycle assessment, Principles and framework (2020)
24. BSI: BS EN ISO 14044:2006+A2:2020: Environmental management. Life cycle assessment. Requirements and guidelines (2022)
25. BSI: BS EN 17472:2022: Sustainability of construction works. Sustainability assessment of civil engineering works. Calculation methods (2022)
26. BSI: BS EN 15804:2012+A2:2019. Sustainability of Construction Works: Environmental Product Declarations. Core Rules for the Product Category of Construction Products (2019)
27. ecoinvent v3.11. https://ecoinvent.org/ecoinvent-v3-11/. Accessed 10 Mar 2026
28. Wang, Y., Mu, X., Hu, G., Wang, L., Zhu, X.: Life cycle assessment-based analysis of environmental and economic benefits in construction solid waste recycling. Sustainability. **17** (2025). https://doi.org/10.3390/su17093872
29. Lee, C., Asbjornsson, G., Hulthén, E., Evertsson, M.: The environmental impact of extraction: a holistic review of the quarry lifecycle. Clean. Environ. Syst. **13**, 100201 (2024). https://doi.org/10.1016/j.cesys.2024.100201
30. Sollazzo, G., Longo, S., Cellura, M., Celauro, C.: Impact analysis using life cycle assessment of asphalt production from primary data. Sustainability. **12**, 10171 (2020). https://doi.org/10.3390/su122410171
31. Blengini, G., Garbarino, E.: Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix. J. Clean. Prod. J CLEAN PROD. **18**, 1021–1030 (2010). https://doi.org/10.1016/j.jclepro.2010.01.027

# Reclaiming the Sea: Cagliari's Waterfront Renaissance

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**Abstract.** The relationship between coastal cities and their sea has historically been marked by profound infrastructural divides. In Cagliari, Via Roma roadway has represented a physical and visual barrier between the historic urban fabric and the port for decades. This paper analyzes the regeneration process of the Cagliari waterfront, placing it in dialogue with major international best practices (including San Francisco, Genoa, Marseille, and Oslo) to evaluate its methodological validity. Through a comparative approach, the study examines the spatial redevelopment strategies adopted in the new Masterplan. The analysis focuses on the transformation of the Via Roma roadway axis, the pedestrianization of port areas, and the integration of the new surface light metro system (LRS). Particular attention is given to transport solutions: the introduction of unconventional circular loops ("dog-bone" roundabouts) and the regularization of road sections demonstrate how road declassification does not cause urban paralysis but optimizes unbalanced flows, provided there is strong synergy with the external metro network (SS554 and Asse Mediano). The study concludes that the Cagliari project is not merely an architectural redesign, but rather a profound social and urban redevelopment. The new waterfront aims to be a model of climate resilience and sustainable mobility for Mediterranean urban planning, restoring maritime space to the community.

**Keywords:** Urban regeneration · Waterfront · Intermodal and sustainable transport · New infrastructural layouts · Cagliari

## 1 Introduction

Coastal cities often face a profound spatial and functional paradox: water, a fundamental element and the very reason for their existence, is frequently inaccessible and separated from urban life [1].

Urban coastlines, monopolized by massive port, road, and logistics infrastructure, act as impermeable fences, creating a clear physical and visual division between the urban fabric and the maritime landscape.

Contemporary urban planning has developed a new sensitivity toward these areas, giving rise to the global phenomenon of the "waterfront renaissance." This cultural and design movement aims to reclaim, redevelop, and redesign the coastline, transforming

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it from a logistical barrier into a vibrant social hub. In this vision, the sea is seen not only as an economic resource, but as a "common good," a stage for community and a foundation for quality of life and urban identity [2].

Cagliari, the capital of Sardinia and a profoundly Mediterranean city, fits into this context of global regeneration thanks to its unique morphology, where sea, lagoons, and hills intertwine in a complex ecosystem [3, 4].

The city currently suffers from a pronounced "separation syndrome": its main waterfront, dominated by the majestic facades of Via Roma, serves primarily as a vehicular transit hub. Port fences and heavy traffic impede natural pedestrian access, but Cagliari is now at the center of ambitious redevelopment projects aimed at healing this rift. Key questions guiding this analysis include: can a road conceived as an "invisible wall" between city and water become the cornerstone of their reconnection? Is it really possible to eliminate heavy traffic from a monumental waterfront without paralyzing urban mobility, but rather making it more fluid and green? How can urban greenery and modern rail infrastructure coexist with the rigid identity of a port city? What practical lessons can Cagliari draw from leading international models? To address these questions and fully grasp the potential of Cagliari's challenge, we must look beyond local borders to the recurring dynamics of coastal regeneration around the world.

This comparative study explores various intervention philosophies, as illustrated in Fig. 1.:




**Fig. 1.** Representation of interventions worldwide, author's elaboration

- Removal of infrastructural barriers in San Francisco (The Embarcadero) [5];
- Reconnection of historic center and sea in Genoa (Porto Antico) [6];
- Radical pedestrianization in Marseille (Vieux-Port) [7–9];
- Linear park in Thessaloniki (Nea Paralia) [10];
- Multifunctional regeneration in Auckland (Quay Street and Wynyard Quarter);
- Flow management in Oslo (Dronning Eufemias gate);
- Intermodal hubs and rail focus in Nice and Bordeaux [11].

Through this journey, we show that reclaiming the sea is not just architectural restyling but an unrepeatable opportunity to redefine the city's social, cultural, and economic future: can Cagliari thus become an example for the Mediterranean basin?The original contribution of this paper is threefold: (i) it systematically applies a multi-criteria comparative framework to evaluate Cagliari's Masterplan against seven international waterfront cases, making the selection criteria explicit and transferable; (ii) it provides a technical engineering assessment of unconventional road geometries (dog-bone roundabouts) in a Mediterranean port context, grounded in established capacity models (HCM, LWR); and (iii) it advances the discourse on "traffic evaporation" for Southern European coastal cities where quantitative simulation data remain scarce. Together, these contributions position the paper not merely as a case study narrative, but as a replicable analytical template for waterfront regeneration in comparable urban settings.

## 2 Methodological Framework: Reference Models, Analysis, and Best Practices

To assess the scope and methodological validity of Cagliari's intervention, it is essential to analyze how other coastal cities have resolved conflicts between ports, traffic, and public space. The following comparative analysis ranges from pioneering urban planning interventions to bold infrastructure demolitions, highlighting lessons applicable to Via Roma and Cagliari's historic port.The cases were selected according to four explicit criteria: (1) presence of a physical infrastructural barrier between the urban fabric and the waterfront (analogous to Cagliari's Via Roma); (2) adoption of documented traffic-reduction or road-declassification strategies; (3) integration of public transport and intermodal solutions; and (4) contextual relevance for Mediterranean or Southern European coastal cities. This structured selection allows the analysis to move beyond anecdotal benchmarking toward a replicable comparative methodology, drawing transferable principles rather than merely illustrative precedents.

### 2.1 Mixed Use and Port Identity (Genoa and Auckland)

An analysis of major waterfront urban regeneration projects highlights key strategies for reconnecting former port areas to the urban fabric. Genoa's Porto Antico, designed by Renzo Piano for Expo '92, as illustrated in Fig. 2, pioneered the redevelopment of industrial archaeological sites, such as the Cotton Stores, for their complete reintegration into city life. Its success relies on the seamless integration of culture, leisure, and commerce in mixed-use areas, ensuring year-round vitality and preventing seasonal decay or the "cathedrals in the desert" effect. Internationally, Auckland's Wynyard Quarter exemplifies how infrastructure for large-scale sailing events can integrate with everyday urban life, merging the advanced maritime economy (superyachts and America's Cup bases) with plazas and open spaces [1, 2, 6].

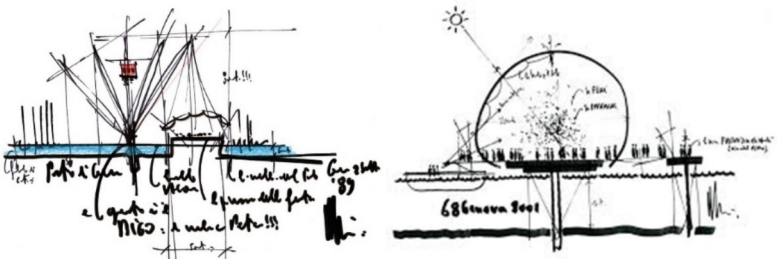

**Fig. 2.** Renzo Piano's early sketches for the Genoa Old Harbour project.[12]

### 2.2 Public Space and Landscape Filters (Marseille and Thessaloniki)

For spatial reconfiguration, Marseille's Vieux-Port (Fig. 3a and Fig. 3b) offers a successful "subtractive" model: continuous pedestrianization with mineral materials and luminous landmarks (such as Norman Foster's Ombrière) restore monumental dignity without obstructing the view, while degraded streets utilize large roundabouts. For longer stretches of coastline, Thessaloniki's Nea Paralia provides the ideal reference: its green ribbon of "themed rooms" serves as the perfect landscape and acoustic buffer between heavy traffic and the promenades along the seafront [7–9].



(a) (b)

**Fig. 3.** (a) Foster's Ombrière [13]; (b) Marseille port Masterplan [7]

### 2.3 Infrastructure and "Traffic Evaporation" (San Francisco, Nice, Oslo, Bordeaux)

The main challenge for any port area is managing transport infrastructure. The demolition of the Embarcadero Freeway in San Francisco has empirically demonstrated "traffic evaporation": reducing lanes does not cause gridlock ("Carmageddon"), but rather a modal redistribution. This principle guides European leaders: Oslo manages surface traffic (Dronning Eufemias gate) with strict low-speed sections; Bordeaux (Fig. 4) has reclaimed the banks of the Garonne by demolishing old logistics volumes ("creating space") and integrating trams; Nice has addressed high traffic density with intermodal hubs (Pôles d'échanges) [14–17].



**Fig. 4.** Bordeaux Quais [18]

## 3 Case Study and Discussion: From the Past, Through the Present, to the New Redevelopment Vision

### 3.1 History and Identity: A Millenary Bond Between City and Sea

Cagliari's urban history is inseparable from its sea and harbor. From Phoenician and Roman origins in ancient Karales, a key Mediterranean crossroads, the medieval Pisan era birthed the Lappola (now Marina) district for port workers, regulated by the 1318 Breve Kallaretani. Aragonese expansion in the 1300s planned the Marina as an economic engine with rectilinear axes parallel to the coast, evolving from Lappola to Marina. Spanish military needs erected coastal walls like the Porta del Molo, severing habitation from docks for centuries. [19–22].

The 19th-century urban transformation began in 1866 with the abolition of the city's fortress status. This led to the demolition of the city walls (illustrated in Fig. 5. Before and after the intervention) and the subsequent development of Via Roma's porticoed palaces. Conceived as a "bourgeois salon," this area served as a monumental gateway for those arriving by sea (Fig. 6. and 7.). However, the 20th century brought the devastation of II World War, followed by postwar logistical isolation, the installation of physical barriers, and mass motorization, which collectively transformed Via Roma into a high-speed traffic artery. Understanding this historical evolution is essential for current interventions aimed at healing this 20th-century "fracture" and reconnecting Cagliari to its waterfront [13, 23].



**Fig. 5.** Historical photos of Via Roma before current facade, [24]



**Fig. 6.** Central walkway with porticos, [24]



**Fig. 7.** Via Roma central walkway, [24]

The 20th century, however, brought new and profound divides. The devastation of World War II bombings (in 1943, the entire port area was razed to the ground) and the subsequent reconstruction favored a purely logistical approach. In the postwar period, the port was isolated by rigid fences, while Via Roma came under pressure from mass motorization, transforming into a barrier of fast and heavy traffic. The current identity of the waterfront is born of this dichotomy: on one hand, the monumental welcome of the porticos; on the other, the fragmentation caused by road arteries. Understanding this complex genesis is today fundamental for analyzing current urban interventions, whose primary purpose is precisely to heal the "20th-century fracture" and reconnect Cagliari to its sea. Until recently, the seafront was fragmented, with Via Roma hosting up to six vehicle lanes, fracturing historic porticos from inhospitable port docks. Convergence between Cagliari Municipality and Port System Authority (AdSP) sparked urban revision. Stefano Boeri Architetti and MATE Soc. Coop's Masterplan transforms Via Roma into a "Linear Forest," shrinking car lanes for pedestrians and active mobility while greening for climate resilience (heat islands, ecological continuity). Funded for intermodal center and transport overhaul, it improves urbanism and architecture but falls short on full mobility resolution [25–28].

AdSP's Historic Port opening shifts heavy cargo to Porto Canale, dedicating Via Roma docks to cruises and yachting, creating a continuous coastal park from Molo Dogana to Su Siccu, Molentargius Natural Park, and Sant'Elia ensuring visual permeability and cultural programming. [29].

### 3.2 Via Roma Redevelopment Project: Integration and Mobility

As depicted in the Fig. 8 and Fig. 9, the proposed intervention aims to integrate linear park walkways, ARST surface light metro, and AdSP historic port/waterfront works, with traffic planning as cohesive glue. [29, 30].




**Fig. 8.** Traffic project in context of other works, author's elaboration

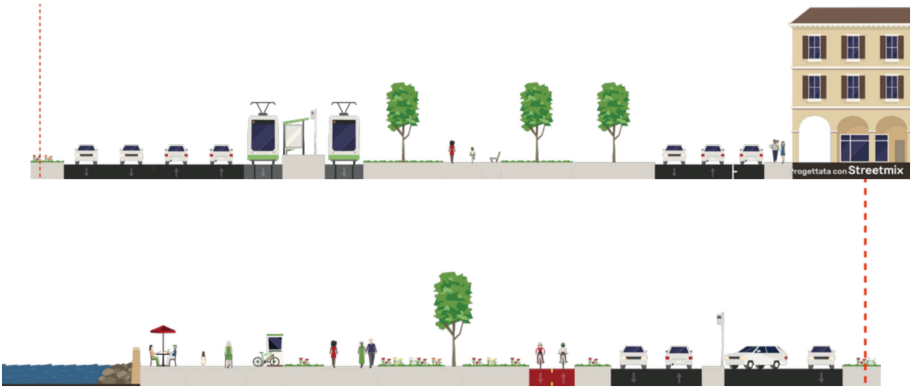


**Fig. 9.** Section A-A representation of portico-facing area project, author's elaboration

### 3.3 Via Roma Configuration (Portico Side and Central Strip)

A new central pedestrian-green axis (horizontal forest) emerges as illustrated in Fig. 10. Portico-side carriageway shrinks from 4 to 2 lanes (widening to 4 at Viale Diaz), with linear park bays for high-priority Local Public Transport (TPL) lines (M, 1, 5) shifting them portico-side for frequency and coverage [25, 26].



**Fig. 10.** Interventions with linear park [16]

### 3.4 Light Metro System

The new rail line links Piazza Matteotti to Piazza Repubblica, connecting center, Policlinico, Settimo San Pietro, and future Sestu/Poetto via Piazzale Cis/Bonaria hub. It optimizes TPL by backtracking lines 29/30/QEX/PF/PQ to Piazzale Cis, reducing Viale Diaz-Matteotti overlaps; creates dual intermodals at Matteotti and Repubblica extremes linked by tram/urban lines. Extra-urban ARST/private lines terminate at Matteotti west, SS554 east as "metro ring," absorbing users via metro—functional gomma-ferro transfer under ARST.

Transport efficiency is guaranteed by the capacity and frequency of the railway, rationalizing loads and reducing congestion and noise. Tariff integration (geographic zones via third party like City Metro) ensures seamless interchanges [29, 30].

### 3.5 Lungomare New York 11 Settembre (Seaside)

The reprofiling of the seaside road section is the cornerstone for ensuring vehicular fluidity:

- The road layout is upgraded from a nominal four-lane configuration, currently restricted to an effective capacity of 1.5 lanes per direction due to spatial constraints, to four fully operational lanes, each with a constant width of 3.50 m (two lanes per direction). According to the principles of the Highway Capacity Manual, geometric regularization restores the lane's ideal saturation flow (S0), bringing the width correction factor (fw) to unity. Even assuming preservation of current peak-hour traffic volumes, this simple widening and rationalization of lanes prevents capacity collapse. It eliminates dangerous overtaking attempts and lateral frictions, thereby nullifying the formation of shockwaves typical of the Lighthill-Whitham-Richards model that cause the deleterious stop-and-go. [31]
- The elimination of complex signalized nodes is entrusted to 2 classic roundabouts and 3 unconventional circular loops, including two "dog-bone" roundabouts and one "cuspide" as seen in Fig. 11, 12 and 13. From an engineering standpoint, the dog-bone roundabout offers decisive advantages on a linear axis [32, 33].



**Fig. 11.** Render of unconventional loop near Molo Dogana, authors' elaboration

### 3.6 Managing Unbalanced Flows and Geometric Benefits

Unconventional circular loops, including dog-bone roundabouts, represent an ideal engineering solution for managing intersections with heavily unbalanced traffic flows. Unlike standard circular configurations, their elongated and centrally "pinched" geometry allows alignment of the main axis with the highest traffic volume direction. This shape naturally favors the dominant traffic flow: vehicles on the main artery benefit from a more linear and fluid path along the long parallel sides of the infrastructure, reducing steering maneuvers and maximizing throughput. Conversely, flows from secondary roads enter through the two rounded ends (the "spectacles" or "lenses" of the spectacles). In these sections, the tighter curve radii force drivers to slow significantly to negotiate the curve and yield, creating a clear physical hierarchy that optimizes the overall efficiency of the intersection, allowing high volumes to flow smoothly without small influxes causing congestion [31–35].

The elongated geometry thus follows the primary desire line (La Playa-Colombo axis), imposing minimal deflection on the main traffic stream, which maintains a continuous regime of constant and harmonized speed (speed harmonization at around 30–40 km/h).



**Fig. 12.** Plan of proposed Matteotti dog-bone roundabout, authors' elaboration




**Fig. 13.** Plan of proposed Deffenu dog-bone roundabout, authors' elaboration

### 3.7 Impact on Road Safety

Regarding safety, dog-bone roundabouts offer significant structural benefits, although they present specific design challenges. Similar to traditional roundabouts (as shown in the render in Fig. 14.), they drastically reduce conflict points by eliminating orthogonal crossings; however, their primary advantage lies in the elongated central island. This physical barrier (the "bridge" of the eyeglasses) sharply separates opposing traffic streams on the main artery over an extended stretch, effectively preventing risky left turns or reckless overtakes. However, infrastructure safety depends on proper speed calibration. Since the main axis path is much straighter than in a classic roundabout, drivers risk not slowing sufficiently. So, design must include adequate entry deflection curves to force fast vehicles to reduce speed near zones where secondary flows enter or cross.

Compared to 32 conflict points at a signalized intersection, the dog-bone configuration reduces them to a maximum of 12, physically eliminating the possibility of high-energy frontal or perpendicular impacts [36].

A robust international evidence base supports the safety case for unconventional roundabout geometries. Retting et al. [37] and Persaud et al. [38]demonstrated, using empirical Bayes methods on 24 U.S. intersections, reductions of 38% in total crashes, 76% in injury crashes, and approximately 90% in fatal and incapacitating crashes following conversion from signal and stop-sign control to modern roundabouts. These findings are consistent with non-U.S. evidence: Elvik [39] meta-analysed 28 European and international studies and found reductions of 30–50% in injury accidents and 50–70% in fatalities when intersections are converted to roundabouts. The most comprehensive synthesis to date, a meta-analysis of 44 studies by Elvik [40], confirmed approximately 65% reductions in fatal crashes and 40% in injury crashes, with results described as robust across different modelling approaches. More recently, Wang and Cicchino [41] documented that double-teardrop roundabouts, haring the same elongated, centrally narrowed geometry as the dog-bone configurations proposed here, an 84% reduction in injury crashes was observed at high-traffic intersections in Carmel, Indiana, with an overall crash reduction of nearly two-thirds. Overall, this dataset strongly supports the safety projections for the dog-bone junctions on Via Roma, regardless of the intersection-level microsimulation.



**Fig. 14.** City center entry roundabout render, authors' elaboration

The dog-bone roundabouts facilitate smooth U-turns, supporting Via Roma's distributive role without penalizing axial flow.

With Port Authority works and seafront parking removal, fragmented crossings between port and porticos become unnecessary as seen in Fig. 15. Pedestrian flows reconfigure longitudinally along three axes (porticos, central linear park, port walkway). Transverse crossings will unify and become continuous, eliminating the current "zigzag" path forcing uncertain intermediate stops between bus lanes and park. Rationalization yields 3 strategic crossings in 500 m (one every ~ 160 m), offering safe, defined paths that reduce collision risks and irregular behaviors from discontinuous routes.



**Fig. 15.** Overall waterfront vision render

Combining roundabouts, pedestrianization fronting Municipio and Viale Cristoforo Colombo, and sea-side parking reduction, with doubled structured stalls at the station (FS), efficiently manages nodes. These zeros out parasitic traffic from vehicles traversing the axis solely for parking searches, U-turns, or port-related exits.

### 3.8 Flow Analysis and the Strategic Role of the Metropolitano Scale (SS554 and Asse Mediano)

The decisions to downgrade the Via Roma section are firmly supported by empirical data, as illustrated in Fig. 16, from the knowledge framework of the Municipality of Cagliari's Sustainable Urban Mobility Plan (PUMS). Origin/Destination (O/D) surveys in the area (Riva di Ponente/Via Roma axis) clearly reveal the historic improper role of the seafront as a "bypass": about 7% of trips involve traffic with origins and destinations external to the municipality.

As much as 30% consists of pure transit traffic (internal-external or vice versa), with no real destination in the city center.

Thus, an estimated 35% to 40% of current traffic is naturally divertible to alternative routes. The Via Roma intervention thus triggers the well-known phenomenon of traffic evaporation, discouraging parasite transit. However, for this flow reassignment to materialize without penalizing the macroscopic system, it is an indispensable condition to commence construction and complete the SS554 enhancement works. The latter must fully assume the role of "metropolitan ring road." Similarly, vital is securing critical points on the Asse Mediano; any bottlenecks, accidents, or slowdowns on the outer ring would cause an immediate rebound of vehicle volumes to the waterfront axis, nullifying part of the decongesting benefits. The synergy between rail prioritization ("cura del ferro" via MetroCA), resizing the "window on the sea" (Via Roma), and strengthening external tangent rings represents the only equation ensuring transport and urban success for the sector [29]. The metropolitan-scale flow redistribution estimates presented in this section, including the 35–40% divertible traffic share and the modal reassignment scenarios conditional on SS554 completion, are supported by macroscopic traffic simulations contained in the municipal PUMS, which model alternative network scenarios with and without the outer ring road works. This provides a robust quantitative foundation for the traffic evaporation argument at the urban and metropolitan scale. It should be acknowledged, however, that intersection-level performance, specifically, capacity, delays, and safety outcomes, of the proposed dog-bone and cusp roundabouts have not been validated through dedicated microsimulation. The lack of intersection-specific modeling is a recognized limitation; future research should address this gap by applying microsimulation tools (e.g., VISSIM) to individual nodes, enabling rigorous verification of the expected geometric benefits and providing a more robust evidence base for detailed design decisions.

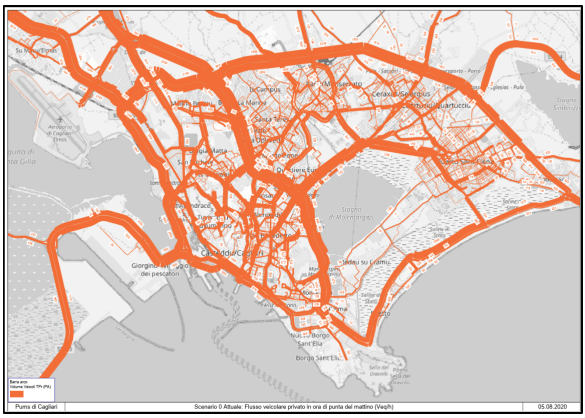

**Fig. 16.** Peak private vehicle flows [29]

## 4 Conclusions and Future Vision: The New Mediterranean Waterfront Paradigm

The regeneration process of Cagliari's waterfront, set within the broader context of global urban dynamics, now allows us to draw objective conclusions and outline a clear vision for the city's future. At the outset of this analysis, several fundamental questions arose regarding the real chances of success of such a radical intervention. By comparing it with leading international models and conducting a technical analysis of the project, we are now able to provide precise answers.

**Can a roadway artery transform from an "invisible wall" to a cornerstone of reconnection?** The answer is yes. As demonstrated by San Francisco's Ferry Building and Oslo's Dronning Eufemias gate, downgrading heavy infrastructure does not result in loss for the city but in its rediscovery. The "Linear Forest" project on Via Roma does not merely narrow the carriageway but fundamentally changes the nature of the space: from a mere vehicular transit area to a "continuous coastal park." The street no longer separates the city from the sea but becomes the physical and perceptual hinge uniting the historic Marina district to the port docks.

**Is it possible to remove heavy traffic without paralyzing urban mobility?** International experience confirms the principle of traffic evaporation. Fear of paralysis (the so-called "Carmageddon") is systematically disproven when reducing space for private cars is paired with smart public transport enhancement and node redesign. Nice's tram/bus intermodal hubs and Bordeaux's fluid Quais validate Cagliari's design choices. Rationalizing lanes to 3.50 m, inserting the surface light metro (with desirable tariff integration), and adopting 5 strategic roundabouts ("dog-bone" and "cuspide") will ensure elimination of bottlenecks and parasite traffic, making mobility smoother, more predictable, and ecological.

**How can urban greening and modern infrastructure coexist with historic identity?** Respect for identity does not mean stagnation. Marseille's example, with its mineral pedestrianization and Norman Foster's iconic Ombrière, teaches us that minimalism and

the insertion of "light" contemporary elements can enhance, rather than diminish, historic monumentality. In Cagliari, urban greening and rail infrastructure are designed not to obstruct visual perspectives: on the contrary, reducing cars at street level will restore to citizens and visitors the uninterrupted scenic backdrop of the Palazzo Civico and 19th-century porticos.

**What practical lessons does Cagliari draw from international models?**

The Sardinian capital is demonstrating that it has absorbed European and global best practices:

- From Genoa and Auckland, it inherits the importance of mixed-use functionality and the role of major events (like sailing competitions) to avoid the "cathedral in the desert" effect and ensure 24/7 economic vitality.
- From Thessaloniki, it adopts the landscape approach: Nea Paralia's sequence of themed gardens is the perfect conceptual model for managing long coastal stretches toward Su Siccu and Molentargius Park.
- From Marseille and Bordeaux, it learns the art of "making space," removing old port volumes to restore open views over the Golfo degli Angeli.

### 4.1 Future Vision

Cagliari's reclamation of the sea represents far more than architectural restyling: it is an act of identity reappropriation. By removing heavy traffic and opening the historic port to pedestrian use, the city positions itself as a new reference point for Mediterranean urban planning. The new waterfront will be more than just a promenade: it will be a resilient urban ecosystem capable of mitigating climate change, fostering sociality, and revitalizing the economy tied to tourism and maritime innovation. Cagliari has finally stopped viewing its sea from a car window and can now fully live it again. From a sustainability perspective, the reduction of private vehicle lanes combined with the introduction of a light metro and active mobility infrastructure directly supports the goals of Sustainable Urban Mobility Plans (SUMP/PUMS), lowering CO2 emissions, reducing urban heat island effects through the linear green corridor, and improving ecological connectivity between the port, Molentargius Natural Park, and the Su Siccu waterfront. From a safety perspective, the replacement of signalized intersections with engineered roundabout geometries (including dog-bone configurations) reduces conflict points from 32 to a maximum of 12, while speed harmonization at 30–40 km/h and the elimination of unregulated pedestrian crossings substantially lower the risk of high-severity collisions. These outcomes collectively advance the planning and design of the examined areas along two of the most critical dimensions of contemporary urban quality: environmental resilience and road safety. Future quantitative validation through microsimulation and post-implementation monitoring will be essential to confirm and refine these projected benefits.

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## References

1. Gehl, J.: Città per le persone. Maggioli Editore
2. URBIT - Urbanistica Italiana, Città e porti: i waterfront come volano di sviluppo
3. Maciocco, G.: La città e il mare. Progetti per il waterfront di Cagliari. Franco Angeli
4. Garau, C., Desogus, G., Maltinti, F., Olivo, A., Peretti, L., Coni, M.: Practices for an integrated planning between urban planning and green infrastructures for the development of the municipal urban plan (MUP) of Cagliari (Italy). In: International Conference on Computational Science and its Applications, pp. 3–18. Springer, Cham (2021)
5. Cervero, R.: Freeway Deconstruction and Urban Regeneration in the United States. J. Urban Des.
6. Gastaldi, F.: Genova: strategie urbane e grandi eventi. Urban. Inf.
7. Euroméditerranée : aménagement et développement économique à Marseille». Consultato: 4 marzo 2026. [Online]. Disponibile su: https://www.euromediterranee.fr/
8. Marseille : la délicate opération du tunnel Joliette». Consultato: 4 marzo 2026. [Online]. Disponibile su: https://www.laprovence.com/article/actualites/1009810/marseille-la-delicate-operation-du-tunnel-joliette.html?id=1009810
9. AA.VV., Marseille-Provence 2013: European Capital of Culture. Urban Regeneration and Social Inclusion. Eur. Plan. Stud.
10. Tratsela, M.: Contemporary landscape architecture in Greece: The Nea Paralia project. Landsc. Res.
11. I quais jardinés bordolesi tra riuso e rigenerazione – GIZMO». Consultato: 4 marzo 2026. [Online]. Disponibile su: https://www.gizmoweb.org/2014/06/i-quais-jardines-bordolesi-tra-riuso-e-rigenerazione/
12. RPBW e R. P. B. Workshop, Re-development of the Genoa Old Harbour». Consultato: 2 aprile 2026. [Online]. Disponibile su: https://www.rpbw.com
13. Gallery of Vieux Port Pavilion / Foster + Partners - 1». Consultato: 4 marzo 2026. [Online]. Disponibile su: https://www.archdaily.com/340004/vieux-port-pavilion-foster-partners/51363238b3fc4ba6630000db-vieux-port-pavilion-foster-partners-photo
14. MacDonald, E.: The Embarcadero, San Francisco. in Boulevard Planning and Design, Routledge
15. ROMA Design Group, The Embarcadero Masterplan»
16. Bordeaux Métropole, Aménagement des Quais de la Garonne. Report istituzionale
17. Ville de Nice, Dossier de presse: Ligne 2 du tramway»
18. Snapshot». Consultato: 24 marzo 2026. [Online]. Disponibile su: https://solutionscomposites.fr/realisation/systeme-daps-tramway/

19. Ministero per i Beni Culturali e Ambientali, Cagliari, Storia e immagine di una forma urbana
20. Spiga, G.: La Storia di Via Roma. Cagliari - Antica Orologeria Candido Operti
21. Cadinu, M.: Urbanistica medievale in Sardegna. Roma: Bonsignori (2001)
22. Conde y Delgado de Molina, R.: Castell de Caller, Cagliari catalano-aragonese. Cagliari: Della Torre (1984)
23. Scano, D.: Forma Kalaris. Cagliari (1934)
24. -». Consultato: 8 maggio 2026. [Online]. Disponibile su: http://www.archiviostatocagliari.it/archiviostoricocagliari/topog.php
25. Stefano Boeri Architetti, MATE Soc. Coop., e others, Masterplan per la riqualificazione del fronte mare di Cagliari - Relazione Generale»
26. Una Promenade Verde | Lungomare di Cagliari. Stefano Boeri Architetti. Consultato: 13 marzo 2026. [Online]. Disponibile su: https://www.stefanoboeriarchitetti.net/project/una-promenade-verde-per-il-lungomare-di-cagliari/
27. AA.VV., Cagliari: il nuovo rapporto tra porto e città. Urban. Inf.
28. Autorità di Sistema Portuale del Mare di Sardegna, Documento di Pianificazione Strategica di Sistema (DPSS)
29. Comune di Cagliari, Piano Urbano della Mobilità Sostenibile (PUMS). BU6PR011 - Quadro Conoscitivo - Relazione generale. Comune di Cagliari, Cagliari, Italia, Documento di Piano, 2021. [Online]. Disponibile su: https://www.comune.cagliari.it
30. 2.10-relazione_generale_e_illustrativa.pdf». Consultato: 13 marzo 2026. [Online]. Disponibile su: https://www.arstspa.info/TEC/LINEA_3/elaborati_progetto_preliminare/2.10-relazione_generale_e_illustrativa.pdf
31. Mohamed, A., Ci, Y., Tan, Y.: A novel methodology for estimating the capacity and level of service for the new mega elliptical roundabout intersection. J. Adv. Transp. 2020, p. 18 (2020). https://doi.org/10.1155/2020/8467152
32. Brilon, W.: Roundabouts: A state of the art in Germany. in National Roundabout Conference, Vail, Colorado (2005)
33. Fathullah, H., Majid, H., Ismael, K., Ahmed, C., Sourkan, S., Abdulsamad, B.: Traffic Circulation Efficiency of Elliptical Roundabouts. ARO- Sci. J. Koya Univ. 11, 65–72 (2023). https://doi.org/10.14500/aro.11150
34. Alozi, A.R., Hussein, M.: Multi-criteria comparative assessment of unconventional roundabout designs. Int. J. Transp. Sci. Technol. 11, fasc. 1, 158–173 (2022). https://doi.org/10.1016/j.ijtst.2021.03.006
35. Cairns, S., Hass-Klau, C., Goodwin, P.: Traffic Impact of Highway Capacity Reductions: Assessment of the Evidence. Landor Publishing
36. National Academies of Sciences, Engineering, and Medicine, Highway Capacity Manual: A Guide for Multimodal Mobility Analysis, 7th ed. Washington, DC: The National Academies Press (2022)
37. Retting, R.A., Persaud, B.N., Garder, P.E., Lord, D.: Crash and injury reduction following installation of roundabouts in the United States. Am. J. Public Health, **91**, fasc. 4, 628–631 (2001). https://doi.org/10.2105/AJPH.91.4.628
38. Persaud, B.N., Retting, R.A., Garder, P.E., Lord, D.: Safety effect of roundabout conversions in the United States: empirical bayes observational before-after study. Transp. Res. Rec. J. Transp. Res. Board, **1751**, 1–8 (2001). https://doi.org/10.3141/1751-01
39. Elvik, R.: Effects on road safety of converting intersections to roundabouts: review of evidence from Non-U.S. studies. Transp. Res. Rec. J. Transp. Res. Board, **1847**, 1–10 (2003). https://doi.org/10.3141/1847-01
40. Elvik, R.: Road safety effects of roundabouts: a meta-analysis. Accid. Anal. Prev. **99**, fasc. Part A, 364–371 (2017). https://doi.org/10.1016/j.aap.2016.12.018
41. Wang, J., Cicchino, J.B.: Safety effects of roundabout conversions in Carmel, Indiana, the roundabout city. J. Safety Res. **82**, 159–165 (2022). https://doi.org/10.1016/j.jsr.2022.05.007

# Author Index


**A**
Addabbo, Martina Caterina 302
Agea, Marieta 224
Amoruso, Paola 38
Anelli, Debora 21, 62, 116, 132, 145
Askarizad, Reza 465, 518
Avola, Giovanni 536

**B**
Baglieri, Orazio 593
Barabino, Benedetto 566
Batista, Paulo Ricardo 501
Bellia, Sheila 518, 536
Bertolini, Marina 3
Bucca, Marcella 207

**C**
Campagna, Carmine 277
Canesi, Rubina 3
Carpentieri, Gerardo 501
Carra, Martina 566
Caselli, Barbara 484
Cerullo, Giuseppe 50
Choong, Rachel Yee-Enn 315
Collini, Enrico 435
Coni, Mauro 612
Conticelli, Elisa 250
Coscia, Cristina 98

**D**
Dastoum, Mana 465
Dattoli, Antonella 289
De Toni, Andrea 336
Del Giudice, Francesco Paolo 50
Delponte, Ilaria 593
Di Liddo, Felicia 38, 156, 172, 190
Di Rocco, Alice Renè 79
Di Sessa, Mattia 593
Distefano, Miriam 536
Dobrotová, Lucia 368
Doretti, Luca 3

**E**
Emmi, Giuseppe 156

**F**
Fanfani, Marco 435
Fariello, Francesca 132, 145, 172, 190
Fong, Zi-En 315
Franchina, Alice 336
Fregonara, Elena 98

**G**
Gajdošík, Tomáš 450
Gajdošíková, Zuzana 450
Galli, Federico 435
Gamannossi degl'Innocenti, Duccio 3
Garau, Chiara 465, 518, 612
Gatto, Rachele Vanessa 224, 236, 264, 277, 289, 302
Giannandrea, Annamaria 264
Giannitti, Sabrina 289
Goh, Xin-Tian 315
Guarini, Maria Rosaria 62
Guida, Carmen 501

**I**
Ignaccolo, Matteo 518, 536

**K**
Kaleyeva, Veranika 553

**L**
Lee, Chien-Sing 315
Legrottaglie, Sonia 302
León, Macarena 224
Locurcio, Marco 38, 172, 190
Luzzatto, Giovanni 3

**M**
Malá, Denisa 353
Maltinti, Francesca 612
Manganelli, Benedetto 50
Marella, Giuliano 3


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Matera, Erica Rosa 264
Miháliková, Laura 353
Mitropoulos, Lambros 581
Morano, Pierluigi 21, 38, 62, 132, 145, 156, 172, 190
Morello, Eugenio 336
Morente, Melania Arenas 50
Murray Svidronova, Maria 386

**N**
Nesi, Paolo 435
Ng, Amanda Sze-Yuen 315
Nicotra, Lorenzo 207
Nocera, Francesco 79

**P**
Palmieri, Consita 289
Panetto, Kevin 612
Pasquino, Francesca 98
Pedilarco, Giulia 484
Petronella, Michele Pio 277
Pezzagno, Michele 566
Pimentel, Ángela 224

**R**
Raccagni, Stefano 566
Rassu, Nicoletta 612
Re, Annalisa Lo 264
Reháková, Mária 402
Riggi, Ezio 536
Rojíková, Darina 402
Roma, Antonella 172
Ruggeri, Aurora 156

**S**
Sabatelli, Emma 21, 132, 145
Sassone, Martina 277
Scorza, Francesco 224, 236, 264, 277, 289, 302
Scuderi, Alessandro 207
Senatore, Chiara 98
Sigrisi, Dalila 302
Soraggi, Daniele 593
Sturiale, Luisa 207
Sýkorová, Katarína 418

**T**
Tajani, Francesco 21, 38, 50, 62, 132, 156
Tedesco, Alberico 236
Tondelli, Simona 250
Torrisi, Vincenza 518, 536
Trovato, Maria Rosa 79

**V**
Vaňová, Anna 402
Vaneková, Beáta 450
Ventura, Roberto 566
Vetturi, David 566
Vitálišová, Katarína 402
Voudouri, Katerina 581

**Y**
Yew, Jia-Wen 315

**Z**
Zaldei, Alessandro 536
Zambujal-Oliveira, João 62, 116
Zamperlin, Paola 435
Zazzi, Michele 484
Zedda, Riccardo 612