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Chiara Garau · Ana Maria A. C. Rocha ·
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Computational Science and Its Applications – ICCSA 2026 Workshops

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

8 Part VIII

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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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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)

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Geomatics for Resource Monitoring and Management (GRMM 2026)

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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)

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Eduardo Bezerra	Federal Center for Technological Education of Rio de Janeiro, Brazil
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Multidimensional Evolutionary Evaluations for Transformative Approaches (MEETA 2026)

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Sabrina Sacco	University of Naples Federico II, Italy

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Building multi-dimensional Models for assessing complex Environmental Systems (MES 2026)

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Marco Rossitti	Politecnico di Milano, Italy

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Computational Mechanics, Intelligence, and Data (MIND 2026)

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Renato Zona	Università della Campania Vanvitelli, Italy

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Donato Perfetto	University of Campania Luigi Vanvitelli, Italy

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

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Valerio Cutini	University of Pisa, Italy

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Chiara Di Dato	University of L Aquila, Italy
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Chiara Anselmi	University of Pisa, Italy

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

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Vita Leonessa	University of Basilicata, Italy

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

Workshop Organizers

Lorena Fiorini	University of L'Aquila, Italy
Lucia Saganeiti	Institute of Methodologies for Environmental Analysis (IMAA) CNR, Italy
Angela Pilogallo	Institute of Methodologies for Environmental Analysis (IMAA) CNR, Italy

Francesco Zullo	University of L'Aquila, Italy
Alessandro Marucci	University of L'Aquila, Italy

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Chiara Garau	University of Cagliari, Italy
Beniamino Murgante	University of Basilicata, Italy
Ljiljana Zivkovic	Republic Geodetic Authority, Serbia
Luigi Santopietro	Institute of Methodologies for Environmental Analysis National Research Council of Italy CNR IMAA, Italy
Ilaria Delponte	University of Genoa, Italy
Carmen Guida	Università degli Studi di Napoli Federico II, Italy
Chiara Di Dato	University of L'Aquila, Italy

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

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Livia Marcellino	University of Naples Parthenope, Italy
Valeria Mele	University of Naples Federico II, Italy

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Marco Lettiero	University of Naples Parthenope, Italy
Francesco Peluso	University of Naples Parthenope, Italy

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

Workshop Organizers

Cecília Coelho	Helmut Schmidt University, Germany
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Luís Ferrás	University of Minho, Portugal
Eliana Costa e Silva	Polytechnic of Porto, Portugal

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Weronika Wojtak	CCG/ZGDV Institute, Portugal
Wolfram Erlhagen	University of Minho, Portugal

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

Workshop Organizers

Lelio Campanile	Università degli Studi della Campania Luigi Vanvitelli, Italy
Mauro Iacono	Università degli Studi della Campania Luigi Vanvitelli, Italy
Michele Mastroianni	University of Foggia, Italy

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Gianni D'Angelo	University of Salerno, Italy
Biagio Boi	University of Salerno, Italy
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Preserving Our Past: Spatial and Remote Sensing Technologies for Cultural Heritage in a Changing Climate (POP 2026)

Workshop Organizers

Maria Danese	Institute of Heritage Science of the National Research Council of Italy (CNR ISPC), Italy
Rosa Lasaponara	Institute of Methodologies for Environmental Analysis (CNR IMAA), Italy
Nicola Masini	Institute of Heritage Science of the National Research Council of Italy (CNR ISPC), Italy

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Valentina Florio	CNR, Italy
Antonio Minervino Amodio	Institute of Heritage Science of the National Research Council of Italy (CNR ISPC), Italy

Scientific Computing Infrastructure (SCI 2026)

Workshop Organizers

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Elena Stankova	Saint Petersburg State University, Russia

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Ashot Gevorkyan	Institute for Informatics and Automation Problems NAS of Armenia, Armenia

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Alexander Bogdanov	St. Petersburg State University, Russia
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Alexander Degtyarev	St.Petersburg State University, Russia
Alexander Bogdanov	St. Petersburg State University, Russia

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

Workshop Organizers

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Francesco Tajani	Sapienza University of Rome, Italy
Felicia Di Liddo	Polytechnic University of Bari, Italy

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Plenary Lectures

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

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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

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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

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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.

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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.

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Smart and Sustainable Island Communities (SSIC 2026)

Identifying Insular Tourism Hotspots at Fire and/or Flood Risk – Case Study Rhodes Island, Greece

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Abstract. In the Climate Change (CC) era, frequency, duration, and intensity of wildfire and flood incidents across Mediterranean areas is predicted to amplify, raising thus policy concerns as to the risks inherent in, among others, tourism hotspot regions, including the insular ones. Experience gained from recent CC-related fire/flood incidents and their devastating impacts on the natural/built environment – particularly in Mediterranean highly-urbanized, tourist-overloaded coastal parts – calls for broadening the scope of planning and policy making in order for resilience of these areas to be strengthened. This highlights the necessity for feeding planning endeavours with spatially-defined fire/flood risk assessments, especially in coastal tourism hotspots, i.e., areas displaying an intense accommodation and tourists' overload. That said, this study develops a framework for identifying tourism hotspot zones that are prone to fire and/or flood risk, with this perceived as a critical input in proactive planning studies aiming to minimize fire/flood risk or conduct fire/flood management plans. This framework integrates: a literature-based indicators' set for featuring tourism hotspots; the Random Forest algorithm through the Forest-Based Classification tool for fire risk assessment; and the officially-delineated flood-prone zones. Implementation of this framework is conducted in Rhodes Island, i.e., a major flagship of Greek tourism; a well-known, of global reach, destination; and a prominent example of Mediterranean island region, exposed to both CC and (over)tourism repercussions. Linking fire/flood hazards with tourism patterns offers insular destinations a useful ground for featuring proactive CC adaptation strategies and/or emergency planning.

Keywords: Insular Territories · Tourism Hotspots · Fire/Flood Risk · Spatial Analysis · Machine Learning

1 Introduction

Mediterranean regions nowadays are perceived as remarkable *tourism hubs*, attracting about 30% of the global tourist flows [1]. Actually in these regions tourism is grasped as a developmental lever and is mainly expanded in the coastal part of both the mainland and the insular territories, taking mostly the form of mass tourism. Speaking of the *insular*

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territories, being at the heart of this work, tourism is grasped as the 'engine' of the islands' economic profile, building the foundation for a Tourism-Led Growth (TLG) paradigm [2], with noticeable contribution to GDP, employment, and foreign exchange earnings. However, the industry's quite extensive and, in many cases, uncontrolled growth [3] is also a main source of: commercialization and degradation of the natural/cultural capital; wasting of scarce resources; intense urbanization of coastal land; extensive urban sprawl along the coast [4]; to name but a few. The latter – i.e. coastal urban sprawl – brings coastal urban zones in close proximity to neighbouring forested areas, giving thus rise to, among others, fire prone Wildland Urban Interfaces (WUIs). Taking into consideration the rapidly expanding tourist flows in the Mediterranean [1], the aforementioned tourism repercussions are expected to further escalate, while the state of *overtourism* is currently presenting a visible trend/threat and a main accelerator of the degradation of fragile natural coastline areas and the identity loss of coastal and particularly insular territories [3, 5–8].

Further to the tourism-originating pressure and related threats, introduced by the mass model prevailing in the Mediterranean coastal and particularly the insular territories, a key challenge that is expected to largely affect the future of these Mediterranean mass tourism hubs is *Climate Change*. CC, as various studies claim, places coastal communities at stake by threatening their livelihoods, infrastructure and ecosystems [9]. Mediterranean in the CC era is confronted with higher risks than the rest regions of the world, as a CC hotspot, heating 20% faster than world average [10]. Primary CC impacts, coastal communities must contend with are the rising sea levels, the escalating storm intensity, the coastal erosion and the habitats' loss; all largely affecting the socioeconomic environment of Mediterranean coastal/insular communities, including tourism as a highly important industry of this region. In addition, insular territories, despite their low contribution to CC, seem to be much more vulnerable to CC-driven impacts, with this vulnerability being largely dependent on their peculiar attributes, e.g. islands' size, morphology, geographical location, adaptive capacity.

CC repercussions are further intensified by the combined influence of non-climatic factors, particularly land use changes. Of critical importance in this respect, as various studies claim [11], are Mediterranean *tourism hotspots*, i.e., highly-sensitive and intensely-urbanized coastal parts, displaying a strong dependence – apart from tourism – on a range of coastal-related economic sectors (e.g. fishery, maritime transportation, marine energy) [12]. That said, the unique vulnerabilities and adaptive capacities of such tourism hotspots as well as their resilience or adaptive needs [13, 14] remain rather underrepresented in relevant CC and developmental studies. Most importantly, the spatial pattern of such vulnerabilities and their relationship with tourism hotspots lacks a well-documented approach which – taking into account also technological advances – can strengthen the context of *placed-based policy decisions*, targeting resilience of these hotspots but also preparing for extreme events' management.

Within such a context, this work attempts to fill the aforementioned gap, by exploring risks tourism hotspots in insular regions are confronted with. Such risks are the outcomes of CC implications but also anthropogenic pressures, and are tightly interwoven with the rapid urbanization of coastal land and the intense urban sprawl for serving the steadily

rising tourism demand. More specifically, *flood and fire risk* and their spatial manifestations in a highly-rated tourism destination, Rhodes Island, Greece are explored; and these are overlaid onto the spatial pattern of tourism hotspots in order for destinations prone to fire and/or flood risk to be identified and thus more informed and proactive policy reaction to be articulated. It should be noted here that this work attempts to step further authors' previous research endeavour [15] by focusing on the field of fire risk assessment using Machine Learning Methods and more specifically the Random Forest algorithm through the Forest-Based Classification tool. Rigorous documentation in this field adds value in the proposed methodological framework, aiming at paving transition pathways of insular but also coastal territories that favour climate-resilient tourist development.

The structure of the study has as follows: in Sect. 2 the methodological approach is presented, coupled with the data sources used for identifying tourism hotspots in the study area and feeding the Forest-Based Classification tool for fire risk assessment; in Sect. 3 results obtained from the implementation of the proposed framework are demonstrated; while in Sect. 4 compound results are critically discussed and key conclusions are drawn.

2 Data and Methodology

2.1 The Methodological Approach

The steps of the methodological approach have as follows (Fig. 1):

- Step 1 delves into the key features of the study region. As such, Rhodes Island is used, being part of the Southern Aegean Region, Greece.
- Step 2 elaborates on the tourism dynamics of Rhodes Island. Towards this end, a good insight of tourism into the study region is accomplished, coupled with the calculation of a number of critical, literature-based, tourism density and intensity indicators and the demarcation of the spatial pattern of tourism infrastructure. Based on this knowledge, the pressure exerted by tourism in the study area is grasped, while tourism hotspots are also identified, i.e. places marked as overloaded due to the excessive tourism accommodation infrastructure and the large seasonal tourist flows.
- Step 3 indulges into the vulnerability assessment of Rhodes Island against the CC and anthropogenic pressures and more specifically against flood and fire risk. Flood prone areas are identified by inspection of the Flood Risk Management Plan, Water District of Aegean Islands, conducted in accordance with the provisions of Directive 2007/60/EC. Then the factors contributing to fire risk in the specific area are explored and the relevant data set is established. This was used as input to the Random Forest algorithm through the Forest-Based Classification tool for assessing fire risk of the various spots of the study region. Results obtained were validated by comparing fire prone areas with those beat by past fire events.
- Step 4 attempts to merge spatially-related results emanating from Steps 2 and 3, in an effort to identify fire and flood prone areas in Rhodes Island and their relationship with the tourism hotspots. Inferences out of this step can feed relevant policy reaction, targeting the protection of both the natural/built environment and the population/visitors of the specific tourism hotspots.

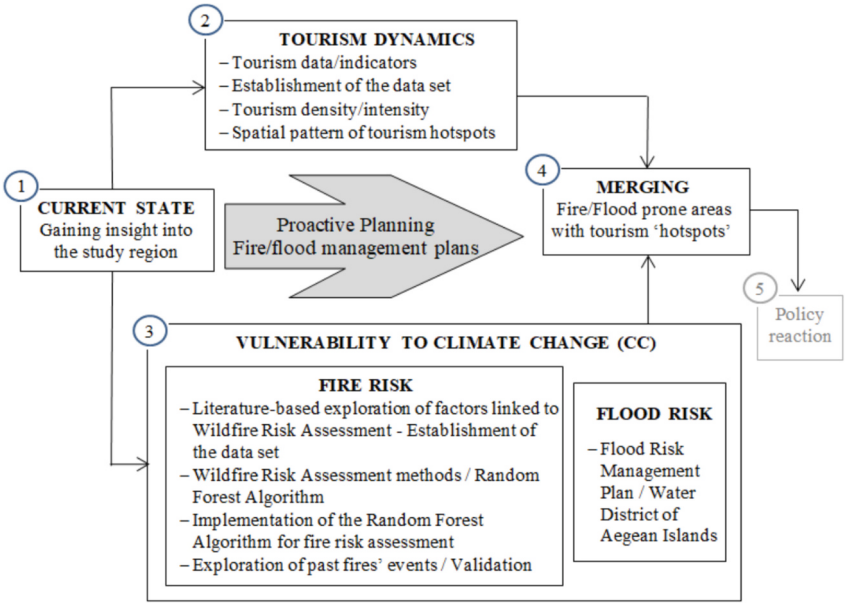

Fig. 1. Steps of the methodological approach. Source: Own elaboration.

2.2 Framing Tourism Pressure in Rhodes Island

The island of Rhodes displays a remarkable tourism and population dynamics, coupled with high rates of built-up expansion [15]. Large scale hotel accommodations prevail in the tourism infrastructure profile, manifesting a high concentration of beds and arrivals and resulting in a rising seasonal population density [16]. To analyse tourism pressure in this island, a set of literature-driven tourism density and intensity indicators was selected, which was meant to capture the key components of tourism supply (accommodation infrastructure). These indicators were calculated across three spatial scales, namely: Rhodes Island, the close neighbourhood of Dodecanese islands' complex, and the broader spatial context of the Region of Southern Aegean; enabling thus a comparative assessment of tourism pressure and unveiling the role of Rhodes as the tourism flagship of this Region. The selected indicators (Table 1) aimed to assess the pressure exerted by tourism accommodation infrastructure – both hotels and short-term rentals advertised on Airbnb – on the local population and the island's natural/cultural resources. The data sources used to compile and calculate these indicators are presented in Table 2.

Table 1. Selected Tourism Pressure Indicators TPI_i

Tourism Pressure Indicators - TPI	Description of Indicator (Calculations are based on 2024 data)
TPI1 – Tourism Accommodation Intensity	[Tourism Accommodation (Hotel and Airbnb beds) / Permanent Population (Residents)] ---- TPI1 features the pressure on population due to tourism accommodation infrastructure
TPI2 – Airbnb Accommodation Intensity	[Total Airbnb beds / Permanent Population (Residents)] ---- TPI2 highlights the pressure on population due to the Airbnb tourism supply
TPI3 – Tourism Accommodation Density	[Tourism Accommodation (hotel and Airbnb beds) / island's surface in km^2] ---- TPI3 features the pressure on its local resources due to tourism accommodation infrastructure
TPI4 – Airbnb Accommodation Density	[Total Airbnb beds / island's surface in km^2)] ---- TPI4 highlights the pressure on local resources due to the Airbnb tourism supply

Table 2. Data sources for Tourism Pressure Indicators

Type / Source of Data
Population: Data on permanent population is derived from the 2021 National Census of the Hellenic Statistical Authority (ELSTAT) / [17]
Hotel accommodation data: Data were derived from official records provided by the Hellenic Chamber of Hotels / [18]
Airbnb accommodation data: Data derived from the statistical processing and analysis of 2024 datasets published by the Institute of the Greek Tourism Confederation Intelligence (INSETE), with specific reference to the South Aegean Region / [19]
Land area: estimated through the Wikipedia / [20–22]

2.3 Framing Flood and Fire Risk Assessment

For grasping the *flood risk pattern* in Rhodes Island, the officially-delineated flood-prone zones are downloaded from the geoportal of the Greek Ministry of Environment and Energy [23]. Considering the rising CC-related risks, rendering mega-flood events more probable in the short term, the flood-prone zones have a return period of 1000 years (T = 1000) and are identified by inspection of the Flood Risk Management Plan, Water District of Aegean Islands, conducted in accordance with the provisions of Directive 2007/60/EC.

Speaking of the *fire risk assessment*, it is worth mentioning that state-of-the-art methodologies are gaining momentum in recent studies as they appear to be more reliable in assessing the risk and identifying the complexity of a research subject, such as

wildfire risk in the CC era [24, 25]. Due to their computing power, capability to handle large volumes of data and procedures' automation, state-of-the-art methodologies are increasingly replacing conventional ones, with the accuracy of their predictive outcomes becoming one of their strongest asset [24, 26]. In recent literature, a variety of fire-related research dimensions, such as fire susceptibility, fire risk, prediction of fire behaviour or fire occurrence are studied by means of advanced technologically-enabled tools, valuing also the geospatial predictive ability of those solutions [27]. That said, this work delves into the field of fire risk assessment by addressing relevant to the study region fire-risk related factors and variables; and using them as input to the Forest-Based Classification and Regression tool for assessing areas of Rhodes Island that are prone to fire risk.

The selection of fire risk assessment Factors – with *Topography*, *Climate*, *Environment* and *Urban Space* being the most commonly ones used in relevant studies – and related Variables constitutes a critical part of fire-related studies and is grounded in the particularities of the study region at hand. Of critical importance is also the comprehension of the interrelationships among those factors that is grasped through a thorough insight into the study area at hand. In fact, a well-rounded variables' selection process provides both crucial input on the area's particularities and information about the circumstances that can lead to fire occurrences [24]. In addition, a diverse variables' set is to the benefit of a holistic approach, allowing alternative choices for each single particular study area to occur [26, 28]. Furthermore, in the majority of fire-related studies, the selection of variables aims to cover all relevant factors, regardless of the emphasis on a specific research subject; while, a comprehensive list of variables largely contributes to the effective implementation of relevant methodologies and the production of trustworthy results [28]. The variables that are of relevance in fire-related studies are discussed by many researchers; while a literature-enabled analytical list of them is provided by Aksoy et al. [29]. The aforementioned fire risk assessment Factors are shortly discussed in the following paragraphs.

The factor *'Topography'* includes variables like 'Elevation', 'Slope' and 'Aspect', and features an area's morphology. These variables affect the progress of a forest fire event and the actions of firefighting forces [26]. More specifically: 'Elevation' is a decisive dimension of the prevailing meteorological conditions, largely affecting fire behaviour [30]; 'Slope's steepness plays a crucial role in the speed and spread of forest fire [30]; 'Aspect' is associated with the receiving sunlight and the probability of occurrence of a fire, rendering some of them – e.g., the south-southwest 'Aspects' in our study area – more susceptible, depending on the hemisphere [29].

The factor *'Climate'* is a crucial one in fire risk assessment since it directly relates to fire weather conditions; and has a remarkable impact on the progress of a fire event [31]. Extreme heat waves render 'Temperature' a crucial variable, affecting vegetation's flammability [32]. Temperature's combination with 'Precipitation' and 'Relative Humidity' variables is largely influencing vegetation and soil's moisture, thus defining fuel load and directly affecting fire ignition conditions [33]. Finally, 'Wind Speed' affects forest fire speed, therefore fire spreading, and is a major concern for fire suppression strategies [26, 30].

The factor *'Environment'* correlates with vegetation. This determines the fire risk of an area and the progress of a potential event. It includes variables that demarcate

the vegetation attributes, such as 'Dominant Leaf Type' [DLT], 'Tree Cover Density' [TCD] and 'Normalized Difference Vegetation Index' [NDVI]. The type of leaves and the density of the vegetation determine ignition proneness and fuel load availability [30]. These, in turn, are directly influencing firefighting strategies in order for efficient suppression to be attained. Furthermore, vegetation's health condition, being indicated through NDVI, is an equally important variable, delineating fuel availability and vegetation's fire susceptibility [32, 33].

The factor *'Urban Space'* is of great significance, since recent studies indicate human action as one of the main causes of fire ignition and an important part in an area's fire risk probability [34]. Variables such as 'Distance from the Road Network', 'Distance from Rivers' and 'Distance from Settlements' correlate with the proximity to human activities, rendering the nearest forested areas and the Wildland Urban Interfaces (WUIs) more susceptible to fire risk [30]. 'Population Distribution' and 'Land Use' are closely related as well, since dense populated areas near vulnerable ones and specific activities amplify the risk of fire ignition [26, 33].

Taking into consideration the particularities of the study area of this work, coupled with the heavy tourist load and vulnerability to CC impacts, 15 independent variables were selected as input to the fire risk assessment methodology (Table 3). Data selection for the 15 variables was based on availability, accessibility and usability in fire risk assessment methodologies, prioritizing the need for an up-to-date representation of the study area.

Table 3. Variables used as input in the implementation of the fire risk assessment methodology

Raw Data	Factor	Variable	Source	Time Span
Digital Elevation Model (DEM)	Topography	Elevation (m) Aspect (°) Slope (%)	Copernicus	-
Tree Cover Density (TCD)	Vegetation	TCD (%)	Copernicus	2023
Dominant Leaf Type (DLT)		DLT	Copernicus	2023
Normalized Difference Vegetation Index [NDVI]		NDVI	Copernicus	2024
Temperature Wind Speed Relative Humidity Precipitation	Climate	Temperature (° C) Wind Speed (m/s) Humidity (%) Precipitation (mm/y)	E-OBS, Copernicus	2000-2024 Fire Season (May – Oct)
Population	Urban Space	Population Distribution (Nr)	ELSTAT	2021
Settlements		Distance from Settlements (m)	ELSTAT	2021
CLCplus Backbone		Land Use	Copernicus	2023
Road Network		Distance from Road Network (m)	Geofabrik	2026
Hydrographic Network		Distance from Rivers (m)	Geofabrik	2026
Burned Areas	-	Fire/No Fire (Dependent Variable)	EFFIS, Copernicus	2000-2024

All necessary preprocessing procedures and modifications were conducted so that the emerging dataset to be appropriate for use as input to the Forest-Based Classification and Regression tool, which is incorporated in the Modeling Spatial Relationships toolset in ArcGIS Pro software [35]. This tool uses the supervised Machine Learning Random Forest algorithm, developed by Leo Breiman and Adele Cutler [36]; and is grounded in the construction of a model that creates a forest of decision trees, generated from a random subset of the training dataset. These decision trees are used for validating predictions of unknown values of the testing dataset, using the same set of independent variables. The final prediction is an aggregation derived from the entire forest, i.e. the predictions of each decision tree. For classification tasks, the outcome derives from majority voting, whereas for regression tasks this occurs from averaging. As to the performance of the Forest-Based Classification and Regression tool, a number of metrics are automatically derived from this tool, namely 'Accuracy', 'Recall' and 'F1 Score'. 'Accuracy' measures the overall predictive capability of the method; 'Recall' refers to its ability to correctly identify and predict actual positive instances; and 'F1 Score' serves as a balanced metric of the overall performance. Important advantages of the tool are its ability to provide predictions with a smaller set of independent variables, calculate variables' importance and reduce overfitting [35].

3 Implementation of the Methodological Framework - Results

3.1 The Study Region

The Island of Rhodes, located in the Region of Southern Aegean, Greece, is a well-known, highly attractive Mediterranean insular destination. Rhodes is the largest island of the Dodecanese Islands' Complex of this Region and a major administrative and tourism hub. It covers an area of 1401 km^2 and, according to the 2021 Census of the Hellenic Statistical Authority, owns a population of 125,113 inhabitants [17]. Population distribution displays a rather concentrated pattern in the north-eastern and northern coastal part (Fig. 2a).

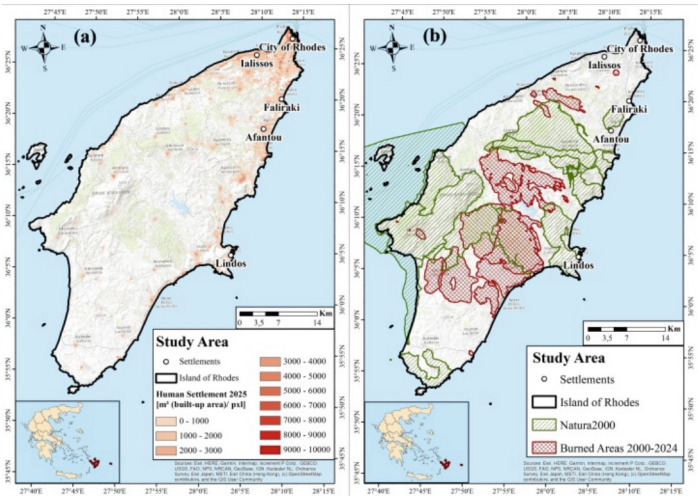

Fig. 2. Rhodes Island - (a) Human Settlement Layer, (b) Natura 2000 regions and Burned Areas in the time span 2000–2024. Source: Own elaboration based on the data from: (a) [37], (b) [38, 39].

Speaking of the island's morphology, Attavyros Mountain dominates in Rhodes landscape, followed by lower hills along with extended Natura 2000 protected areas (Fig. 2b). The island is actually displaying a topographical diversity that is coupled with an extensive urban sprawl, mainly in the coastal seaside. This is due to the population's growth and respective settlements' pattern as well as deployment of the rapidly escalating tourist accommodation infrastructure [15]; and results in expanded Wildland Urban Interfaces (WUIs), i.e. urban and peri-urban zones that are in close proximity to rough terrain morphology, extended across the island's coastal part. The rising seasonal population during summertime, a period coinciding with the fire season (May to October), coupled with the expanded WUIs raises vulnerability concerns and calls for assessment of relevant risks – fire and flood in this work – in order for proactive planning strategies and fire/flood management plans to be properly informed and resilience to such crises to be strengthened [26].

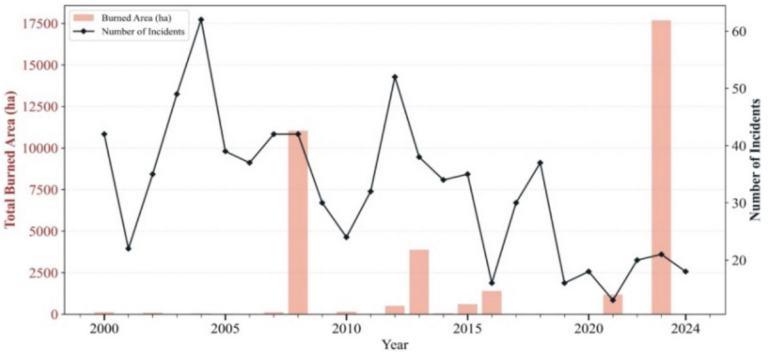

Fig. 3. Wildfire incidents and cumulative Burned Areas (ha) in Rhodes Island during the Fire Season (May – October) for the time span 2000–2024. Source: Own elaboration based on data from the Hellenic Fire Service [40].

Open data from the Hellenic Fire Service demonstrate the number of *fire incidents* occurred in Rhodes Island, coupled with the cumulative burned areas (in ha) throughout the last 24 years (2000–2024) (Fig. 3) [40]. Notably, the wildfire of July 2023 was the most devastating one, with severe consequences to forested areas (17,653 ha of burned areas) and noticeable failures in rapid and safe emergency evacuation of both residents and visitors [41]. Next to this destructive fire incident of 2023, in November 2024 the largest *flood phenomenon* in the island's history occurred, beating the northern coastal part of the island with a volume of water equivalent to three months falling in a few hours.

3.2 Sketching Tourism Pressure in Rhodes Island

The steadily expanding tourism supply in Rhodes Island demonstrates the dynamics of the sector. As authors' previous work featured [15], tourism supply during the last decade (2014–2023) displayed an increase of 8.32%, 16% and 20.36% in the number of hotels, rooms and beds respectively. Worth noticing was the rising of 5*, 4* and 3* hotels, reaching an increase of 105.9%, 35.51% and 13.53% respectively in this decade, while the 1* and 2* hotels displayed a certain downward trend (-10.41% and -14.03% respectively). A similar pattern was noticed in the number of hotel rooms, where 5* hotel rooms display an increase of 113.25%, 4* rooms are rather stabilized (+6.58%) and 3*, 2* and 1* hotel rooms demonstrate a remarkable decrease (–16.79%, –27.73% and –14.89% respectively). This tourism supply profile is in alignment with a mass, high class destination model, marked by large scale, luxurious and resource-intensive tourism accommodation infrastructure.

Results presented in Table 4 provide interesting insights into the pressure that tourism exerts in the island of Rhodes. More specifically, Rhodes displays a slightly higher tourism accommodation intensity (TPI1 = 1.12) compared to the Dodecanese average (1.10), while it remains lower than the regional average in Southern Aegean Region (1.35). Similarly, Airbnb accommodation intensity (TPI2 = 0.29) exceeds the Dodecanese average (0.26), yet remaining significantly below the regional level (0.62). These

findings suggest that in terms of visitors to population ratios, Rhodes experiences a moderately higher tourism pressure than the Dodecanese average, while not as intense as the broader regional context demonstrates. However, a different picture emerges when examining density indicators. Rhodes exhibits substantially higher tourism accommodation density (TPI3 = 99.20) compared to the average in both the Dodecanese complex (83.90) and the Southern Aegean Region (83.96). This indicates a strong spatial concentration of accommodation infrastructure (hotel and airbnb) in the island. A similar pattern is observed in Airbnb density (TPI4 = 25.69), which is higher than the average in Dodecanese complex (19.75), though still lower than the Southern Aegean Region's average (38.74).

Table 4. Tourism Pressure - Position of Rhodes in its broader neighbourhood

Tourism Pressure Indicator (TPI)	Rhodes Island (2024)	Dodecanese Islands' Complex (Average Value 2024)	Region of Southern Aegean (Average Value 2024)
TPI1 – Tourism Accommodation Intensity	1.12	1.10	1.35
TPI2 – Airbnb Accommodation Intensity	0.29	0.26	0.62
TPI3 – Tourism Accommodation Density	99.20	83.90	83.96
TPI4 – Airbnb Accommodation Density	25.69	19.75	38.74

Overall, the divergence between intensity and density indicators shows that tourism pressure in the island of Rhodes is not just a matter of the sector's size, but mainly of its spatial distribution. While intensity measures suggest a moderate pressure, density indicators reveal a strong geographical concentration of tourism accommodation infrastructure. This pattern intensifies localized pressure on land use, public infrastructure, and natural resources, particularly in coastal ecosystems. At the same time, the coexistence of hotel-based accommodation and the recently rapid growth of short-term rentals (Fig. 4a and 4b respectively) points to a dual tourism structure that may further reinforce spatial inequalities and intensify competition for land.

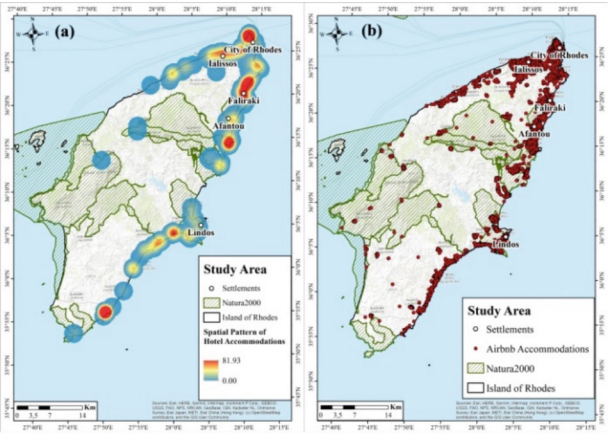

Fig. 4. Rhodes Island - Spatial pattern of: (a) Hotel accommodation, (b) Airbnb accommodation. Source: Own elaboration based on data from: (a) [42], (b) [43].

As a well-established mass tourism destination, the island of Rhodes hosts extensive tourism infrastructure, primarily concentrated along its coastline. A defining feature of the island is the strong presence and continuous expansion of 5* hotel developments, which represent a highly land-consuming form of tourism infrastructure, particularly in the already saturated coastal areas [15]. This pattern contributes to the formation of distinct *tourism hotspots* along the coastal part of the island (Fig. 4a and along the coastal part of the islandb), largely aligned with existing population distribution (Fig. 2a), while also expanding into environmentally sensitive land. As such can be mentioned the areas in the neighbourhood of Lindos, Afantou, Faliraki and Ialissos settlements as well as in the city of Rhodes. The spatial overlap between tourism constellations, Natura 2000 protected areas and other environmentally vulnerable zones (Fig. 4) questions sustainability and resilience achievements of Rhodes Island in the longer run. These patterns may further intensify the island's exposure to CC-related hazards, particularly wildfires and floods, as increasing land-use pressure and tourism-related infrastructure deployment place additional stress on natural systems and weaken local adaptive capacity.

3.3 Assessing Fire and Flood Risk

For assessing fire risk in the neighbourhood of the tourism hotspots of Rhodes Island, the Random Forest algorithm through the Forest-Based Classification tool was implemented. The dataset of the Burned Areas for the period 2000–2024 [39], provided by the European Forest Fire Information System (EFFIS) of the Copernicus Emergency Management Service (Copernicus EMS), was used to derive the fire occurrence points. These points were supplemented with non-fire points (unburned areas), establishing the binary dependent variable (Fire = 1; No Fire = 0) as training input for the implementation of the tool. The dataset was randomly separated into training (80%) and testing (20%) subsets. Table 5 presents the distribution of Importance Values of the 15 independent variables, as these were derived from the Forest-Based Classification and Regression tool.

Table 5. Importance values of the independent variables according to the Forest-Based Classification Tool

Variable	Importance Value (%)	Variable	Importance Value (%)
Humidity	8.59	Distance from Settlements	7.18
Precipitation	8.12	Temperature	7.00
NDVI	8.12	Distance from Rivers	6.18
Slope	7.82	Wind Speed	5.82
Population Distribution	7.70	Land Use	5.23
Aspect	7.53	TCD	3.18
Distance from Road Network	7.35	DLT	3.00
Elevation	7.18		

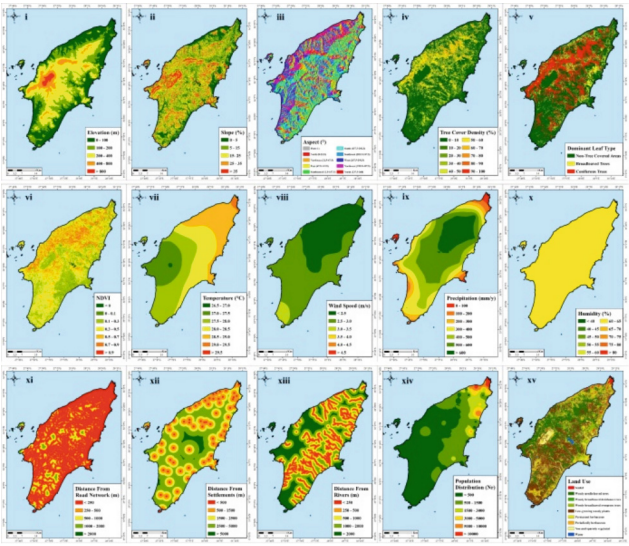

Fig. 5. Visualization of independent variables: i) Elevation, ii) Slope, iii) Aspect, iv) TCD, v) DLT, vi) NDVI, vii) Temperature, viii) Wind Speed, ix) Precipitation, x) Humidity, xi) Distance from Road Network, xii) Distance from Settlements, xiii) Distance from Rivers, xiv) Population Distribution, and xv) Land Use. Source: Own elaboration.

Visualization of all independent variables is presented in Fig. 5; while in Fig. 6 the probability of fire risk and its spatial pattern in the study area is displayed, i.e. the final output of the Forest- Based Classification tool. The fire risk assessment results are coupled with the (Fig. 6a to 6f respectively): Burned Areas for the time span of 2000–2024 [39]; Natura 2000 areas [44]; flood zones in Rhodes Island (T = 1000) [23]; settlements and population's distribution in 2021 [17]; distribution of Airbnb [43], and distribution of hotels [42]. ArcGIS Pro 3.3 was used for the implementation of the

Forest-Based Classification tool, the spatial analysis, the mapping of variables and the production of the final forest fire risk map (Fig. 6), displaying fire risk probability values that ranges from 0.00 to 0.87.

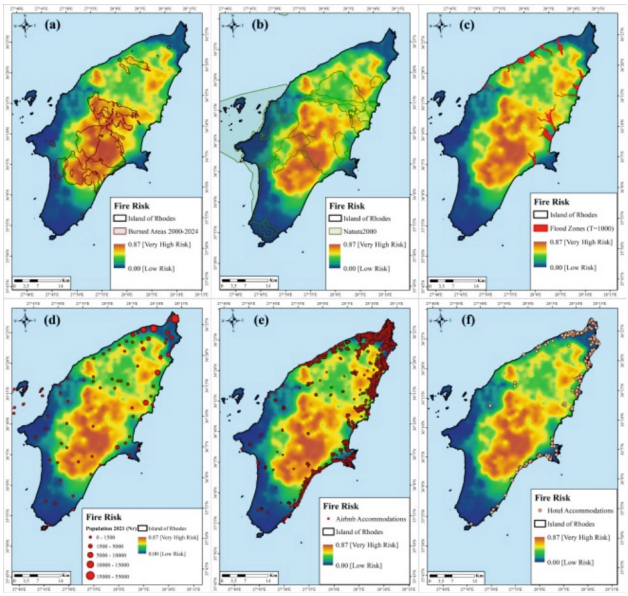

Fig. 6. Forest Fire Risk Assessment maps overlaid by: a) Burned Areas (2000–2024), b) Natura 2000, c) Flood Zones (T = 1000), d) Settlements and Population Distribution in 2021, e) Airbnb Accommodation and f) Hotel Accommodation. Source: Own elaboration based on data from: a) [39], b) [44], c) [23], d) [17], e) [43] and f) [42].

The *spatial pattern* of fire risk unveils very high fire risk values (brown colour) in the central part of the island, with a more pronounced occurrence in the mountainous areas, as well as the eastern and western coastal areas of the northern part of Rhodes Island. High fire risk values (yellow colour) appear in the perimeter of very high risk areas, followed by moderate fire risk values (green colour). These are relatively extended to the northern central area. Low fire risk values (blue colour) are mostly found to the northern and southern part, along with a part of the western coastal area.

According to the automatically derived evaluation metrics, results obtained present high consistency and predictive performance. During the training stage, the tool has displayed a high overall performance with a score of 0.98 to all three metrics (Accuracy, Recall, and F1 Score); while during the validation stage, these metrics demonstrated a more conservative yet successful predictive performance, with scores of 0.78 for Accuracy, 0.76 for Recall and 0.74 for F1 score.

Flood prone zones are presented along with fire risk spatial pattern in Fig. 6c. Flood prone areas seem to expand across the coastal part of the island, especially in the north-eastern and north-western coastline; and align with moderate to very high fire risk areas.

Taking into account that tourism hotspot areas are located at this intersection, this fact render them susceptible to combined fire- and flood-related risks.

4 Discussion and Conclusions

CC repercussions in the Mediterranean, particularly in coastal and insular tourist areas, lie today at the heart of the planning and policy discourse [10]. However, the lack of integration – in a concrete and spatially-defined way – of CC-related risks into urban/regional as well as disaster management planning discourse is noticeable. Exploration of the intensity and spatial reference of CC-driven risks, including the anthropogenic ones, seems to be a prerequisite for handling, in a proactive manner, destructive incidents and targeting sustainability and resilience objectives. This seems to be quite crucial in the Mediterranean area, i.e. an area which is featured, among others, as a combined *CC and tourism 'hotspot'* [45], with the repercussions in terms of damages in the natural and built environment as well as human losses being incalculable.

Having this in mind, this work established a methodological framework that is replicable to insular or mainland-based coastal areas; and attempts to identify/map tourism hotspots as well as address their exposure to mainly CC-driven but also anthropogenic fire and/or flood risks. The proposed methodology is implemented in Rhodes Island, Greece, a well-known and highly attractive Mediterranean insular destination. However, the modular structure of this methodology allows tourism-pressure indicators, fire-risk modelling variables, and flood-exposure layers to be adapted to data availability, planning context, hazard profile, and territorial characteristics of other destinations as well, ensuring thus its replicability. The targeted outcome of this methodology is the assessment of flood/fire threats ahead in overloaded tourist areas for informing planning endeavours and guiding more targeted policy decisions that mainly address resilience of tourism hotspots.

The effort to identify tourism hotspots in Rhodes Island is partly grounded in previous authors' work [15] and is based on well-established, literature-driven tourism density and intensity indicators as well as the spatial analysis of accommodation infrastructure – i.e. the tourism supply. The outcome of this stage unveils a highly concentrated pattern of tourism accommodation, expanding in the island's north-eastern and north-western coastal part and marked by a number of tourism hotspots, being the City of Rhodes and the settlements of Lindos, Afantou, Faliraki, and Ialissos (Fig. 4a and 4b).

Speaking of the fire risk assessment, being the core subject of this research for stepping further previous work, a well-round approach is established, displaying high predictive overall performance. Indeed, all three evaluation metrics exhibited a differentiation between the training and the validation stage, with validation performance being more rigorous and the noticed differentiation suggesting overfitting. As to the limitations of the proposed approach, the small size of the study area and the limited size of the dataset can be mentioned. Indeed, the high dimensional complexity of the research subject requires larger volumes of data and of higher quality in order for complex patterns and the interrelationships among contributing factors to be identified and more robust estimations to be produced, both influencing generalization and making it a challenging task. Accuracy performance (0.98/0.78) demonstrates a robust overall predictive capability, whereas values of F1-score (0.98/0.74) and Recall (0.98/0.76) indicate that the

proposed tool is capable of identifying fire prone and non-fire prone areas; and adequately capturing the complex patterns of fire occurrence. The spatial pattern of the predicted Forest Fire Risk (Fig. 6), demonstrates fire risk probability values ranging from 0.00 to 0.87.

By overlaying Burned Areas for the time span of 2000–2024, Natura 2000 areas, flood zones (T = 1000), the distribution of settlements and Rhodes' population in 2021, and the distribution of Airbnb and hotel accommodation onto the fire risk assessment map, certain interesting results are noticed. In particular, very high fire risk appears to be more prominent in the central mountainous part of the island, indicating strong compliance with burned areas of the past (Fig. 6a), and extending to the northern part of the island. Moreover, Natura 2000 protected areas (Fig. 6b) span on the central and upper central part of the island and the eastern coastline, aligning with fire risk areas ranging from low to very high values, rendering them areas of high risk due to their particularity and indicating the necessity for their steady monitoring for serving conservation purposes.

As far as the Flood Zones are concerned, these extend across the northern half part of the island, expanding towards both the western and eastern seaside (Fig. 6c). In the vicinity of the areas under flood risk are expanding the tourism hotspots of the island, e.g. Lindos, Afantou, Faliraki and Ialissos. Worth noticing is the fact that the aforementioned tourism hotspots lie in coastal parts of the island, where flood risk coincides with moderate to high fire risk (Fig. 6e and 6f); while the same holds for the majority of the island's settlements (Fig. 6d). Thus it seems that tourism hotspots, mostly coinciding with overpopulated settlements, are confronted with a *compound flood and fire risk*. Such a risk is expected to further intensify due to the rising climatic threats, the lack of well-established risk management plans as well as the continuously expanding and poorly planned urban sprawl, contributing to the enlargement of Wildland Urban Interfaces. That said, the spatial pattern of fire and flood risk, coupled with the developmental model of Rhodes Island that is grounded in mass tourism, indicates the aggravating exposure and vulnerability of the coastal zone. Provided that Rhodes Island is one of the most visited Mediterranean landscapes, proactive policies that are capable of managing CC and anthropogenic risks and maintaining the island's identity and integrity are of imperative need.

Such policy directions are further justified by recent climate change (CC) trends and projections, which stress the importance of developing climate-resilient urban and regional development pathways, particularly in the Mediterranean as a hotspot in multiple respects, including tourism and CC [45]. Contemporary spatial analysis approaches, tools, and technologies can produce more concrete and well-documented risk assessments, supporting targeted, place-based, and risk-sensitive spatial policies. Especially in the highly sensitive coastal land, hosting a variety of anthropogenic activities as well as valuable and vulnerable ecosystems, met also in the study area of this work, urban sprawl and further expansion of tourism zones should be limited, redirected, or being subject to stricter resilience standards, while more sustainable tourism modes should be sought. Such a direction is also supported by the IUCN [1], which calls for a fundamental shift in Mediterranean tourism from a growth-oriented paradigm towards one that is regenerative, inclusive and climate-resilient.

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Towards Smart and Sustainable Management of Construction and Demolition Waste in Island Communities

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Abstract. Construction and Demolition Waste (C&DW) represents one of the largest waste streams in the European Union and poses specific challenges in disadvantaged regions, such as islands, where logistical constraints, inadequate infrastructure, and high transportation costs hinder the transition to circularity. The transition to sustainability in the construction industry requires integrated and efficient C&DW management strategies, based on pre-demolition audits, selective demolition, traceability, recycling, and digitalization. This paper presents the results of a survey conducted among Italian and French construction companies to assess operational practices, perceived barriers, and opportunities for improving C&DW management in both continental and island regions. The analysis compares the Italian and French contexts, reserving a specific focus on the differences between islands and coastal continental territories, identifying recurring issues such as costs, transportation, documentation complexity, treatment and recycling constraints, and emerging trends such as digitalization, selective practices, and interest in recycled materials. The results are critically analyzed and discussed, and recommendations are proposed to support smart, resilient, and circular management of C&DW, particularly in the most disadvantaged areas such as islands.

Keywords: Construction and Demolition Waste · Circular Economy · Waste Management · Cross-border Cooperation

1 Introduction

Construction and Demolition Waste (C&DW) constitutes approximately 30–40% of global waste generation and represents one of the most significant solid waste streams globally. In the European Union (EU) alone, annual production reaches hundreds of millions of tonnes, with recent estimates ranging around 800 million tonnes per year. Beyond volume, C&DW management is inherently complex due to its heterogeneity, the need for selective demolition, and stringent regulatory requirements [1, 2].

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In this context, island communities face additional structural challenges, such as limited land availability, geographic isolation, low economies of scale, dependence on external infrastructure, and high waste transportation and treatment costs. These constraints make C&DW management particularly challenging in island communities, resulting in islands being disproportionately affected by waste accumulation, scarcity of treatment facilities, and environmental vulnerabilities. However, island contexts can be at the forefront of circular innovation, if supported by appropriate governance frameworks [3–6].

Within this framework, the Interreg Italy-France Maritime Programme promotes cooperation between coastal and island regions to strengthen environmental sustainability, competitiveness and resource efficiency. The IMPACT+ project [7] specifically addresses the challenge of improving C&DW management through benchmarking and mapping of C&DW treatment facilities in the cross-border area, the development of innovative solutions, training activities and pilot actions for companies in the sector.

This paper analytically and critically illustrates the results of a cross-border survey aimed at understanding practices, challenges and opportunities at construction company level in C&DW management, with particular attention to the comparison between island and continental territories of the Italy-France maritime area, following the principles of Smart and Sustainable Island Communities (SSIC).

2 Background and Related Work

C&DW management has become a key research topic in sustainability and circular economy studies, especially in regions where material flows, logistical constraints, and infrastructure limitations converge, amplifying systemic inefficiencies. C&DW currently accounts for approximately one-third of global waste generation, posing both environmental and economic challenges for the construction sector. Despite growing political and scientific attention, the sector still lacks unified frameworks for implementing circularity, reliable traceability tools, and standardized decision-making support systems. Indeed, although recycling, selective demolition, and material reuse are recognized as key elements of circularity, their effective adoption remains uneven, hampered by regulatory fragmentation, limited technical capacity, and insufficient infrastructure in many regions [1, 8–11].

When examining island and coastal territories, these structural constraints tend to intensify, as geographic isolation, transport dependence, land scarcity, and reduced economies of scale make C&DW management an inherently fragile field [3–6, 8]. Waste flows often accumulate in contexts lacking adequate treatment infrastructure, resulting in increased environmental pressures and greater vulnerability. In such contexts, sustainable waste management strategies must integrate logistical optimization, decentralized pre-treatment solutions, and governance models adapted to small-scale and resource-constrained systems. Islands that adopt community-based or collaborative models tend to achieve more resilient outcomes, combining social engagement with operational improvements [12–15].

In the EU context, the push towards circularity is supported by a variety of cross-border and regional initiatives, many of which have produced highly relevant methodologies and tools for C&DW management. For example, the CIRCULA project focuses

on strengthening skills to support circular economy models and the exchange of good practices for companies in the Mediterranean sustainable construction supply chain [16]. The CHARM (Circular Housing Asset Renovation & Management) project aims to optimise (re)use of material and natural resources and to demonstrate innovative approaches for housing renovation and asset management that prevent downcycling [17]. The CONDEREFF (Construction & demolition waste management policies for improved resource efficiency) project aims to exchange experiences and practices on how to move forward from existing procedures on C&DW management towards the adoption and further exploitation of the best practices and measures applied in the field [18]. The MED 3R (Euro-Mediterranean Strategic Platform for Adapted Waste Management) project proposes to strengthen coordination and cooperation between territories and the different groups of actors involved in the waste cycle to develop integrated waste management systems that are effective, intelligent, virtuous and adapted to local contexts [19]. The PORT 5R (For a sustainable management of waste in Mediterranean ports) project has adopted the 5R strategy: Reduction, Reuse, Recycling, Collection, Recovery and has provided for the definition of guidelines for the development of a joint plan for the prevention, reduction and disposal of waste in port areas [20]. In Sardinia, the MEISAR project (Materials for Sustainable Building and Infrastructure - Recycled Aggregates) addresses the issue of overexploitation of land related to the extraction of building materials and intends to promote, through participatory and applied research, the use of recycled materials for the construction of structures and infrastructure [21].

Even from these research and project contexts, a recurring theme emerges: circularity in construction cannot advance without a solid understanding of current practices, obstacles, and levels of preparedness within the construction sector. This is particularly true in island and coastal areas, where the interaction between geographic constraints, infrastructure, and economic structures requires context-sensitive solutions, also guided by empirical and specific assessments tailored to the specific territory. The research presented in this article addresses precisely this still lacking framework, providing insights into how construction companies operate and manage C&DW, and the specific obstacles and opportunities that exist in both the island and continental regions of the Italy-France maritime space. Thus, the study contributes new empirical evidence to a field where robust, geographically specific data remain limited, despite strong community interest in the circular economy, sustainability, and island's smart governance.

3 Materials and Methods

The methodological approach of this study combines a survey conducted through a questionnaire administered to construction companies in the Italian-French cross-border area, the harmonization of qualitative and quantitative data derived from the responses, and a comparative analysis to capture the operational realities of C&DW management.

The research starts from the IMPACT+ (Innovation in the selective management of building waste towards the activation of circular economy processes in order to reduce energy consumption and minimize CO_2 emissions) project [7], developed within the Interreg Italy-France Maritime Programme, which aims to improve the management of C&DW in coastal and insular areas, involving the cross-border regions of Var and the

Maritime Alps, Corsica, coastal Tuscany, Liguria, and Sardinia. It addresses common territorial issues, particularly acute in Sardinia and Corsica, where geographic isolation and limited treatment capacity exacerbate C&DW-related pressures. The project adopts a participatory and practice-oriented methodology, directly involving companies and enterprises active in the construction sector in identifying operational needs, jointly developing technical tools, and testing innovative solutions on pilot construction sites. It is structured in three integrated phases: i) territorial analysis and tool development; ii) experimental activities on selected pilot sites and construction sites; iii) cross-border consolidation through shared models and guidelines. The project's cross-border partnership, combining institutional, technical, and academic expertise, ensures that the solutions are scientifically sound and operationally relevant. The goal of the research is to integrate circular economy principles into routine construction practices and strengthen the sector's capacity to manage C&DW sustainably even after the project's conclusion.

In particular, the research illustrated in the paper is the result of collaboration during the first phase of the project between the Universities of Cagliari and Genoa, the two research institutions belonging to the IMPACT+ project partnership.

The survey was designed to collect consistent information from companies operating in different regulatory, territorial, and organizational contexts. To ensure comparability while respecting national specificities, two parallel questionnaires were developed, one in Italian and one in French, using a fully aligned structure, obtaining 21 responses from Italian companies and 17 from French companies. Both instruments explore the same thematic areas.

The questionnaire is structured around seven coherent thematic areas:

1. Company Identification Data

This section, designed to contextualize the sector landscape in the cross-border area, concerns the company identification and its operational characteristics, such as geographic location, number of employees, number of active construction sites, and turnover.

2. Operational Profile

This section, designed to gather information on company characteristics that could influence the production and management of C&DW, concerns the nature of its activities, including the predominant sector (e.g., residential construction, commercial construction, industrial works, or artisanal services) and the type of customer.

3. Regulatory Compliance and Planning

This section, designed to understand companies' perceptions of the regulatory framework, explores the adoption of waste pre-sorting practices, as well as the level of internal structuring of waste management procedures, through systematic protocols, dedicated storage areas, or other organizational arrangements.

4. Operational Waste Management

This section, aimed at understanding the operational aspects associated with C&DW management, assesses the types and volumes of waste produced based on the European Waste Code List [22] for the C&D stream, allowing companies to identify the categories

most frequently generated on their construction sites and estimate the annual quantity of C&DW produced. This section also explores the economic dimension of C&DW management by estimating annual management costs, identifying the cost components with the greatest impact, and identifying any strategies implemented by companies to reduce disposal costs.

5. Human Resources and Critical Issues

This section explores the type and quantity of human resources, such as environmental managers, on-site sorting personnel, drivers, and administrative staff, employed by companies in C&DW management. The section also identifies any critical issues encountered, including problems with on-site sorting, limited availability of treatment facilities, high transportation costs, bureaucratic burdens, or uncertainty regarding regulatory updates.

6. Treatment and Disposal

This section, designed to examine companies' relationships with external stakeholders and the decision-making processes related to the selection of C&DW treatment facilities, identifies the criteria used in selecting landfills/disposal centers, including distance, cost, type of waste accepted, opening hours, and the need for specific documentation. It also identifies difficulties encountered in managing mandatory documentation, such as C&DW identification forms or traceability records.

7. Circular Economy Practices

This section identifies the use of recycled materials, the promotion of circular economy practices in construction projects, and the perceived added value of sustainable C&DW management in terms of enhancing corporate image or opening up new market opportunities.

The survey responses were harmonized through a process designed to ensure comparability across countries and thematic areas: categories were standardized, qualitative responses were coded thematically, and cross-border taxonomies, such as C&DW type and cost category, were aligned (Fig. 1). The resulting dataset was used to develop descriptive statistics and comparative analyses between Italian and French companies, and between island territories (Sardinia and Corsica) and mainland territories (Var and the Maritime Alps, coastal Tuscany, Liguria).

It is worth emphasizing that the purpose of this paper is not to draw generalizable statistical inferences, but rather to use the survey conducted on C&DW management as an exploratory and diagnostic tool useful for providing context-specific empirical evidence, given the structural heterogeneity of the analyzed territories, particularly the island ones, and the absence of consolidated datasets on the topic at the construction company level.

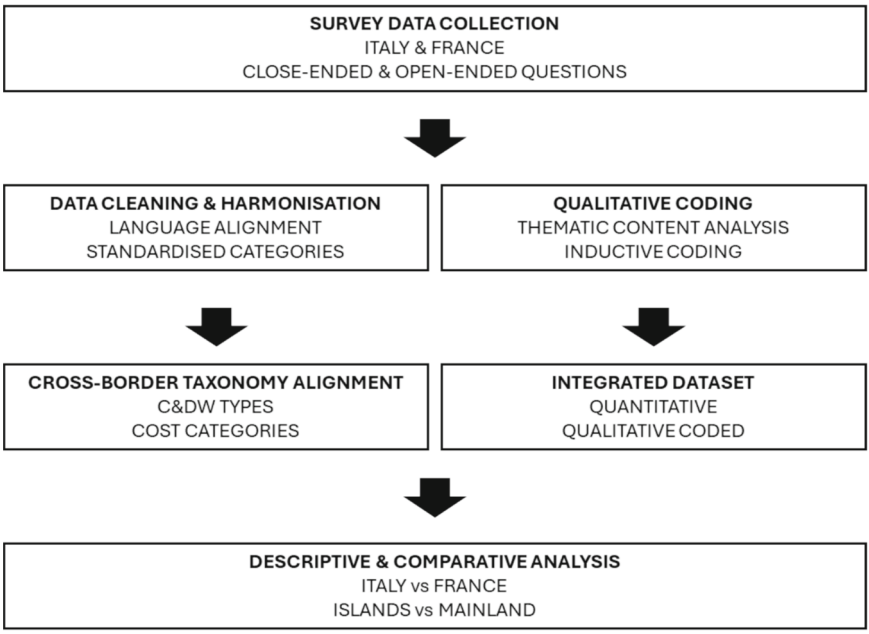

Fig. 1. Flowchart of the methodology for processing and analyzing questionnaire responses.

4 Results

Based on the methodological approach described above, the results summarize quantitative indicators, such as annual waste volume, cost typologies, adoption of pre-demolition audits, use of recycled materials, and qualitative data relating to organizational practices, operational obstacles, and regulatory constraints. The analysis aims to provide a coherent overview of current C&DW management practices in the considered area, highlighting both converging trends and territorially specific patterns, with particular attention to the different conditions observed in island versus continental contexts. Figure 2 shows the territorial distribution of the companies that participated in the survey.

The survey results first reveal a certain degree of diversification among both Italian and French companies in terms of staff, turnover, number and size of construction sites managed, and predominant operating sector, which is reflected in the varying approaches to managing C&DW. However, overall, the predominance of small firms emerges, primarily operating in the residential construction sector.

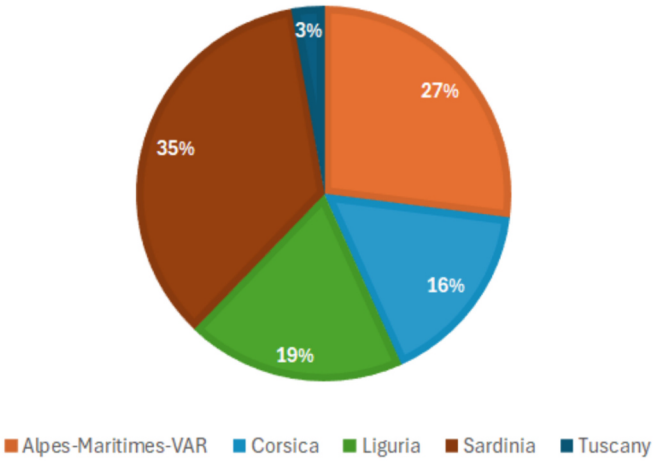

Fig. 2. Territorial distribution of the participants in the survey.

The prevalence of small/medium-sized enterprises is also confirmed by the analysis of the annual volume of C&DW generated, which stands at less than 50 tons for both Italian and French companies (Fig. 3).

It should be noted, however, that the results of this survey are influenced by the fact that almost half of the companies interviewed were unable to estimate their annual volume of C&DW produced. This result is probably due to the fact that C&DW management processes are often not structured in an organised way, so some data are not acquired in a systematic way by the companies themselves.

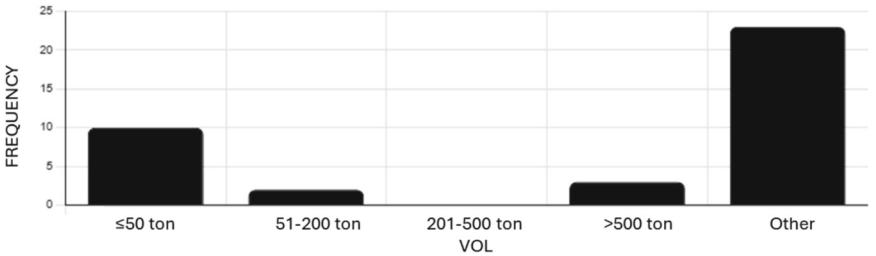

Fig. 3. Annual C&DW volume. "Other" includes non-quantifiable responses such as "unable to estimate", incomplete or invalid entries, and values that could not be classified within the predefined volume ranges.

Regarding the financial costs associated with C&DW management, the results show that the majority of Italian and French companies report costs below €15,000 per year, with the exception of a few companies managing multiple construction sites, which report significantly higher costs. The most significant cost factors are transportation, landfill disposal, and recycling operations (Fig. 4).

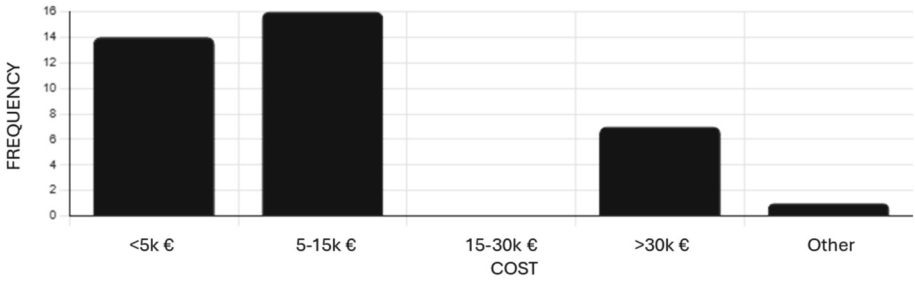

Fig. 4. Annual waste management costs

Regarding planning procedures, the adoption of pre-demolition audits, essential for selective demolition, appears to be somewhat heterogeneous (Fig. 5), consistently more widely adopted by French companies than by Italian ones, due to the aforementioned different regulatory framework.

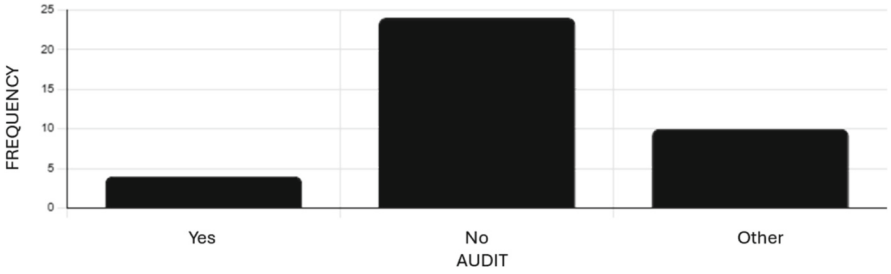

Fig. 5. Pre-demolition audits. "Other" includes responses such as "only for certain projects", partial or ambiguous answers, and entries that could not be classified unequivocally as "Yes" or "No"

Regarding the use of recycled materials, it is interesting to note that this is an emerging practice, albeit still in a heterogeneous and unstructured manner (Fig. 6).

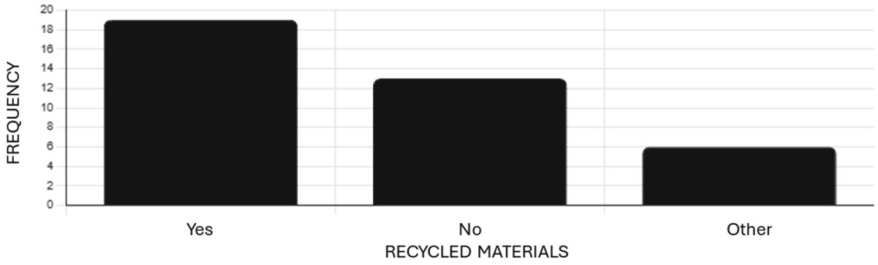

Fig. 6. Use of recycled materials. "Other" includes ambiguous, incomplete or non-standard responses that could not be classified as "Yes", "No".

Indeed, it is noted that several companies still use these materials only occasionally, influenced by the current limited availability, associated costs, and concerns about their technical performance. Distance from the construction site, the types of waste accepted and their associated costs, as well as the logistical and infrastructural constraints, particularly in the island regions of Sardinia and Corsica, influence the choice of treatment and recovery facilities.

Regarding documental aspects associated with C&DW management procedures, the survey highlights difficulties in acquiring mandatory traceability registers or waste identification forms, resulting in delays in management operations and exposing companies to the risk of non-compliance. These difficulties may be linked to the internal organization of companies, which appears to vary significantly (Fig. 7), as some companies adopt structured procedures, including dedicated storage spaces and codified internal protocols, while others rely on informal practices.

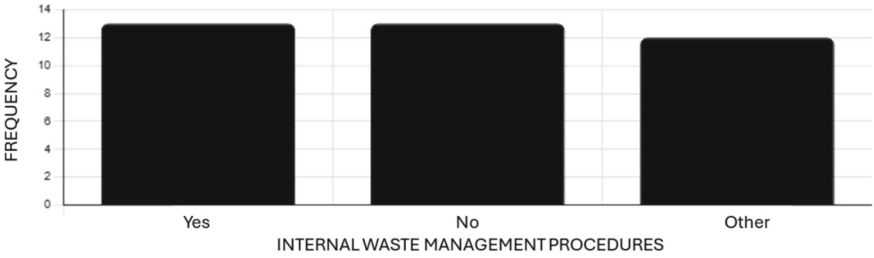

Fig. 7. Internal waste management procedures. "Other" includes responses such as "currently under development", "applied only to certain construction sites", unclear or incomplete answers, and cases where no response was provided.

Finally, the analysis of responses regarding perceived critical issues confirmed several recurring obstacles, including problems related to on-site C&DW sorting, limited availability of treatment and recovery facilities, high transportation and disposal costs, lack of adequately trained personnel, regulatory uncertainty, and concerns about the quality of recycled materials (Fig. 8). These findings highlight the structural and organizational constraints that hinder the full adoption of circular economy practices.

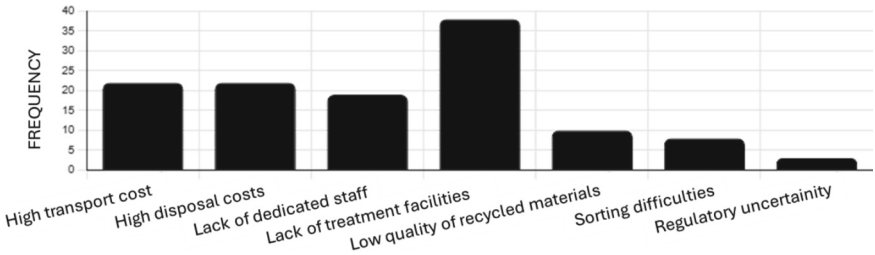

Fig. 8. Recurring themes in operational difficulties

5 Comparative Analyses

5.1 Italy vs France

The comparison between Italian and French companies highlights some distinctions, primarily arising from differences in national regulatory frameworks, but also from the level of organizational maturity and the characteristics of the local construction market.

French companies are generally characterized by a more advanced level of systematization of C&DW management procedures, primarily due to the long-standing enforcement of management practices that are not yet mandatory in Italy. These practices encourage pre-demolition audits, selective demolition, and the adoption of clear and codified internal protocols. Italian companies are a more diverse group, as some, especially those operating in large urban centers, often report adopting structured internal protocols, while many others rely on informal or experience-based approaches, often dependent on the nature of the project or the client's needs (Fig. 9).

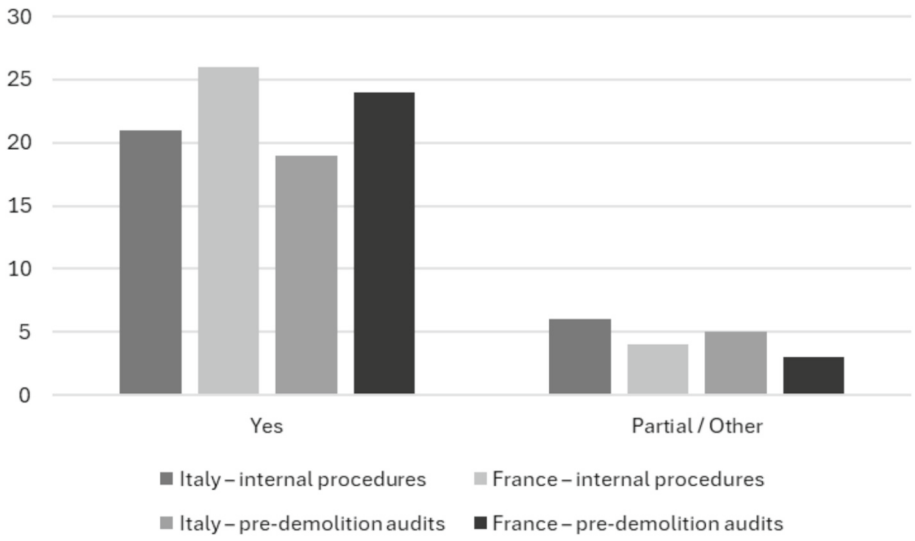

Fig. 9. Organizing of C&DW management practices. Italy vs France.

Some differences also emerge with regard to perceived critical issues. Italian companies point to economic pressures, particularly transportation and disposal costs, often amplified by territorial fragmentation and limited local treatment capacity. French companies, while reporting similar challenges, emphasize the importance of organizational and quality aspects of supply chain management, likely due to the greater integration of C&DW management into workflows (Fig. 10).

Despite these differences, both regions share a growing awareness of the principles of circular and sustainable construction and recognize the potential value generated by improved C&DW management practices.

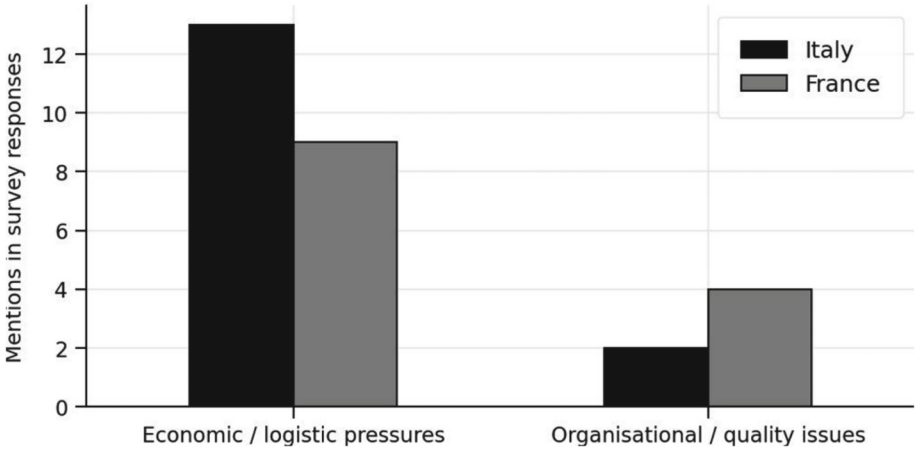

Fig. 10. Perceived critical issues in C&DW management. Italy vs France.

5.2 Islands vs Mainland

The comparison between island and mainland territories highlights the structural impact of geographic characteristics on C&DW management. Indeed, companies operating in Sardinia and Corsica face significantly more stringent and impactful constraints, limitations, and critical issues than companies operating in the mainland regions of Var and Maritime Alps, coastal Tuscany, and Liguria (Fig. 11).

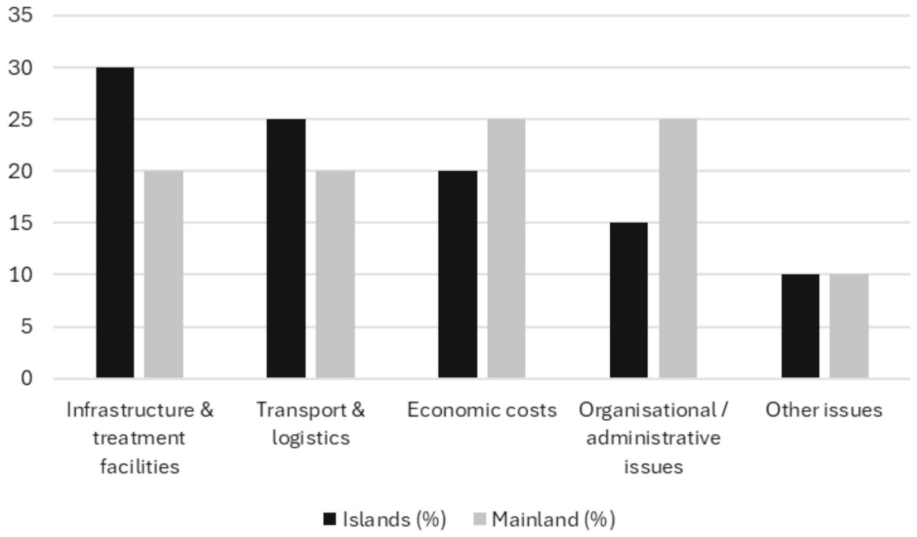

Fig. 11. Perceived critical issues in C&DW management. Islands vs Mainland.

A very significant island challenge is due to the limited availability of authorized treatment facilities and their sparse distribution across the territory, which forces companies to take longer transportation routes and rely on a smaller number of suppliers, resulting in higher costs and operational delays. This constraint also significantly impacts the management of selective demolition and temporary storage of C&DW, which also become critical phases in the management chain.

Mainland companies, while not exempt from regulatory, administrative, and logistical challenges, can benefit from denser infrastructure networks, greater accessibility and diversification of recycling treatment facilities, and more generally from a more stable operating environment less affected by transportation constraints or seasonal variability.

Overall, although companies in both territories share common obstacles, island ones face a combination of geographic isolation, limited infrastructure, and higher logistics costs, highlighting the need for specific strategies and cross-border coordination to mitigate structural disparities.

6 Discussion

The results derived from the questionnaire administered to construction companies in the Italy-France maritime cross-border area provide a comprehensive overview of C&DW management, highlighting the structural characteristics of the sector and the main critical issues perceived by respondents.

It is worth emphasizing that the constraints on more sustainable C&DW management revealed by the analysis of the questionnaire results confirm generally expected trends. In this context, this study aims to provide a structural interpretation of these constraints through a territorially differentiated perspective, rather than identifying new barriers. This helps to construct a specific framework of critical issues and opportunities in the analyzed territories and gather evidence for planning corrective actions.

To this end, a comparison was conducted between the island and mainland contexts in the two national regions of Italy and France. This comparison highlights not only the presence and typology of the issues, but also their configuration, concentration, and operational relevance, which differ depending on geography and governance characteristics. This analysis thus stimulates reflection on the strategies needed to guide the sector toward more sustainable C&DW management.

It is also important to note that the survey conducted through the questionnaire is intended to provide the basic knowledge necessary to effectively design and implement, in a targeted and geographically differentiated manner, the subsequent analytical phases envisaged in the IMPACT+ project, including on-site assessments and material flow analysis (MFA). At this stage, it was decided not to conduct MFA because the objective of the study is to preliminary identify and characterize the barriers, obstacles, and organizational, regulatory, and territorial constraints that influence the sustainable management of C&DW, rather than quantifying physical waste flows.

The key aspects emerging from the analysis of the results fall primarily into two categories: the role of the regulatory framework and the influence of the geographical context.

Regarding the regulatory framework, it emerges that the more consolidated regulatory framework in France favors the adoption of planned procedures, pre-demolition

analyses, and selective demolition by companies. In Italy, on the contrary, companies operate within a more complex and evolving regulatory framework, which includes the recent introduction of mandatory elements, such as digital traceability, that have not yet been fully assimilated by the sector.

These differences powerfully underscore the need for a stable and harmonized regulatory framework, including across borders. They suggest the opportunity for both cross-border knowledge and best practices exchange and for implementing training activities for sector operators to facilitate the transition to greater sustainability in C&DW management.

Regarding the influence of geographic context, the data highlights the disadvantages faced by the island territories of Sardinia and Corsica. In these regions, C&DW management is heavily impacted, especially by infrastructural constraints on mobility and accessibility, and by a limited supply of treatment and recycling services. This results in a general increase in management costs and a hindrance to the implementation of virtuous recycling practices. This situation highlights the need to study and plan specific C&DW management improvements, appropriately tailored to the geographical and structural characteristics of the most disadvantaged territories.

It is worth emphasizing, however, that despite the critical issues highlighted, companies still recognize the potential environmental, economic, and reputational benefits associated with more sustainable management of the C&DW supply chain. This demonstrates the presence of fertile ground for innovation, which should be embraced but also accompanied by streamlining documentation procedures and training for operators, who still have uncertain perceptions of the quality of recycled materials.

The concept of smart C&DW management fits into this framework, and is understood here as companies' organizational and procedural readiness for digitalization. This readiness, interpreted as an essential prerequisite for the smart governance of the C&DW management process, is captured by indicators such as the degree of internal structuring of companies, the adoption of traceability practices, including mandatory digital tools, and planning and compliance capabilities (e.g., pre-demolition audits).

Overall, therefore, the survey results suggest that the transition to more sustainable C&DW management in the cross-border area analyzed should be an organic and systemic process, harmoniously involving regulation, infrastructure, training and awareness-raising, and organizational capacity, positively impacting the resolution of the main structural constraints in the most disadvantaged areas.

7 Conclusions and Future Work

This paper critically illustrates the results of a questionnaire on the perception of the current state of the art regarding C&DW management, administered to 38 construction companies operating in the Var and Maritime Alps, Corsica, coastal Tuscany, Liguria, and Sardinia regions of the Italian-French cross-border area.

The questionnaire compares both the national situation in the two countries considered and the regional situation, focusing particularly on the differences between continental coastal regions and island regions (Sardinia and Corsica), placing island territories at the center of the analysis as structurally disadvantaged contexts.

The survey explores seven aspects related to how companies approach C&DW management, including:

- Regulatory Compliance and Planning
- Operational Waste Management
- Treatment and Disposal
- Circular Economy Practices
- Human Resources and Critical Issues.

The limited and heterogeneous sample size and reliance on self-reported data preclude statistical generalizations, which, however, are not the objective of this study. The study adopts an exploratory and diagnostic approach, aiming to provide a useful tool for providing context-specific empirical evidence, given the structural heterogeneity of the analyzed territories, particularly the island ones, and the lack of consolidated datasets on the topic at the construction company level.

The survey results identify several barriers to more sustainable C&DW management, including:

- high transportation costs
- limited availability of treatment facilities
- regulatory complexity
- organizational weaknesses within companies.

In this context, the main contribution of the paper is to provide a structural interpretation of these constraints through a territorially differentiated perspective. This interpretation highlights that in the island regions of Sardinia and Corsica, critical issues are concentrated and pervasive, affecting multiple stages of the C&DW management chain. In coastal continental regions, similar challenges are mitigated by denser infrastructure networks and greater operational flexibility. This confirms the importance of geographic, territorial, and morphological factors in the vulnerability of the C&DW management chain, which is particularly acute in island regions.

The survey also highlights companies' weaknesses in aspects such as the degree of internal organization, the adoption of traceability practices including mandatory digital tools, and planning and compliance capabilities. These, on the one hand, hinder smart C&DW management, understood as companies' organizational and procedural readiness for digitalization, and, on the other, highlight that technological solutions alone are insufficient without parallel investments in organizational capacity, training, and territorial coordination.

It should also be noted that the survey also reveals a growing awareness of the importance of sustainability and circularity, and the use of recycled materials, although a certain mistrust regarding the reliability of these materials persists.

A critical analysis of the questionnaire results highlights several operational priorities, particularly for island contexts:

- strengthening internal organizational structures
- promoting adherence to traceability and compliance practices
- supporting systematic pre-demolition audits that encourage selective demolition
- implementing decentralized or intermediate pre-treatment solutions to reduce long-distance transport

- promoting the use of recycled materials.

At the general policy level, the value of cross-border coordination and cooperation emerges to address regulatory fragmentation, replicate good practices already in place in different territories, and mitigating the specific infrastructural and logistical constraints of island communities.

Future research may build on the investigation conducted in this paper, focusing on the implementation of targeted and specific actions, such as:

- study of cross-border MFA models for managing C&DW flows in pilot construction sites
- development and testing of digital or semi-digital decision-support tools
- training and information activities to improve the culture of sustainable C&DW management and the use of recycled materials
- engaging additional stakeholders, particularly public administrations and regulatory bodies.

Overall, therefore, the study conducted in this paper highlights the structural specificity of island contexts and provides the basis for planning and designing targeted and site-specific solutions, framing island regions as potential laboratories for implementing resilient, circular, and smart C&DW management strategies.

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Islands of Meaning: Reconceptualising Coastal Wellbeing Through Identity and Tourism Dynamics in Mediterranean and Southeast Asian Contexts

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Abstract. Coastal and island cities are most often analysed by considering the lens of tourism growth, resilience, and environmental risk, without paying attention to how these places generate meaning and wellbeing for the people who live in them, use them, and move through them. This paper introduces the idea of islands of meaning to reinterpret coastal environments as socio-spatial systems where water-based identity, tourism, and everyday practices interact to shape coastal wellbeing. Rather than treating wellbeing as an individual condition or as a by-product of economic success, the paper understands it as a relational outcome emerging from the way these dimensions come together in practice. The originality of this work lies in introducing the *Islands of Meaning* framework which shifts the focus from individual or economic metrics to a relational understanding of wellbeing, emerging from the practical interaction of these dimensions. The framework is organised around three main domains, water-based identity, tourism intensity, and everyday practices, considered in relation to governance and environmental conditions. Drawing on a comparative reading of Mediterranean and Southeast Asian contexts, the paper highlights the threshold effects of tourism pressure, the role of accessibility and environmental comfort, and the uneven distribution of the benefits associated with blue amenities. The paper also introduces an Operational Layer Assessment Model (OLAM), an analytical tool, as a first step for assessing the conditions under which coastal contexts are able to sustain, weaken, or fragment coastal wellbeing.

Keywords: Coastal wellbeing · islands of meaning · water-based identity · tourism intensity · public space · coastal urbanism · coastal tourism · Southeast Asia · Mediterranean contexts

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1 Introduction

Coastal and island urban regions have historically been interpreted through growth-oriented and risk-based paradigms, producing a consolidated literature that has clarified their spatial and functional dynamics [1, 2]. However, these perspectives have focused primarily on quantitative indicators (arrivals, capital investment, land-use change) [3], not considering one of the most important, but also difficult to measure, dimensions of the social life of these places: the production of meaning and coastal wellbeing, understood as lived or experiential wellbeing. Such an imbalance necessitates a reframing of analytical concerns that can interweave economic, spatial, cultural, and experiential dimensions into a crosscutting interpretative framework. For that reason, that the authors introduce the concept of "*islands of meaning"*, as a theoretical construct that progressively emerges from the recognition of coastal urban regions as socio-spatial systems in which water, identity, and tourism practices interact in the co-production of lived experience.

The introduction of this concept requires a shift from static and sectoral interpretations of coastal space towards a relational perspective, in which coastal environments are inherently defined by the interaction between land and water, by considering a particular condition that produces both physical and symbolic effects. Water shapes the spatial configuration of the city by considering edges, horizons, and environmental conditions, and, at the same time, it also acts as a powerful cultural medium, embedding narratives of memory, heritage, and identity. These elements are not fixed but are constantly being reinterpreted by everyday actions and by socio-economic transformations; when tourism dynamics are added to this already complicated system, they introduce more layers of interaction, changing how people use, access, and understand these specific places. In this context, islands of meaning can be perceived as environments where wellbeing arises from the congruence (or incongruence) between spatial affordances (conceptualised here in a Gibsonian framework as action possibilities shaped by morphology and accessibility [4–7]), symbolic recognition, and quotidian practices, rather than solely from economic performance.

Indeed, this perspective addresses the common idea that the development of coastal tourism improves the quality of life and it is due by considering tourism a key driver of economic growth, especially in coastal regions, in which its social, cultural and spatial effects go far beyond the economy. In Mediterranean contexts, for example, tourism often builds on strong heritage systems, where coastal landscapes, architectural continuity, and maritime identities support a cohesive sense of place. However, redevelopment can redistribute access and redefine the criteria for legitimate the use of waterfront spaces [8] and at the same time changes in public-space layout may also affect both use and belonging [9]. The key issue is therefore not tourism itself, but the threshold at which use shifts into consumption, reducing the capacity of space to support everyday practices and activities.

In Southeast Asian coastal regions, similar pressures emerge within faster processes of urbanisation and global tourism integration. In these contexts, the relationship with water is often more dynamic and adaptive, shaped by changing livelihoods, infrastructural development, and environmental conditions. Hu and Chen [10] contend that coastal identity is continuously redefined in reaction to these pressures, resulting in hybrid configurations that combine traditional practices with contemporary forms of urbanisation.

However, this fluidity should not be romanticised, because it often indicates infrastructural pressure and uneven access. New waterfront developments can redefine the symbolic and functional role of water through globalised design models, sometimes making local differences less visible rather than more evident [11]. These processes can provide economic opportunities and/or can improve infrastructure, but they can also cause displacement, inequalities, and can destroy meanings that are important to the local community.

In light of the above, the relation between coastal developments and wellbeing is made even more complicated in both Mediterranean and Southeast Asian contexts by also considering environmental risks. Climate change adds uncertainties in the forms of sea-level rise, coastal erosion and extreme weather events, which threaten to destroy physical infrastructures while disrupting the symbolic and experiential aspects of coastal life. In this sense, environmental vulnerability is both a physical condition and a socio-cultural one, affecting how individuals and communities relate to their environment and experience wellbeing.

Within this perspective, coastal wellbeing is approached in this paper through the notion of coastal happiness, understood as the lived and perceived dimension of wellbeing in coastal environments. The two terms are therefore used as closely related, and as conceptually overlapping, insofar as coastal happiness makes explicit the affective, experiential and place-based qualities through which wellbeing is produced and recognised along the coast. Namely, coastal happiness is conceptualised as an individual psychological state, a by-product of economic prosperity, as well as an emergent property of socio-spatial systems, produced through the interaction between accessibility, environmental quality, social interaction, and symbolic attachment. Studies such as Shiiba et al. [12] highlight the importance of environmental comfort and spatial design in supporting positive experiences in waterfront areas; Linh and Son [13] emphasise the role of inclusive and accessible public spaces in sustaining everyday practices and social cohesion. There is a common understanding in which wellbeing in coastal settings relies on the ability of urban systems to reconcile multiple and sometimes competing, demands such as tourism development, environmental preservation, and social inclusion.

The above observations raise the key question of how coastal and island urban regions can be conceptualised and managed as islands of meaning in a way that can be possible to foster inclusive but sustainable modalities of coastal wellbeing, by considering persistent pressures from tourism and environmental change. This question reflects the need to go beyond dichotomous solutions which are manifesting only either growth or resilience independently, and to establish a relational, dynamic and integrated coastal urbanism framework grounded in social-ecological systems.

To meet this need, this paper is organised as follows: in Sect. 2, the conceptual and analytical framework of islands of meaning is developed. Water-based identity and symbolic attachment and tourism intensity and socio-spatial transformation are analysed respectively in Sect. 3 and 4. In Sect. 5, the everyday dimension of life at the land-water interface is analysed, considering issues such as mobility, leisure rhythms, environmental comfort, and the inclusiveness of public space. The conclusions are in Sect. 6 in which are integrated the findings, discussing policy implications, and reflecting on how coastal

urban regions can be planned and governed as islands of meaning capable of sustaining wellbeing over time.

2 Conceptual Framework: Islands of Meaning as a Relational System

The conceptualisation of coastal and island urban regions as *islands of meaning* requires clarification of its operative mechanisms within the framework. If, as established in the previous section, coastal environments are understood as socio-spatial systems where water, identity, and tourism practices co-produce coastal wellbeing, the focus shifts to how these dimensions interact, under which conditions they reinforce each other, and when they instead generate tensions or imbalances. Accordingly, this section presents islands of meaning as a relational system structured around three core domains (water-based identity, tourism intensity, and everyday practices) whose interaction is shaped by governance and environmental conditions. This relational structure is synthesised in Fig. 1, which represents the framework as a system of interdependent components and not a linear process.

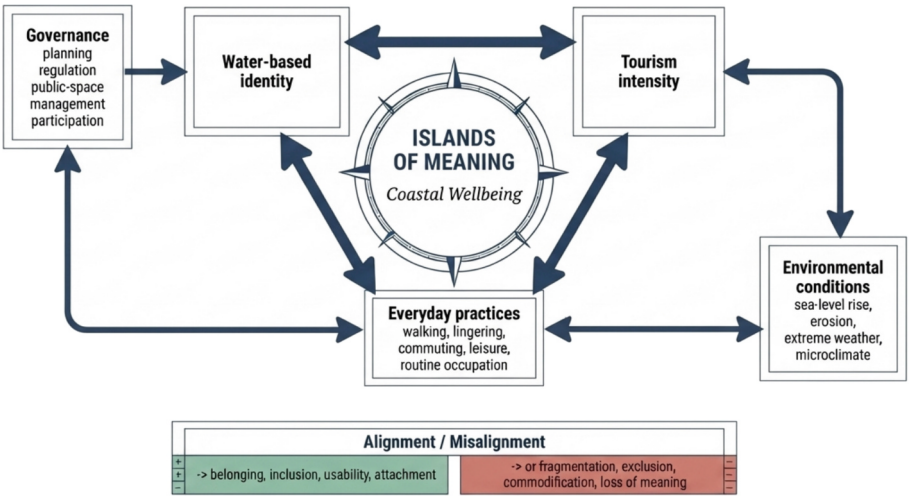

Fig. 1. Relational structure of the *Islands of Meaning* framework (Source: Authors elaboration)

Figure 1 positions *Islands of Meaning* at the centre as an emergent condition, generated through the continuous interaction between the three core domains that are represented as mutually connected elements linked by bidirectional relationships, indicating that their interaction is recursive, not unidirectional. Water-based identity and tourism intensity influence each other, as cultural meanings attract tourism while tourism simultaneously reshapes and selectively amplifies those meanings. Both domains converge on everyday practices, which represent the most immediate and observable dimension of how coastal space is lived, while everyday practices in turn feed back into identity

construction and tourism dynamics over time. Coastal space therefore operates as a performative environment where meaning is produced through use; water functions both as a morphological driver and as a symbolic medium through which identity is constructed and communicated; coastal environments offer distinct perceptual conditions shaping experience that contribute to the formation of distinctive experiential qualities. These qualities affect perception, orientation, and the likelihood of repeated use, thereby structuring attachment over time. Spatial affordances (as underlined before, intended in this paper as the set of action possibilities shaped by accessibility, continuity, and environmental comfort) become key conditions enabling or limiting interaction between people and place.

At the same time, spatial conditions alone are not sufficient to explain meaning, in fact the symbolic dimension, such as heritage, memory, and identity, plays an equally important role in shaping interpretations and values. In Mediterranean contexts, coastal identity is often shaped by long historical narratives and by ways of interpreting the relationship between land, sea, and urban life that have developed over time.

García-Ayllón [14] describes coastal transformation as characterised by a persistent tension between development and the need to preserve identity; Pallarés [15] highlights that maritime landscapes can still retain a strong cultural readability. These studies suggest that identity not reside in the physical form of the waterfront alone, but is selectively codified and reproduced through governance, planning practices, and cultural discourse. This can be seen in different Mediterranean waterfronts, such as the Vieux-Port in Marseille, Porto Antico in Genoa, Port Vell in Barcelona and in the area of the Port of Cagliari, where heritage, tourism, and public-space redesign have not cancelled local identity altogether, but have reshaped it, emphasising some meanings.

In Southeast Asian contexts, the relationship between identity and coastal space often appears more fluid and adaptive, largely due to the faster processes of urbanisation and socio-economic change, where traditional relationships with water coexist with new forms of development. Despite these differences, meaning still emerges when people are able to connect places with shared or personal narratives.

The third dimension of the framework relates to how space is lived and experienced in everyday practices such as walking, lingering, commuting, or informally occupying public space. It is important to consider that these uses shift across a day and through seasons, with tourism often generates those changes more visible, indeed more visitors can bring movement, encounters, and activity, but they can also disturb familiar routines, put pressure on shared spaces, and make everyday uses less present. This means that the dynamics of these dimensions are never completely stabilised, and their impact is greatly contingent on maintaining a balance between them.

When accessibility, environmental quality, and inclusive design support local practices, coastal environments can function as effective islands of meaning. When consumption overrides everyday use, this alignment weakens, leading to processes of fragmentation and loss of meaning.

Governance acts as a mediator that shapes access, use, and representation across all domains, as shown in Fig. 1, as well as planning decisions, regulatory frameworks, and public space management strategies determine the allocation of access, the heritage preservation, and the balance between tourist and local uses. Shcherbina and Nguyen [16]

highlight how governance is a factor that drives accessibility and inclusion along waterfronts, particularly in fast-growing coastal cities, and similarly Hansasooksin et al. [17] argue that without the direct involvement of local communities in decision-making, such governance arrangements risk reinforcing exclusion rather than mitigating it. The effectiveness of coastal environments therefore depends as much on institutional arrangements as on physical and cultural conditions.

Environmental conditions (sea-level rise, coastal erosion, and extreme weather events, etc.) make coastal spaces even more fragile and variable, affecting physical and experiential conditions in non-linear ways. These dynamics may disrupt patterns of use and weaken attachment, although their effects remain context-dependent and difficult to generalise. As Shiiba et al. [10] note, environmental comfort is an important part of a positive waterfront experience, but, at the same time, climate-sensitive design on its own cannot ensure that coastal spaces will remain usable and attractive over time. The real issue is what happens when these different conditions no longer hold together and what matters is not the presence of these dimensions, but how they hold together in practice.

3 Water-Based Identity and Symbolic Attachment

If coastal and island urban regions are interpreted as *islands of meaning*, identity has to be considered a primary dimension through which meaning is produced, stabilised, and contested. In coastal contexts, identity is rarely a fixed attribute or a simple inheritance from the past, indeed it is formed, and continually adjusted, through the ways in which people relate to the water environment. The sea, rivers, lagoons, or waterfronts shape not only the physical organisation of space, but also how places are remembered, described, and emotionally recognised. In this sense, water becomes part of the cultural language of a place, it influences everyday practices, collective memories, and forms of belonging, especially in settlements where the boundary between land and water is a physical edge, but also a central element of urban life and local meaning.

Through this lens, the concept of water-based identity, or blue identity, can be understood as the set of meanings and forms of recognition produced through repeated and embodied interaction with water environments. It can include the symbolic role of the sea in local narratives, the traces of memory embedded in waterfront spaces, and the sense of familiarity that develops when water is part of everyday experience in social practices, and cultural interpretation. This form of identity cannot be reduced to visual or aesthetic perception alone because it emerges through practice: through routines, habits, and ongoing contact with coastal space, as well as through the cultural frameworks that interpret water as heritage, a source of livelihood, or a threshold between different conditions [18]. In this sense, blue identity is something that is continuously produced and negotiated, as well as it is therefore relational: it links environmental conditions, social practices, and cultural interpretation into a single experiential field.

In Mediterranean coastal cities, this process is frequently framed by institutionalised through heritage rules and narratives of continuity. The sea has long been part of the way coastal cities developed, through trade, mobility, defence, and exchange, as well as through all the memories and meanings around these activities. These traces are still visible at the level of port areas, seafronts, promenades, and older urban fabrics. These

material and symbolic references transmit the coastal identity into the present, keeping some images of the past alive in everyday experience [3].

García-Ayllón [12] shows how Mediterranean tourist coastal change is intimately related to the divergence between development and the need to preserve territorial identity, while Pallarés [13] in turn, highlights the interpretative capacity of maritime landscapes as carriers of cultural legibility. What these studies make clear is that identity does not survive on its own but it is sustained through concrete choices, through the way places are represented, and through strategic preservation actions.

Heritage does not simply preserve meaning; it also selects, orders, and stabilises particular narratives, sometimes at the expense of others. When coastal identity is mobilised within tourism-led development, the risk is that heritage becomes simplified into a consumable or a simplified image: a waterfront to be visited, photographed, and consumed, rather than a place that people use, remember, and inhabit in everyday life.

It has been observed in several studies that, in tourism-led waterfronts, change impacts on uses do not necessarily impact equally. The attractive, profitable and aesthetic breakthroughs tend to gain priority, while everyday practices are more easily pushed aside [19, 20]. Other studies report that in the context of tourism-induced public-space transformation, accessibility and land use, as well as the experiential quality of experience (understood as the way people identify themselves with that particular place) change the sense of the place [21–23]. The challenge is therefore not one of whether heritage exists or not, but how it is understood, managed and (re)positioned in the context of contemporary coastal living.

This relation between water and identity had usually a different path in the Southeast Asian coastal regions. Historically, water has shaped settlement and mobility, work and adaptation in even more fluid and dynamic ways. For millennia, rivers, deltas, canals, estuaries, and coasts have long sustained forms of everyday life in which water is less a stable symbolic background and more an active agent in urban and territorial formation. Other studies observes that waterfront developments reinterpret water as a strategic urban resource [24, 25], often combining local references with globally circulating design models. What is significant in these cases is that blue identity does not disappear under transformation, but becomes hybrid, unstable, and negotiated [26, 27].

In Mediterranean and Southeast Asian contexts, identity is shaped by the interaction between inherited meanings and contemporary pressures. What varies is the relative weight of institutionalised heritage, the speed of transformation, and the modes through which local narratives are incorporated into planning and development.

Memory is central to this process because it mediates how people experience in space with the meanings they attach to it over time and particularly on the coast, memory operates as a bridge between physical space and culturally constructed meanings, thanks to the official narratives or heritage as well to the ordinary habits. This is evident in discussions of waterfront promenades as sites where public memory, everyday practice, and place attachment co-evolve, producing a durable sense of place beyond mere visual aesthetics [28, 29]. These repeated experiences can create attachment even when they are not formally acknowledged as heritage. Looking at memory in this broader way helps avoid reducing identity to monuments or institutional recognition alone. It also makes visible the importance of everyday repetition in stabilising meaning. Coastal

places become meaningful because they are historically important, as well as because they are repeatedly inhabited, recognised, and incorporated into daily life.

For this reason, symbolic attachment is inseparable from the practical conditions that allow people to engage with coastal space, in fact, it becomes more difficult for a water-based identity to persist when the waterfront is less accessible, when public space is increasingly privatised, or when environmental conditions undermine its everyday use. Recent studies underline the importance of environmental quality and the sensory experience of "blue spaces" are fundamental for urban wellbeing [30, 31], as well as, at the same time, other studies emphasise the role of accessibility and inclusiveness in maintaining meaningful costal public use [32, 33]. These contributions are important because they show that identity is not only cultural in a narrow sense; it is also spatially enabled. Belonging depends on narratives and on the material possibility of inhabiting the spaces through which those narratives become real.

At this point, tourism becomes a crucial factor because it can both reinforce and destabilise water-based identity. Tourism can provide visibility in some cases to coastal heritage, attract investment in waterfront regeneration, and reinforce the symbolic role of maritime landscapes. In addition, it may shift the meaning of these spaces away from local use and toward external consumption when coastal identity is reformulated primarily for visitors, losing importance in this way as an everyday structure of belonging. The space may still be attractive, but its meaning is no longer the same and the waterfront becomes less part of everyday collective life and more a carefully shaped place for leisure. This is one of the key tensions within the idea of islands of meaning: the same processes that activate coastal value economically may also erode the social and symbolic conditions that sustain coastal wellbeing.

In this light, water-based identity conceptualises an important key component of coastal wellbeing because it links environment, recognition, and everyday experience. Within the broader framework conceptualised in this paper, blue identity can be seen as the first fundamental condition through which the islands of meaning are formed: it anchors the relationship that exists between water and a sense of belonging, clarifies the role of memory and heritage in shaping coastal experience, and explains why tourism and development needs to be evaluated in terms of economic production and of what they preserve, transform (or constructively disrupt) in the lived structure of place.

4 Tourism Intensity and Socio-spatial Transformation

Whereas water-based identity represents the cultural and symbolic basis of coastal environments, tourism intensity is a key force in the restructuring, reinterpretation, and, in many cases, in contesting these specific contexts. In coastal and island urban regions, tourism is not simply an additional activity, but can be considered as a driver that reorganises spatial configurations, redistributes access, and redefines the relationship between residents, visitors, and place. Tourism intensity needs to be examined beyond its quantitative dimension (through arrivals, densities, or economic outputs), by considering also its qualitative effects on the organisation and experience of space.

Tourism intensity can be understood as the extent to which tourism reshapes the organisation and everyday life of a coastal urban system. These processes are particularly sharp in coastal areas, so this is usually where the land-water interface is the

arena of clearest conflicts around economic pressures and social practices versus environmental concerns. One of the more stark impacts that tourism intensity has is how public space becomes reconfigured: waterfronts, promenades, and beaches are designed, built and managed for high visitor numbers, meaning that space becomes standardised, and consumption-oriented uses of the space take priority. These transformations might increase in visual quality and accessibility but decrease in use diversity, limiting the non-tourist usages and functions e particularly for public spaces, use and perception can change gradually under the pressure of tourism.

These areas may gradually become more similar to one another as tourism intensity increases. What is promoted as distinctive may, paradoxically, produce more standardised coastal spaces, organised around the same visual qualities, leisure functions, and visitor-oriented experiences. Thus, coastal areas shaped by increasing tourism intensity may gradually lose their capacity to sustain the diversity of social uses that once characterised everyday life, weakening locally rooted practices and meanings [34–36].

This process is closely linked to commodification [37], through which coastal environments become marketable assets. Coastal landscapes are selectively reshaped to highlight elements such as scenic views, heritage, and leisure amenities, while less marketable aspects of local life become less visible. As a result, waterfronts tend to shift from spaces of everyday interaction and mobility to spaces increasingly organised around consumption and economic value [38].

However, the impacts of tourism intensity are not uniform and depend on governance, planning choices, and local socio-economic conditions.

Importantly, tourism intensity follows a non-linear pattern: up to a certain threshold, it can enhance vibrancy, maintenance, and accessibility, but beyond that point, crowding increases, everyday usability declines, and the ordinary meaning of place begins to weaken (Fig. 2).

This dynamic is particularly evident in Mediterranean coastal areas, where tourism tends to concentrate in specific locations, generating spatial pressure and social tension; In Southeast Asian, the situation is often more complex, as tourism develops alongside rapid urbanisation and waterfront transformations are therefore tied to visitor economies as well as to broader processes of urban expansion, resulting in spatial patterns that are dynamic and adaptive, yet often fragmented and uneven in terms of access and distribution of benefits.

Environmental conditions may further intensify these dynamics, indeed, tourism can place additional pressure on already fragile coastal ecosystems, with consequences that also affect the quality, comfort, and usability of waterfront spaces [39]. At the same time, climate-related risks, such as sea-level rise and extreme weather events, influence safety, accessibility, and everyday practices.

Within the islands of meaning framework, tourism intensity can therefore be understood both as a source of pressure and as a key mediating force. It affects the relationship between spatial affordances, symbolic meanings, and everyday life, while also showing how economic forces are translated into territorial change, social restructuring, and new ways of inhabiting the waterfront. The next section moves more directly to this lived dimension by focusing on experience at the land-water interface.

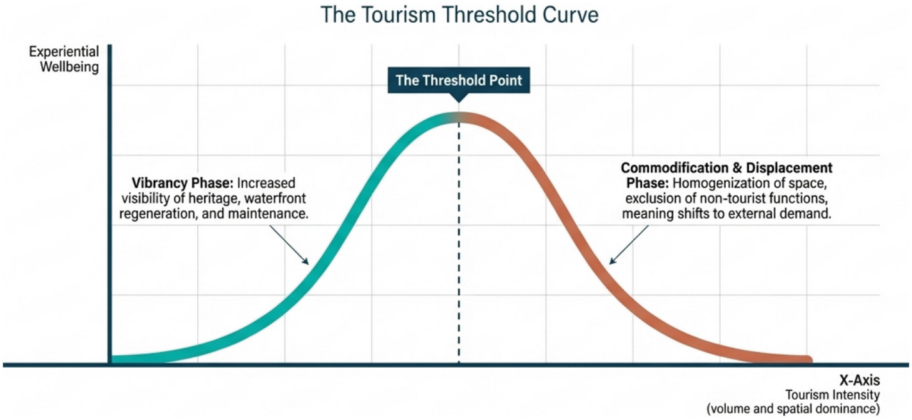

Fig. 2. The tourism threshold curve (Source: Authors elaboration)

5 Everyday Practices at the Land-Water Interface

As previously underlined, whereas intensity explains structural transformation, or, how coastal spaces can be transformed at a structural level, everyday practices reveal how these transformations are lived, negotiated, and stabilised through daily interaction. According to the *islands of meaning* framework, the land-water interface is a physical limit of demarcation but also a socio-spatial arena where mobility, leisure, social interaction, and environmental perception converge and meet together. This interface represents the most immediate experience of identity and tourism activity in everyday life, this is where becomes most visible the ability of coastal environments to sustain wellbeing. The focus shifts, then, from broader processes to the scale of actual use, where the relationship between people and place is continually transformed through practice.

Everyday practices in coastal environments are first and foremost conditioned by spatial accessibility. Any meaningful interaction with the waterfront depends first on the simple possibility of reaching it, entering it, and moving along it. Accessibility is not only a matter of physical proximity, but also of how different users can reach, cross, [40], and use coastal spaces, depending on spatial configuration, connectivity, and barriers [41–44]. When waterfronts are well integrated with the rest of the city, they more easily become part of everyday routines, strengthening familiarity and place attachment over time.

In addition to accessibility, everyday practices are also shaped by temporal rhythms, linked both to natural cycles (light, tides, and weather) and tourism seasonality. During peak periods, waterfronts may become more vibrant [45, 46], but also more active and transient; while outside these periods local routines and slower uses tend to re-emerge.

Environmental conditions also shape these practices in very concrete ways, especially through comfort at the micro-scale. Heat stress, lack of shade, or exposure to wind and humidity can make these spaces less comfortable and less usable, reducing both social interaction and everyday presence. Experiential quality therefore depends not only on symbolic and spatial attributes, but on the capacity to support comfortable and adaptable conditions for daily life.

The arrangement of public spaces is also crucial because their design influences how people move, where they stop, and how they interact with others. On the one hand, inclusive and flexible public spaces can accommodate diverse practices, allowing different user groups to coexist and negotiate space; on the other, specialised or rigidly programmed spaces may limit the range of possible uses, favouring certain activities while excluding others. In tourism-oriented contexts, the balance between residents and visitors becomes fragile: residents depend on waterfronts for daily mobility and social life, while visitors often use them for leisure and consumption. As tourism intensifies, local practices may lose ground due to changing atmospheres, rising costs, and less comfortable or accessible conditions.

Mobility makes this tension even more visible, since coastal areas are both destinations and connectors within the wider urban system. The quality of slow mobility networks, including continuity, safety, and integration with other modes, directly shapes how waterfronts are used and experienced. When mobility networks are well designed, waterfronts can support everyday functions as well as recreational ones, strengthening their role as shared urban spaces. When movement is fragmented or dominated by traffic, barriers become more evident and the overall coherence of the waterfront is weakened.

In addition, the interaction between everyday practices and tourism also has implications for the production of meaning: changes in practice produce shifts in meaning and identity, indeed meaning remains layered and inclusive when local routines persist alongside tourism.

Governance again is extremely important in shaping these outcomes, because thanks to it, it would be possible to determines how space is regulated, maintained, and programmed. Decisions regarding public access, land use, infrastructure, and environmental management all influence the conditions under which everyday practices occur. Governance therefore mediates whether everyday practices are sustained or displaced.

All of these dimensions can be synthesised as a single operational layer, where (i) the three domains, water-based identity, tourism intensity, and spatial conditions, are continuously translated into lived experience; (ii) this interaction is translated into observable spatial behaviours and outcomes; (iii) at a theoretical and operational level, this single layer is formalised through an **Operational Layer Assessment Model** (OLAM), conceived as a unified framework for translating the alignment between water-based identity, tourism intensity, and everyday practices into measurable variables.

OLAM does not simply describe the operational layer, but makes explicit how alignment or misalignment emerges from the interaction of identity, tourism intensity, and everyday practices within a single analytical structure.

Table 1 and Fig. 3 summarise this operational Assessment Model (OLAM), including variables, parameters (sub-indicators), and expected effects on coastal wellbeing.

Within OLAM, the operational layer is assessed through a composite **Operational Layer Index** (OLI), which aggregates the eight dimensions summarised in Table 1: Accessibility (A), Mobility routines (M), Temporal rhythms (T), Environmental comfort (E), Public-space design (P), Everyday practices (D), Resident-visitor balance (R), and Governance and management (G).

Table 1. Operational Layer Assessment Model (OLAM): variables, parameters, and expected effects on coastal wellbeing. (Source: Authors elaboration)

Variable	Symbol	Example sub-indicators / parameters	Operational meaning	Expected effect when high	Expected effect when low
Accessibility	A	continuity of waterfront access; permeability of edges; inclusiveness of connections	Measures the extent to which users can physically and equitably access the land-water interface	repeated use, familiarity, attachment	fragmented access, exclusion, weakened belonging
Mobility routines	M	walkability; cycling integration; modal continuity; presence/absence of barriers	Measures how the waterfront is integrated into daily mobility systems	socio-spatial integration; routine appropriation	isolation, reduced usability, tourist-oriented segregation
Temporal rhythms	T	daily intensity balance; seasonal coexistence of uses; resident/visitor temporal overlap	Measures the temporal compatibility between local routines and tourism cycles	adaptive coexistence across time	congestion, conflict, displacement during peaks
Environmental comfort	E	shading; thermal exposure; wind conditions; humidity; perceived safety	Measures the extent to which environmental conditions support prolonged and positive use	longer stays, sociability, restoration	avoidance, stress, reduced permanence
Public-space design	P	flexibility of use; seating; land-water transitions; pause/encounter opportunities	Measures the design capacity of space to support diverse practices and interactions	inclusive and meaningful shared use	over-specialisation, rigid use, exclusion

(*continued*)

Table 1. (*continued*)

Variable	Symbol	Example sub-indicators / parameters	Operational meaning	Expected effect when high	Expected effect when low
Everyday practices	D	diversity of practices; frequency of use; continuity of routine occupation	Measures how far coastal space is enacted as lived space through repetition and ordinary use	reinforcement of meaning and social cohesion	externalised or commodified use, loss of attachment
Resident-visitor balance	R	coexistence index; conflict intensity; displacement dynamics	Measures the social sustainability of shared coastal use	layered meanings, mutual visibility	tension, symbolic loss of place, local displacement
Governance and management	G	maintenance quality; access rules; programming; stewardship capacity	Measures institutional capacity to regulate and sustain inclusive use	stable liveability, balanced use	privatisation, uneven benefits, erosion of public relevance

The Operational Layer Alignment Model (OLAM) translates the relational framework into a set of observable variables, capturing how alignment or misalignment emerges across the three domains under specific governance and environmental conditions. In its simplest standardised form, the index can be expressed as:

$$\mathrm{OLI} = \frac{A + M + T + E + P + D + R + G}{8}$$

where each variable is normalised on a common scale from 0 to 1, with 0 indicating severe misalignment and 1 indicating optimal operational performance. A weighted version may also be adopted when specific coastal contexts require differentiated relevance among variables:

$$\mathrm{OLI} = w_A A + w_M M + w_T T + w_E E + w_P P + w_D D + w_R R + w_G G$$

with

$$w_A + w_M + w_T + w_E + w_P + w_D + w_R + w_G = 1$$

OLI captures the degree to which the three domains of the framework converge within the same operational space. Each variable can be operationalised through a set of sub-indicators. A high OLI indicates strong alignment between spatial conditions, everyday use, and governance support; a low OLI signals misalignment, expressed through fragmentation, exclusion, and reduced usability of coastal space.

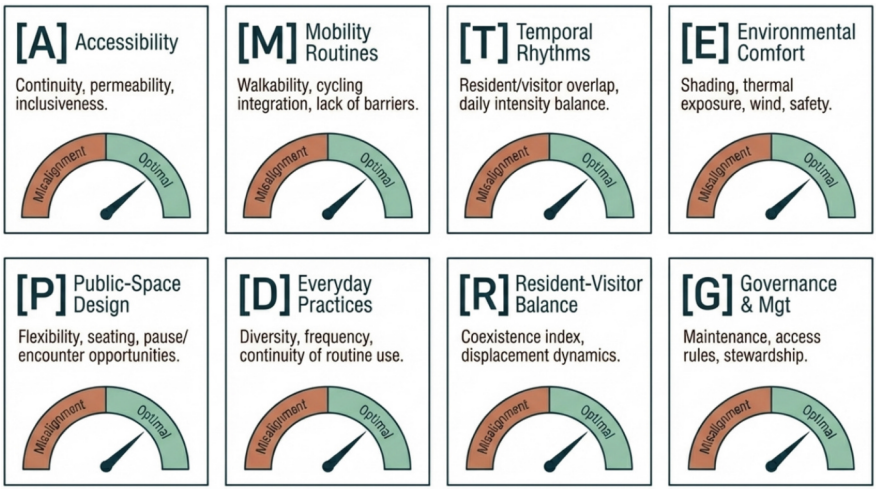

Fig. 3. Operational Layer Assessment Model (OLAM): Symbol, variables, and parameters (Source: Authors elaboration)

6 Discussion and Conclusions

This main goal of this paper is considering coastal and island urban regions as islands of meaning, namely socio-spatial systems in which water, identity, tourism intensity, and everyday practices interact to produce coastal wellbeing or, conversely, socio-spatial stress. This paper represents the preliminary desk-based study of the project *Coastal Happiness & Analytics for Regional Meaningful Places and Tourism* (CHARM), developed in collaboration between the University of Cagliari and Universiti Malaya. The future development of this research, within the CHARM project, will focus on the field application of the Operational Layer Assessment Model (OLAM) through the Operational Layer Index (OLI).

Instead of analysing these dimensions separately, the analysis found that it is their interaction (more exactly their alignment) that is a fundamental condition through which coastal environments deliver or diminish wellbeing. These dimensions converge into a single functional and operational layer, that does not invalidate the conceptual framework but rather heuristically expresses the interaction between its three primary domains into manageable forms.

The key question posed in the introduction asked basically how coastal and island urban regions can generate meaningful and inclusive forms of coastal wellbeing under conditions of tourism pressure and environmental change. A first primary answer developed in this paper is that such wellbeing emerges only when the symbolic, spatial, and practical dimensions of coastal life remain aligned, without one dimension being considered secondary to the others. Coastal wellbeing cannot be simply quantified through tourism growth, heritage value or environmental quality in isolation but relies on the maintenance of balance such that coastal space remains comparable to everyday life and thus approachable, identifiable, usable and acceptable whilst still catering for tourism without pressure from displacement of local meaning.

Where this alignment is maintained, coastal environments support belonging, sociability, and inclusion; where it is disrupted, they tend toward overcrowding, exclusion, and fragmentation or loss of attachment. In this viewpoint, the operational layer is the level at which the relational structure of the framework becomes observable through everyday conditions and practices. In order to make this dimension analytically useful, the paper introduces the **Operational Layer Assessment Model** (OLAM) as a part of the Islands of Meaning framework.

The model allows for comparison among different coastal contexts through an assessment of how coastal wellbeing is encoded by the interaction among eight variables, namely: accessibility, mobility routines, temporal rhythms, environmental comfort, public-space design, everyday practices, resident-visitor balance, and governance and management.

These eight dimensions would serve as the observable pillars of the operational layer and could be studied through a mixed-methods design combining spatial analysis, behavioural observation, environmental measurements, and perception-based surveys.

OLAM does not measure these variables separately, but evaluates their alignment through the **Operational Layer Index** (OLI), which allows comparison among different coastal systems in terms of their ability to support daily use and meaning.

The main value of such a model is that it would allow researchers to identify not only whether a coastal place is economically successful or environmentally exposed, but how it works in lived terms. It would also make it possible to compare cities with very different cultural and climatic conditions while retaining a common analytical structure. Within the broader contribution of this article, this research agenda confirms that the future of coastal urban theory lies in connecting symbolic attachment, tourism transformation, and daily spatial practice through a framework that is both critical and operational. In this sense, the Islands of Meaning approach offers not only a theoretical reinterpretation of coastal urbanism, but also the basis for a more precise and policy-relevant investigation of what makes coastal environments liveable and meaningful.

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Sustainable Energy Planning in the Cyclades Islands, Greece: Problems and Perspectives in an Era of Climate Crisis

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Abstract. In an era of climate crisis and geopolitical realignment, achieving energy neutrality has become a global development priority. Sustainable energy planning requires the responsible use of renewable energy sources, respecting the physiognomy and carrying capacity of places / landscapes. Thus, resource management and the protection of natural, cultural, and man-made ecosystems are essential for a sustainable energy transition that meets local energy needs at the spatial planning level. In this context, the main challenge lies in developing national policies for a sustainable energy transition, as well as using innovative technology to create new methods of producing, storing and distributing energy from renewable sources. In this regard, the dominant global trend is to organize sustainable energy communities at the inter/intra-regional level. Particular interest is held for island regions due to their location, size, energy demand (e.g. shipping, tourism and coastalisation), complexity, vulnerability, seasonality and peripherisation. These characteristics require sustainable resource management and small-scale infrastructure to achieve energy self-sufficiency. This article contributes to the ongoing debate by exploring the potential for inter-island cooperation in creating renewable energy communities in the Cyclades. To this end, the article sets out a methodology for identifying hub islands and defining their roles within these communities. A set of spatial / energy criteria has been proposed to determine favourable and limiting parameters for the energy transition on islands.

Keywords: sustainable energy planning · development policy · spatial planning · renewable energy sources · climate crisis · energy neutrality · renewable energy communities · insular regions

1 The Research Framework

The sustainable transition to energy independence is emerging as a key priority in the spatial planning and development policies of insular countries. At the same time, current experience and practice emphasise the importance of a cooperation strategy that takes everything into account for successful local / interregional implementation. Island regions of all sizes have their own unique characteristics. Thus, it is necessary to systematically and dynamically monitor development options, as well as the spatial changes

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and energy needs that accompany them. This is crucial for island regions, which have incredibly delicate natural, cultural and human ecosystems [1–3].

The diversity of islands in terms of size (i.e. surface area, population density, production base), location (remote/offshore), spatial dispersion and degree of interaction with the mainland (dependence, cooperation), combined with the structure, size, dynamics and specialisation of island economies, exacerbates the phenomena of abandonment and seasonality and reinforces their peripherisation. At the same time, islands' different energy needs result from their development patterns (e.g. shipping, services and tourism), as well as the number of permanent residents and visitors. Therefore, achieving energy autonomy for islands requires innovative methods to produce, store and distribute energy from renewable and marine energy sources (RES/MRE). This is particularly important for non-connected islands (NIIs), which lack the planning, funding or knowledge to utilise RES/MRE effectively [4, 5].

A sustainable energy transition is notably important for island regions that depend on tourism or have a concentration of supra-local infrastructure and activities, such as transportation, education (e.g. universities, research centers), and production. It is also important for small, remote, and inland islands because they have difficulty connecting to the national grid and/or depend on the energy infrastructure of larger neighboring islands. In recent decades, increased urban sprawl on islands due to tourism development and pressure to become trans-regional renewable energy hubs has posed a significant threat to local identity, resilience and sustainability [6–10].

However, gaps remain in the implementation of the institutional framework and the use of spatial planning tools for modernization, spatial planning, and achieving energy neutrality in Greece. Despite its insular nature and the fact that it is made up of many small, isolated and remote islands, Greece still lacks a clearly formulated island policy and a national energy transition plan to achieve energy autonomy for its islands. This gap is reinforced by the lack of an integrated coastal area management strategy and the inability to finalize local, regional and sectoral plans These include the *National Spatial Strategy for the Marine Space* (NSSMS), the *Marine Spatial Framework*, the revised/new *Marine Spatial Strategy Plans* (MSSPs), the *Special Spatial Planning Frameworks for Renewable Energy Sources* (SSPF-RES) and for *Tourism* (SSPF-T), as well as the proposed or in-progress *Local Urban Plans* (LUPs) and *Special Urban Plans* (SUPs) as part of the *Konstantinos Dioxides Urban Planning Programme* (Sect. 3).

In these circumstances, contemporary discussions and practices at the global level highlight the organisation of renewable energy communities at the local, inter/intra-regional levels as a means for countries and their regions to transition to sustainable energy. These communities are particularly significant for insular regions, which are the focus of this article. Such communities are formed through collaboration between islands with the aim of developing the infrastructure needed to produce, store and distribute renewable energy [11]. This development must take into account the positive and limiting environmental, regional, social, economic and spatial factors affecting each island. Therefore, the local scale is important for energy planning, as it prevents the uncritical adoption of energy transition autonomy models that do not align with the specifics of each location. Islands are autonomous entities. However, they also act as nodes in wider networks, forming relationships with each other and with mainland regions. In order

to understand islands, it is necessary to consider two things: what makes them unique and what they require, and the wider spatial context of their activities and interactions. This is a key to creating an effective methodology for identifying sustainable, renewable energy communities (Sects. 2.1, 4, 5).

In the context of the energy transition on islands, the main objective is to promote sustainability and resilience at local and regional levels. This requires optimising the use of modern technology and practices to develop small-scale energy infrastructure, while avoiding the conversion of islands into supra-local energy stations. This is particularly important for islands that have experienced intense tourism development, as well as for abandoned islands that are rich in natural and cultural resources.

In Greece, the favourable factor for establishing renewable energy communities on islands is their potential for generating energy from wind, solar and marine sources. However, limiting factors include the fragmented structure of island spaces and their variety, such as island size and development patterns. Other equally important factors include the characteristics and limitations of marine spaces, such as the exclusive economic zone (EEZ) and continental shelf depths and usage [12]. The richness of terrestrial and marine landscapes, both natural and man-made, is also a critical consideration. Therefore, it is necessary to simultaneously assess the favourable and restrictive conditions for the use of renewable energy sources in relation to the energy planning of the Greek islands (and the country as a whole). This assessment will highlight issues related to selecting renewable energy sources and locating their infrastructure within an island cooperation model. The ultimate goal is to achieve a more balanced spatial distribution of energy infrastructure while taking into account the identity and carrying capacity of operating sites. Thus, Greece could serve as a challenging case study for re-evaluating energy transition and autonomy standards, as well as for trialling new innovative renewable energy sources (Sect. 2.2).

Against this backdrop, the article contributes to the ongoing debate by exploring the potential for establishing renewable energy communities on islands. The Cyclades archipelago in the Aegean Sea has been chosen as the location for the pilot study. The aim at this stage is to study the developmental dynamics and energy potential of the islands, in order to evaluate the proposed renewable energy communities (hubs and connections) as an autonomous system more effectively. Therefore, the role of the hub islands at the local- regional levels is of great interest. To this end, a methodology based on spatial and energy criteria has been developed to identify favourable and restrictive parameters for energy utilisation on each island. The scope is to determine which islands could form renewable energy networks/communities and what their respective roles would be. The first comprises the largest islands, which have seen growth in infrastructure and an increase in their permanent population. The second includes smaller, less densely populated islands with limited development. However, these islands have experienced significant residential expansion and growing tourism. This attempt to define renewable energy networks in insular regions paves the way for the next stage: an investigation into the role of islands in achieving energy neutrality in Greece based on quantitative indicators (Sects. 2, 4, 5).

The research is organised around two main issues that currently pose significant challenges to energy and spatial planning. The first is of a political nature and relates to the

role of islands in their respective countries' energy transition policies. In other words, it remains to be seen whether and to what extent islands will be treated as supra-local/supra-national poles of renewable energy communities (i.e. small-scale infrastructure), the main goal of which is to achieve energy transition autonomy at the local/regional level. The second is a planning matter concerning the development of expertise in the optimal use of renewable energy sources while respecting natural, cultural, and man-made ecosystems/landscapes. This is a crucial issue for ensuring the sustainability of islands. Therefore, it must be addressed (Sect. 2).

The article is divided into six sections. The first addresses the research framework. The second presents the research methodology and the study area. The third discusses sustainable energy planning in insular areas. The fourth focuses on the Cyclades and attempts to identify islands that could serve as nodes in renewable energy networks. This identification is based primarily on an assessment of the islands' energy profiles and dynamics. In other words, it is based on an analysis of the existing framework and prospects for exploiting renewable energy sources (RES/MRE) through an evaluation of national energy policy, case law from the Council of State, and energy demand and supply indicators. The fifth presents a pilot case study of four islands - Andros, Tinos, Paros and Naxos - that emerged from energy profile research. Using a multifactorial approach incorporating spatial / energy criteria, this section examines the favourable and limiting factors of using these four islands as main nodes in renewable energy networks / communities. At the same time, it identifies smaller, less developed islands within these wider spatio-functional zones. The proposed energy communities could include these islands. The article concludes with a sixth section that highlights key issues that must be addressed in the energy transition of island nations such as Greece.

2 Methodology and Spatial Reference of Research

2.1 Methodology and Sources

The research focuses on organising sustainable renewable energy communities (RES/MRE) to facilitate the energy transition and autonomy. This involves conducting two complementary surveys to identify island hubs and their roles at national, regional and local levels. These surveys provide a basis for understanding current conditions and perspectives. This will enable future studies to examine underlying levels (i.e. islands or island complexes) using quantitative and qualitative indicators to define proposed renewable energy communities. Specifically:

The first survey focuses on assessing the energy profile/ dynamics of the Cyclades. This is based mainly on an analysis of official planning principles and guidelines. The analysis considers the islands' historical connection to the national energy grid, their contribution to national energy production through the use of RES/MRE, their current level of energy autonomy and their potential future role in Greece's energy transition. Attention is given to recent decisions from the Hellenic Council of State, as well as changes in energy indicators, such as production and consumption. The focus is on the north-eastern Cyclades, specifically Andros, Tinos, Paros and Naxos, due to their substantial contribution to national energy production from renewable sources. These islands also support smaller, less developed ones, such as Antiparos, Ios, Sikinos, Folegadros,

Koufonisia, Schoinoussa, Irakleia, Donoussa and Amorgos (Sect. 2.2). The energy relationship observed between the largest islands and their smaller neighbours seems to suggest that through the appropriate planning of infrastructure and networking between these islands, RES energy communities could be formed that are capable of ensuring their own energy transition / autonomy (Sects. 4, 5, 6).

The second survey covers the islands of Andros, Tinos, Paros and Naxos. The first survey identified these islands as having the potential to become key renewable energy hubs due to their development and energy resources. At this stage, the main favourable and limiting factors of using these islands as hubs for renewable energy communities are examined. It also identifies secondary hubs - i.e. neighbouring islands connected (IIs) or not connected (NIIs) to the national energy grid - with which cooperative relations could be established to help achieve energy autonomy at local / intraregional levels. This second survey is based on the assessment criteria for local spatial development and energy demand characteristics. Its purpose is to identify any potential risks posed by renewable energy sources. These criteria have already been tested in previous research into the energy sustainability of small islands [8, 10]. They are as follows: (i) *geographical location*, (ii) *locus* [i.e. settlements, geomorphology, climate], (iii) *nature- culture- landscape* [i.e. natural-cultural heritage sites, and protected areas], (iv) *population* [inhabitants, % population change (2011–2011)], (v) *local economy - production sectors* [i.e. primary, secondary, tertiary (% change by sector 2011–2021)], (vi) *accessibility/networking* (Multimodal Hub (i.e. MH: port and airport)], (vii) *services and infrastructures of supralocal reach* (i.e. administrative, technical and social), (viii) *construction activity* [i.e. building permits, rate of change (2011–2021)], (ix) *tourism* [indicators: ship/ferry passengers (2013–2021), airplane passengers (2011–2021), cruise passengers (2013–2021), overnight stay (2010–2021) and full occupancy (2010- 2021)], και (x) *energy* [i.e. energy demand, energy consumption rate, production rate from conventional and renewable sources (2011–2021)]. This survey revealed the following renewable energy communities: (1) Andros and Tinos, (2) Paros (including Antiparos, Ios, Sikinos and Folegadros), and (3) Naxos (including the Small Cyclades and Amorgos) (Sect. 5).

The implementation of the above two surveys is based on a critical approach to the following: a) Official European and Greek strategic texts on spatial development and energy neutrality; b) Contemporary energy planning policies and practices focusing on island areas; c) The Greek institutional framework, relevant Council of State case law, and existing spatial / energy planning tools (Sect. 3). In order to gain a better understanding, emphasis was placed on studying islands' geomorphological, climatic, natural, cultural, demographic, socio-economic, spatial, and energy features. This was achieved using spatial analysis and assessment methods, as well as GIS mapping. The processing resulted in thematic maps at various spatial scales, such as the Cyclades and individual islands. These maps make it possible to identify specific features, common issues, and favourable, restrictive, or prohibitive factors relating to the energy transition / autonomy of islands. Official databases of international, European, Greek bodies were utilised as sources (Sects. 4, 5, 6).

2.2 The Island Complex of the Cyclades in Greece

The choice of the Cyclades and the four islands on which the research was focused was not made at random (Fig. 1). The key factors were: a) the central location of the complex; the variety of local identities; the development dynamics; the prospects for using renewable energy sources; and the favourable climatic conditions; b) the ever-increasing and diverse energy requirements of the islands due to residential expansion and tourism; and c) the local-level pressures faced by the interconnected islands (IIs) due to their planned role as new providers within the national energy grid (Sect. 4). By spatial reference category, the following were identified:

The Broader Spatial Level of Research: The Cyclades are one of two complexes in the southern Aegean region. The other is the Dodecanese. The 33 inhabited Cycladic islands are close together, with a combined population of 120,989. There are also numerous smaller islands and island groups. Of particular interest are the six small islands between Naxos and Amorgos, collectively known as the Small Cyclades. These are Upper/Lower Koufonisi, Irakleia, Schoinoussa, Donoussa and Keros. The Cyclades are an extremely interesting island group in which to conduct research into natural-cultural resource management, climate and energy crises, coastal urbanisation, tourism and natural disasters (e.g. seismic/ volcanic activity, rising sea levels, heat waves). This is due to the variety of their structures, sizes, natural and cultural wealth, development potential, port networks and relations with Athens and Piraeus. The Cyclades are also a popular tourist destination worldwide. According to the Institute of the Association of Greek Tourism Enterprises (INSETE), the number of overnight stays almost doubled between 2021 and 2022, rising from 3,131,225 to 5,758,194. The growing number of incompatible human activities and infrastructures in territorial and marine areas, along with overtourism and urban sprawl, increases the vulnerability of islands as they put pressure on natural and cultural ecosystems, threatening landscapes and increasing energy demand. Given the multiple pressures they are under, achieving energy neutrality is a priority for the islands' sustainability and resilience.

The Focus Spatial Level of Research: The north-eastern Cyclades islands of Andros, Tinos, Paros and Naxos are exceptional research cases, as confirmed by the results of the evaluation of the proposed spatial, functional and energy criteria (i)–(x), which are included in themes A–C. Theme A refers to the centrality of the islands. Theme B covers the characteristics / peculiarities of the islands' natural, cultural and man-made ecosystems, as well as their developmental dynamics. Finally, theme C focuses on the islands' existing energy profile and the opportunities presented by their level of interconnection to the national grid, namely whether or not they are connected and the extent to which they utilise renewable energy sources. Analysis of the proposed criteria revealed the following:

Themes A and B [criteria (i)-(ix)]: Geographical location and infrastructure are the reasons why all four islands are characterised by high centrality and developmental dynamics. As the largest islands in the Cyclades, they have a high population density and geomorphological variety, as well as a rich natural and cultural heritage. Andros and Naxos have the highest concentrations of Natura 2000 protected areas, at 59.32% and 44.64% respectively. Paros and Tinos islands have significant concentrations of archaeological sites, at 7.6% and 4.4% respectively. Paros and Naxos demonstrate the

strongest signs of tourism development. They have a high concentration of hotels and short-term rentals, as well as airports and cruise ports. Tinos and Andros are close behind, with a large number of holiday homes and a growing tourism sector. Tinos, Paros and Naxos have water infrastructure, including boreholes and desalination plants, as well as sewage and waste management systems. The same islands have a thriving primary and secondary sector, as well as a mining industry. Naxos has many small manufacturing units. The highest population densities are found in Andros, Paros, Naxos and Tinos, in that order. Tinos and Andros boast the most traditional settlements.

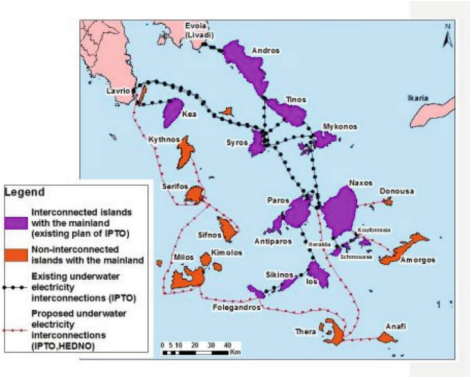


Fig. 1. Cyclades: Interconnected (IIs) and Non-Interconnected islands (NIIs) in the national energy grid [own elaboration] [25, 26]

Theme C [criterion: (x)]: The first phase of the Cyclades Connection Programme involves connecting the four investigated islands to the national energy grid. The four islands currently use renewable energy sources. These include wind and solar farms. Tinos has the greatest potential for wind power. However, Andros has the most wind farms because it is directly connected to the national grid via the Evía - Livadi line. In order to evaluate the pace of the energy transition and the autonomy of the focal islands, it is useful to consider the time at which they were integrated into the grid, as well as the geographical distribution of thermal power stations. This confirms the central role of Andros and Paros. Andros was connected to Syros and Mykonos prior to the addition of Naxos, and subsequently to Paros and Mykonos. Andros and Paros are two of the twelve Cycladic islands with thermal power stations. Syros, Mykonos, Donoussa and Amorgos, on the other hand, have stations located nearby. The Andros and Paros stations supply Tinos and Naxos, respectively. Meanwhile, the Donoussa and Amorgos stations serve local needs as they are not interconnected (Fig. 1).

The research showed that the northeastern islands of the Cyclades are expected to face the greatest pressure as supra-regional hubs for the production, storage, and distribution of renewable energy for two reasons. Firstly, as part of the country's national energy grid, they can supply national needs by exploiting forms of renewable energy in their territorial and maritime areas. Secondly, their favourable climatic and geomorphological characteristics ensure high participation rates in the national production of renewable energy. Andros and Naxos, for example, have the ideal topography for wind turbine

installation. Meanwhile, Tinos, the Small Cyclades and Amorgos are renowned for their strong winds. These features could help the country achieve energy neutrality. However, at a local level, they could affect the resilience and sustainability of the islands. Therefore, a clearly defined island policy is needed to determine their role in the country's tourism development and energy transition (Sect. 6).

3 Sustainable Energy Planning in Insular Regions: The Debate

This section summarises the key time periods that have shaped perceptions of energy neutrality in the context of the climate crisis. It also emphasises the main impact these periods have had on relevant European and Greek policies, particularly in island regions, and their effect on the energy autonomy of the Greek islands. Specifically:

The debate on the use of renewable energy sources in Europe began after 1997 with the publication of the White Paper for a Community Strategy and Action Plan [13]. Over the past 27 years, two distinct periods have emerged in the transition to clean energy. The first period began in 1997 with the formulation of EU-level energy transition laws and directives. Of particular interest is the second period, which began in 2008 and is still ongoing, as significant progress has been made in the energy transition during this time and interest in blue energy has grown. The years 1997, 2006 and 2009, along with the period after 2015, are seen as significant milestones in the shift towards renewable energy sources. The period after 2007, and especially after 2012, was pivotal for Greece as it sought to align itself with the broader objectives of the *Paris Agreement*, the *European Green Deal*, the *European Climate Law*, the *Climate-Neutral & Smart Cities EU Mission*, and the revised Renew*able Energy Directive*[1] [14–17].

In terms of the sustainable energy transition, and the autonomy of island regions in particular, the European Commission's Clean Energy for EU Islands initiative is of interest [5]. This initiative promotes long-term energy planning for the 2,200 inhabited islands in Europe. In this context, each island prepares a *Clean Energy Transition Agenda* (CETA) by taking the following steps: a) assembling a transition team, b) mapping the island dynamics, c) developing an island clean energy vision and island transition paths, and d) disseminating results and arranging follow-up. To date, more than 38 Community Energy Transition Agreements (CETAs) have been drawn up, seven of which concern Greek islands, including Halki, Chios, Kasos, Symi, Sifnos, Kos and Samos. Several other Greek islands, including Andros, Syros and Spetses, have also received technical support relating to the energy transition. These plans emphasise the importance of

[1] COM(97)599 Energy for the Future; COM(2006)105 Green Paper; COM(2007)575 Blue Paper; 2008/56/EC Marine Strategy Framework Directive; 2009/28/EC Renewable Energy Directive; COM(2012)494 Blue Growth; COM(2014) 8 Blue Energy; EUCO/169/14 2030 Climate and Energy Policy Framework; 2018/1999/EU European Climate Law; 2018/2001/EU Revised Renewable Energy Directive; COM(2019)640 The European Green Deal; COM(2020)80 European Climate Law; COM(2020)741 An EU Strategy to harness the potential of offshore renewable energy for a climate neutral future; (2021) European Council (2021) Fit for 55: EC proposal to revise the directive and raise the target for 2030 to 40%; European Commission (2022) REPowerEU Plan at a glance: new EC proposal to further raise the renewable energy target; EU/2023/2413 Revised Renewable Energy Directive.

taking local geomorphological and climatic conditions into account, as well as local identity. This includes natural and cultural heritage, the landscape, infrastructure, and aspects such as production, technology, transport and society. The focus is on the development model, which influences the energy supply, demand, and dynamics of the islands. This includes determining whether the islands are interconnected and how they utilise renewable energy sources in terrestrial and marine areas. The diversity of the islands means that innovative methods are required for the production, storage and distribution of sustainable energy.

In 2006, Greece set a binding target for the proportion of electricity produced from renewable sources [18]. In 2008, Greece adopted the Special Framework for Spatial Planning and Sustainable Development for Renewable Energy Sources (SFSPSD-RES) [19] which is under review. Aligning the Greek institutional framework with that of the EU will transform how the energy transition is perceived. Examples include Law 4513/2018 on energy communities [12] and the National Energy and Climate Plans (NECPs) [20]. The latter document serves as Greece's foundational strategic roadmap for energy and climate policy up to the year 2030. Both the Special Framework for Renewable Energy Sources (SFSPSD-RES) and the National Energy and Climate Plans (NECPs) state that any islands selected for the utilisation of renewable energy must be connected to the mainland network in order to contribute to the national balance. Additionally, two decisions by the Hellenic Council of State (1421/2013 and 1429/2022) have played a key role in promoting the use of renewable energy sources in island regions, particularly the Cyclades. These decisions recognise the need to consider the unique characteristics of the islands during their energy transition, emphasising the importance of protecting and sustainably managing their natural and cultural resources [21]. Finally, the text of Approval of Stage B1 of the Study *Evaluation, Revision and Specification of the Regional Framework for Spatial Planning and Sustainable Development of the South Aegean Region*, outlines considerations regarding the energy transition of the Cyclades [22]. In conclusion, the Greek institutional framework sets national targets in line with European directives. However, these targets do not consider the country's unique geological, natural, cultural and economic features or its distinct spatial and social units. At a local level, this has consequences, as renewable energy developments are carried out in terrestrial and marine areas without considering how to distribute them more evenly in terms of resilience, sustainability, and social justice.

4 Identifying Dynamic Renewable Energy Hubs in the Cyclades

4.1 Current Context and Dynamics

The energy profile of the Cyclades complex was evaluated using an ArcGIS analysis of official strategic energy planning documents and geoinformatics data [24–27]. The analysis was based on the following four parameters: (1) the climate characteristics of the islands; (2) their integration into the national energy network [i.e. whether they are interconnected (IIs) or non-interconnected (NIIs)], and their contribution to the national energy balance through renewable energy sources (RES/ MRE); (3) their local energy demands; and (4) their potential for renewable energy development within the framework of the national energy transition. Specifically:

Climatic - Geomorphological Advantages: The South Aegean region (the Cyclades and the Dodecanese) has favourable climatic - geomorphological characteristics. Its extensive maritime space makes it ideal for exploiting renewable energy sources. Due to their mountainous terrain and high wind potential, the islands of Andros, Tinos and Naxos are particularly well-suited to the development of wind farms. All islands are ideal locations thanks to their exceptional solar potential.

The Islands' Connection to the National Energy Grid and Intra-regional Networks: Andros and Tinos (Evía, 2003) and Kea (Lavrio, 2003) were the first Cycladic islands to be connected to the mainland grid by an underwater cable. The interconnection of the islands is an ongoing process taking place in phases. Currently, there are two groups of islands: the Interconnected Islands (IIs) and the Non-Interconnected Islands (NIIs). The former includes the northeastern Cyclades (excluding Donoussa and Amorgos, which form part of the Naxos Prefecture), and the latter comprises the southeastern Cyclades (Thira and Milos, with a planned connection), as well as the western Cyclades (Kythnos, Serifos, Sifnos, Milos and Kimolos). The existing connections between the north-eastern Cyclades islands meet most of the region's local electricity needs, forming two energy networks with a local - regional scope: (a) Andros–Tinos; (b) Paros–Antiparos–Ios–Sikinos–Folegandros–Naxos–Schoinoussa–Koufonisi–Irakleia. The main nodes of these networks are the islands of Andros, Tinos, Paros and Naxos (Fig. 5).

Islands	Existing projects in operation (MW)			Recommended projects (MW)		
	Wind farms	Photovoltaic stations (PV)	Total	Wind farms with production licenses and AEPO	Permitted wind farm installations	Total
The focus spatial level of research (Andros, Naxos, Paros, Tinos)						
Andros	20	1,3	21,3	234,6	0	234,6
Naxos	8,76	2,1	10,86	73,6	0	73,6
Paros	3,6	2,5	6,1	73,6	0	73,6
Tinos	2,7	0,8	3,5	23	0	23
Mykonos	3	1,1	4,1	1,8	0	1,8
Milos	2,65	0,7	3,35	0	0	0
Syros	2,64	1,9	4,54	1,7	0	1,7
Sifnos	1,8	0	1,8	0	0	0
Thira / Santorini	1,2	0,7	1,9	0	1,32	1,32
Ios	1,2	0	1,2	0	1	1
Kea	0	0	0	0	4,8	4,8
Kythnos	0,9	0	0,9	0	0	0
TOTAL	**48,45**	**11,1**	**59,55**	**408,3**	**7,12**	**415,42**

Fig. 2. Cyclades: Electricity generated from renewable energy sources: existing and projected following the completion of energy transition projects [own elaboration] (2011–2021) [23–26]

Thermal Power Plants Produce Electricity Using Conventional Sources: Oil-fuelled thermal power stations still largely meet the energy needs of the Cyclades islands. The thermal power stations on Sifnos, Kythnos, Anafi, Donoussa and Amorgos will remain operational until they are connected to the mainland grid. The following island energy networks continue to support energy needs by operating active thermal power plants within their territories and/or on nearby islands: (a) Andros and Tinos, (b) Paros, Antiparos, Ios, Sikinos, Folegadros, Naxos, Schoinoussa, Koufonisi and Irakleia, (c) Milos and Kimolos, and (d) Mykonos and Delos [23–25].

Utilization of Renewable Energy Sources: Fig. 2 provides an overview of energy production in the Cyclades. It illustrates current power production alongside the projected

output of the recommended renewable energy projects, both expressed in megawatts. Compared to Paros and Tinos, Andros and Naxos generate the most energy from renewable sources, primarily from wind farms. Andros's superiority is clear. Conversely, although Paros and Tinos currently show no notable potential, they are expected to play a crucial role in the future [23–26] (Fig. 2).

The data shows that Andros, Paros, Naxos and Tinos stand out among the Cyclades islands in terms of the use of renewable energy sources. These islands have seen the most activity and investment interest in proposed renewable energy projects, particularly wind farms. This is no coincidence. They all have favourable climatic conditions and were among the first islands to be connected to the national power grid. This means that local sources have the capacity to meet not only the energy needs of the Cyclades, but also those of the rest of the country. However, their role in the national energy transition must be considered during the planning process to prevent degradation of the landscape and local identity (Sects. 5, 6).

4.2 Emerging Renewable Energy Hubs: Andros, Tinos, Paros and Naxos

A multifaceted research study was conducted to better understand the role of the four islands in the development of sustainable energy communities. The study evaluated the *seasonality* and *peripherisation* of these islands in the context of an investigation into the various factors that could influence the role of the four islands in establishing sustainable energy communities in the Aegean. This approach enables us to evaluate the energy demands of the islands and neighbouring smaller islands, and determine the feasibility of meeting them using renewable energy sources. The key factors in achieving this are: a) the *development dynamics of the four islands* (i.e. settlement structure, urban density, construction activity, demographic data, production sectors, tourism and infrastructure); b) the *local identity* (i.e., the natural-cultural environment, the landscape, and the memory); and c) the *energy profile*, (i.e. energy sources, consumption and needs). Evaluating the above factors enables us to identify islands that could play a key role in establishing sustainable energy communities, confirming the superiority of Andros, Tinos, Paros and Naxos. Particular attention was paid to assessing the demographic and socio-economic characteristics of the specific islands. To this end, quantitative indicators were used to measure the development dynamics of the islands during critical periods (Fig. 3), while the infrastructure table takes the form of a checklist stating what is available and in what quantity (Fig. 4).

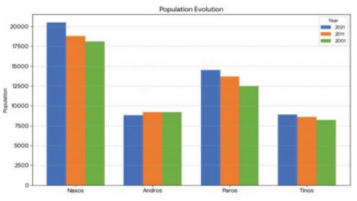
In brief, the findings regarding population change, the local economy, production sectors, tourism development, construction activity and the urban and traditional settlement networks are as follows (22, 25, 26, 27):

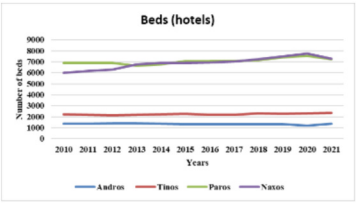
Population change (2011–2021): Naxos experienced the highest population growth (8.86%), followed by Paros and Tinos, while Andros recorded a decline of 4.28%.

Local Economy - Production Sectors (2011–2019): There are significant cultivated areas on all four islands, and beekeeping is also a key activity. The most important livestock areas are found on the islands of Andros, Naxos and Tinos. The main fishing areas are located between Paros and Naxos, and between Koufonisia islands and Amorgos. Hence, fishing activity is mainly concentrated around Paros and the smaller islands of the Naxos archipelago, particularly Amorgos, Irakleia and Schoinoussa. Mining is also an

important industry. The marbles of Paros, Naxos and Tinos are renowned for their quality. Most manufacturing and craft enterprises produce goods related to local traditions and the primary sector. They operate within a limited market. However, some products from Paros, Naxos and Tinos have a wider market (e.g. cheese, wine, local sweets). These islands have facilities for producing, preserving and processing fruit/vegetables (Naxos), meat (Naxos and Tinos) and dairy products (Paros, Naxos, and Tinos). There are also olive mills on the islands of Andros, Naxos and Paros. Between 2011 and 2021, a significant increase in the primary sector (comprising agriculture, livestock and fisheries) was observed in Paros (94.44%) and Andros (31.90%), while Tinos experienced a decline (−4.93%). Tinos experienced the largest decrease in industrial activity, at −21.29%. There was also a decline in construction activity in Andros (−34.19%), Tinos (−31.62%) and Naxos (−26.18%). These decreases may have been affected by the economic crisis. Therefore, the period after 2019, particularly the post-Covid era, will be an interesting time to examine.

	Andros		Tinos		Paros		Naxos	
Island Area (km²)_ Population (2011-2021)								
(km²)	377.69		194.73		196.23		428.4	
	2011	2021	2011	2021	2011	2021	2011	2021
	9221	8826	8636	8934	13715	14520	18904	20578
% change	-4,28%		3,45%		5,87%		8,86%	
Production and Entrepreneurial (2014-2019)								
A_ Primary Sector : Agriculture, Live-stock, Fishery (2014-2019)								
	2014	2019	2014	2019	2014	2019	2014	2019
total units	442	583	365	347	198	385	949	1.026
% change	31,90%		-4,93%		94,44%		8,11%	
B_ Secondary Sector : Craft / Industry (2011-2019)								
	2011	2019	2011	2019	2011	2019	2011	2019
total units	69	60	108	85	139	118	181	163
% change	-13,04%		-21,29%		-15,10%		-9,94%	
C_ Tertiary Sector : Construction (2011-2019)								
	2011	2019	2011	2019	2011	2019	2011	2019
total units	272	179	253	173	498	389	527	389
% change	-34,19%		-31,62%		-21,88%		-26,18%	
C_ Tertiary Sector : Trade (2011-2019)								
	2011	2019	2011	2019	2011	2019	2011	2019
total units	268	210	328	271	673	646	710	626
% change	-0,21%		-0,17%		-0,04%		-0,11%	
C_ Tertiary sector : Recreation/ Leisure (2011-2019)								
	2011	2019	2011	2019	2011	2019	2011	2019
total units	334	286	367	354	958	973	1.059	1.163
% change	-14,37%		-3,54%		1,56%		9,82%	
D_ Tourism Development (2010-2021)								
Hotel beds								
	2010	2021	2010	2021	2010	2021	2010	2021
total	1381	1354	2237	2336	6893	7255	6003	7277
% change	-1,95%		4,42%		5,25%		21,22%	
Overnight stays								
	2010	2021	2010	2021	2010	2021	2010	2021
total	58711	55623	114874	76041	324818	354859	70191	252703
% change	-5,25%		-33,80%		9,24%		260,02%	
E_ Built Surface with Building Permit (2011-2021)								
	2011	2021	2011	2021	2011	2021	2011	2021
total (sqm)	16422	2096	11.342	6739	47.556	62692	32.762	31094
% change	-87,23%		-40,58%		31,82%		-5,09%	
Decade total (sqm)	56.044		63.815		343.358		286.813	
F_ Urban Network TOTAL (traditional settlements) (2021)								
	2021		2021		2021		2021	
total	88 (35) - [40%]		60 (36) – [60%]		75 (10) – [13%]		65 (19) – [29%]	





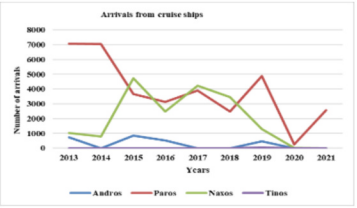
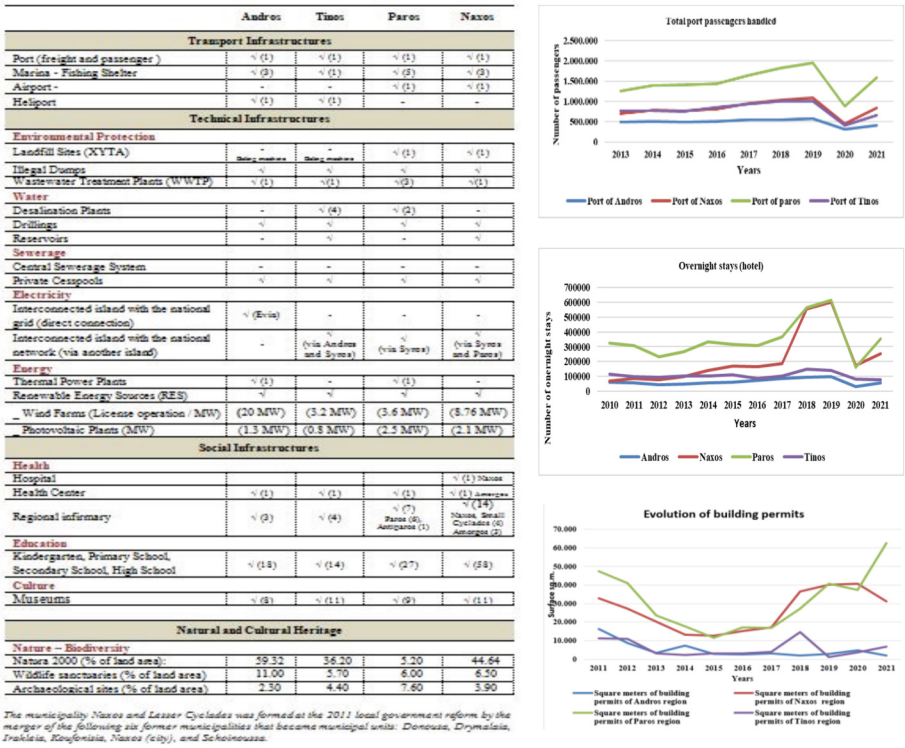


Fig. 3. Demographic and socio-economic characteristics [own elaboration] [23–25]

Tourism Development (2010–2021): In addition to the coastal areas, the inland urban network and traditional settlements are under intense pressure due to the impact of tourism. Thus, alongside areas of intense tourist development, primarily in Paros and Naxos, the mountainous regions of the islands are also witnessing a trend of converting abandoned settlements into holiday homes or short-term rental properties, (Airbnb) particularly in Andros and Tinos. Based on the number of hotel beds, the islands of

Paros, Naxos and Tinos excel as tourist destinations. Although Paros and Tinos are much smaller than Naxos, they have a similar number of hotel beds. At the same time, the 21.22% increase in the number of beds on Naxos threatens the island's sustainability and resilience. Paros, on the other hand, had the most overnight stays, while Naxos had the highest percentage increase (260.02%), establishing itself as a new tourist hotspot. In contrast, Tinos saw a decline of 33.8%. This is an interesting trend to analyse. There is relatively little cruise traffic, primarily due to a lack of infrastructure in Andros and Tinos. Undoubtedly, increased tourism leads to more built-up areas and a higher demand for energy [6, 8–10].



	Andros	Tinos	Paros	Naxos
Transport Infrastructures				
Port (freight and passenger)	√ (1)	√ (1)	√ (1)	√ (1)
Marina - Fishing Shelter	√ (2)	√ (1)	√ (5)	√ (2)
Airport -	-	-	√ (1)	√ (1)
Heliport	√ (1)	√ (1)	-	-
Technical Infrastructures				
Environmental Protection				
Landfill Sites (XYTA)	- Being realized	- Being realized	√ (1)	√ (1)
Illegal Dumps	√	√	√	√
Wastewater Treatment Plants (WWTP)	√ (1)	√(1)	√(2)	√(1)
Water				
Desalination Plants	-	√ (4)	√ (2)	-
Drillings	√	√	√	√
Reservoirs	-	√	-	√
Sewerage				
Central Sewerage System	-	-	-	-
Private Cesspools	√	√	√	√
Electricity				
Interconnected island with the national grid (direct connection)	√ (Evia)	-	-	-
Interconnected island with the national network (via another island)	-	√ (via Andros and Syros)	√ (via Syros)	√ (via Syros and Paros)
Energy				
Thermal Power Plants	√ (1)	-	√ (1)	-
Renewable Energy Sources (RES)	√	√	√	√
_ Wind Farms (License operation / MW)	(20 MW)	(3.2 MW)	(3.6 MW)	(8.76 MW)
_ Photovoltaic Plants (MW)	(1.3 MW)	(0.8 MW)	(2.5 MW)	(2.1 MW)
Social Infrastructures				
Health				
Hospital				√ (1) Naxos
Health Center	√ (1)	√ (1)	√ (1)	√ (1) Amorgos
Regional infirmary	√ (3)	√ (4)	√ (7) Paros (6), Antiparos (1)	√ (14) Naxos, Small Cyclades (4) Amorgos (2)
Education				
Kindergarten, Primary School, Secondary School, High School	√ (18)	√ (14)	√ (27)	√ (58)
Culture				
Museums	√ (8)	√ (11)	√ (9)	√ (11)
Natural and Cultural Heritage				
Nature – Biodiversity				
Natura 2000 (% of land area):	59.32	36.20	5.20	44.64
Wildlife sanctuaries (% of land area)	11.00	5.70	6.00	6.50
Archaeological sites (% of land area)	2.30	4.40	7.60	3.90

The municipality Naxos and Lesser Cyclades was formed at the 2011 local government reform by the merger of the following six former municipalities that became municipal units: Donousa, Drymalaia, Irakleia, Koufonisia, Naxos (city), and Schoinoussa.

Fig. 4. Infrastructures and Natural-Cultural Heritage [own elaboration] [23–25]

Construction Activity (2011–2021): Paros and Naxos have seen the greatest increase in built-up area, followed by Tinos and Andros. However, the data shows that Paros saw a significant increase of 31.82% in the number of new building permits issued, while Andros and Tinos experienced dramatic decreases, namely 87.23% and 40.58% respectively. These new permits are probably intended for large hotels.

Urban Network and Traditional Settlements (2011–2021): Andros and Naxos are similar in size, but Andros has more settlements. Similarly, despite their similar size, Tinos has fewer settlements than Paros. Tinos has the largest percentage of traditional settlements in its urban network by far, followed by Andros. In contrast, Naxos and

Paros have much smaller percentages, giving Tinos and Andros a distinctive traditional character. Therefore, their energy transition must be approached with the utmost respect for their cultural heritage and landscape.

With regard to infrastructure (i.e. transportation, technical and social), as well as elements of natural and cultural heritage, the following is noted [25, 26] (Fig. 4):

Infrastructures: In addition to their main port, which caters for commercial - tourist needs, the four islands have marinas and fishing shelters. Paros Port has the highest passenger traffic index (2013–2021), followed by Naxos and Tinos, with Andros in last place. Paros and Naxos have airports with direct international connections, making them important tourist gateways. Paros has the highest number of arrivals. All the islands face significant technical infrastructure challenges, particularly with regard to water, waste management and energy. These issues are exacerbated during the tourist season. The lack of healthcare and educational facilities is also a cause for concern. However, it is worth noting that there are a significant number of museums and other cultural facilities across the four islands.

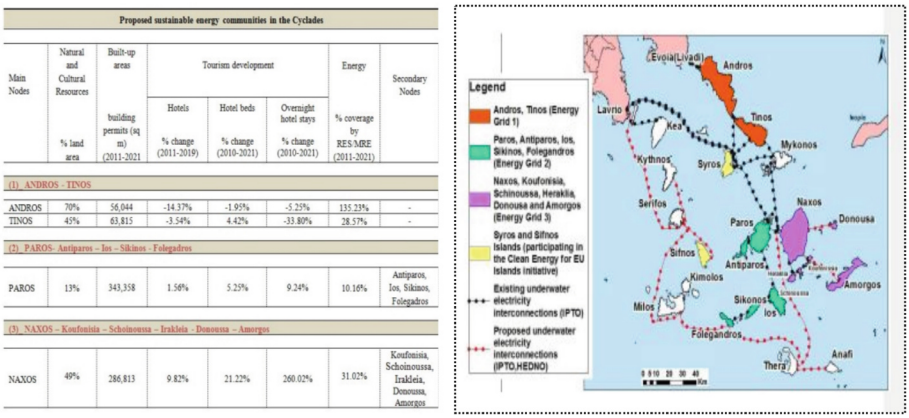
Natural and Cultural Heritage: Only 5.2% of Paros is designated as a protected area, whereas 59.32% of Andros falls within protected areas. There are also marine protected areas on both islands. Overall, approximately 11% of Andros is covered by wildlife sanctuaries, compared to 6.5% for Naxos, 6% for Paros, and 5.7% for Tinos. Paros has the largest percentage of land occupied by archaeological sites (7.6%), followed by Tinos (4.4%), Naxos (3.9%) and Andros (2.3%). Meanwhile, Andros has the greatest number of underwater archaeological sites. It should be noted that some archaeological sites and wildlife refuges are located within Natura 2000 areas. In any case, the intense spatial dispersion of archaeological sites and traditional settlements across the islands poses significant challenges to the planning of their energy transition, particularly with regard to the location and size of renewable energy facilities.

In summary, all four islands boast significant natural and cultural heritage, as well as diverse landscapes. At the same time, some are strengthening their local economies by developing the primary sector. However, all the islands have problems with their technical and social infrastructure. Paros and Naxos are the most dynamic in terms of economic growth. However, both islands are under significant pressure due to intense urban development, particularly along the coast, as well as overtourism. These factors have led to a substantial increase in energy demand. Unfortunately, meeting these requirements remains challenging in Paros and Naxos, despite there being sufficient renewable energy potential. The situation in Andros is better, but remains weak in Tinos. The reason for this is that Greece has no overall plan for its energy transition.

5 Proposed Sustainable Renewable Energy Communities: A Multifactorial Typological Approach Through Networking

This section introduces the proposed sustainable, renewable energy communities in the Cyclades. The primary and secondary nodes of these communities were identified through an assessment of the energy potential of the islands and their capacity to utilise renewable energy sources (1st survey), combined with an investigation into development models that could establish the islands as main hubs in these communities (2nd survey).

Focusing on the development model of the hub islands using demographic and economic indicators provides insight into their energy demands, as well as those of neighbouring smaller islands that depend on them, either directly or indirectly, for development or energy. This is due to the nature and frequency of the energy production required to meet their needs, as well as the degree of interconnection (i.e. whether the islands are connected to the national grid or local grids).



Proposed sustainable energy communities in the Cyclades

Main Nodes	Natural and Cultural Resources	Built-up areas	Tourism development			Energy	Secondary Nodes
			Hotels	Hotel beds	Overnight hotel stays		
	% land area	building permits (sq m) (2011-2021	% change (2011-2019)	% change (2010-2021)	% change (2010-2021)	% coverage by RES/MRE (2011-2021)	
(1) ANDROS - TINOS							
ANDROS	70%	56,044	-14.37%	-1.95%	-5.25%	135.23%	-
TINOS	45%	63,815	-3.54%	4.42%	-33.80%	28.57%	-
(2) PAROS- Antiparos – Ios - Sikinos - Folegadros							
PAROS	13%	343,358	1.56%	5.25%	9.24%	10.16%	Antiparos, Ios, Sikinos, Folegadros
(3) NAXOS – Koufonisia – Schoinoussa – Irakleia - Donoussa – Amorgos							
NAXOS	49%	286,813	9.82%	21.22%	260.02%	31.02%	Koufonisia, Schoinoussa, Irakleia, Donoussa, Amorgos

Fig. 5. Proposed sustainable renewable energy communities in the Cyclades [own elaboration]

In principle, the study identifies three communities that could play a significant role in the Cyclades' energy transition, as well as that of the country as a whole, by using sustainable renewable energy. From north to south, these are: (1) Andros and Tinos, (2) Paros, Antiparos, Ios, Sikinos and Folegadros, and (3) Naxos, Koufonisia, Schoinoussa, Irakleia, Donoussa and Amorgos. All three proposed communities are of particular interest in terms of sustainable energy planning. Specifically, the first energy community could serve as a case study due to the key role its islands play in the country's energy transition and the local-level challenges this role poses, particularly with regard to protecting and managing natural and cultural resources while respecting the islands' vulnerability. Similarly, the second and third renewable energy communities are of equal research interest due to the increased need for connectivity between the main hub islands (Paros and Naxos) and neighbouring smaller islands. This requires the development of smaller-scale energy infrastructure on land and at sea, which is particularly important in vulnerable areas such as island regions, given their fragmented and complex geography (Fig. 5).

The three proposed renewable communities represent an initial identification approach that will require further investigation through pilot studies in a subsequent phase. The aim of these studies should be to identify and measure the developmental and energy demands of the islands within the proposed communities. Thus, the communities will be analysed using quantitative indicators at two basic levels. The first level will focus on identifying how the proposed renewable energy communities could achieve energy neutrality and self-sufficiency. The second will examine how renewable resources on the

islands could be used to generate nationwide energy. The focus will be on developing innovative infrastructure for the production, storage and distribution of energy that takes into account the carrying capacity and local identity of the islands.

6 Open Issues for Building Sustainable Island Communities

In the context of the climate and energy crises, utilising renewable energy sources presents both a challenge and an opportunity to promote sustainability and resilience Research in the Cyclades revealed the need for an integrated island policy to determine the islands' developmental role and their position in the energy sector. Given their size, fragility and characteristics (i.e. *insularity*, *peripheralisation* and *seasonality*), the islands must ensure energy autonomy and protect their natural and cultural resources and landscapes from reckless exploitation within their territories.

Against the backdrop of the ongoing debate on the energy transition, insular countries must seek answers in the form of sustainable energy communities that are ready to utilise available resources while respecting the identity and carrying capacity of the islands. The aim should be for these island communities to generate renewable energy to meet their own needs throughout the year while preserving their unique character. In this context, achieving energy autonomy for the islands must be the main objective. It is also crucial to prevent islands from becoming supra-local hubs for the production, storage and distribution of energy intended for national consumption or export. This is because it could have a negative impact on their territories [8, 10, 28].

In line with this, the research on the Cyclades seeks to highlight the significance of islands and insular regions as research sites. The objective is to highlight the role of islands in the energy transition, paving the way for the identification of sustainable methods of utilising renewable resources through novel practices that honor human scale, local identity and resilience in the next phase. Insular regions can present challenges when it comes to planning renewable energy communities due to their complexity. This is mainly because small-scale installations are required to enable flexibility in energy production and consumption. This is particularly important in the current era, when energy autonomy is a key factor in a country's development policies, given the recent impact of military conflicts on countries that dominate the global energy scenery.

It is clear from the above that a sustainable energy transition and energy self-sufficiency are vital for the resilience and competitiveness of vulnerable island regions. To this end, it is proposed that achieving energy neutrality requires the classification of island development dynamics by type, alongside an evaluation of local energy needs and the challenges presented by each island. Such challenges include factors such as size, the natural and man-made environment, and landscape quality. Therefore, to ensure a successful energy transition, a multifactorial research approach is strongly recommended, assessing geographical, environmental, spatial, socio-economic and energy criteria simultaneously. Issues that need to be investigated at the next stage, with particular attention paid to the local level, include organising new, innovative planning tools for location selection, and developing production, storage, and distribution units [5, 8, 9, 11].

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Beyond the Station: Multimodal Interchange Hubs in Coastal Cities for Urban Integration

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Abstract. Railway stations are increasingly moving beyond their traditional role as mono-functional transport infrastructures and becoming complex multimodal environments, where different mobility systems intersect and where important relationships with urban space are continuously negotiated in relation to accessibility, spatial continuity, pedestrian experience, and the changing role of infrastructure within the city. The issue is particularly relevant in coastal cities, where interchange hubs are shaped not only by transport networks, but also by waterfront conditions, historic urban fabrics, and spatial constraints that are often difficult to reconcile. Starting on this perspective, this paper shows the preparatory work developed before the "Progetto-guida B.5" within the Municipal Urban Plan of Cagliari and it examines multimodal interchange hubs in selected European cities, analysing how transport efficiency, spatial hierarchy, and urban integration are connected in practice. The Cagliari railway station is used as a case study because of its role as a strategic coastal gateway, were metropolitan flows, the historic city, and the maritime edge meet without always forming a continuous urban system. The findings suggest that the "success" of a hub cannot be captured by transit metrics alone, but its effectiveness also depends on the clarity of its spatial organisation, on the readability of pedestrian routes, and on the capacity to maintain continuity across infrastructural barriers. In the case of Cagliari, the coastal station appears as a functional node and also as a possible catalyst for urban restructuring, especially in reconnecting the city's historical identity with its waterfront and future coastal development.

Keywords: Multimodal Interchange Hubs · Coastal Cities · Urban Integration · Railway Stations · Mobility Design · Waterfront Regeneration · Pedestrian Continuity · Cagliari (Italy)

This paper is the result of the joint work of the authors. "Abstract", and "3. Methodological Framework" (with sub-paragraphs) were written jointly by the authors. Chiara Garau wrote "2. Conceptual Framework: Multimodal Interchange and Urban Integration", "5. Discussion: Multimodal Interchange Between Spatial Organisation and Urban Interface" and "6. Conclusions". Francesca Maltinti wrote "1. Introduction". Mauro Coni wrote "4. Case Study: The Cagliari Station Area as a Coastal Interchange". Chiara Garau and Mauro Coni coordinated and supervised the paper.

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1 Introduction

Urban mobility systems increasingly shape accessibility [1–3], spatial organisation [4, 5], and also urban quality [6, 7]. Railway stations and multimodal interchange hubs can be understood as key infrastructural nodes [8], acting both as interfaces between transport modes and as points of contact with between the physical city [9]. Their role therefore goes beyond mobility performance, influencing urban connectivity, socio-spatial interactions, and the wider structure of cities.

As urban environments have become more complex, railway stations have gradually evolved from mono-functional infrastructures into integrated multimodal systems. They are now expected to accommodate different transport modes, manage diverse flows, and ensure accessibility across several spatial and functional layers. For this reason, their design must combine technical efficiency with legible spaces, ease of use, and a clear relationship with public space. However, understanding how to effectively organise these systems remains a significant challenge, particularly in contexts characterised by spatial constraints and overlapping urban functions.

Such a challenge, in coastal cities, becomes even more crucial when interchange hubs are displaced in territories negotiated by the imbalance of transport networks, waterfront dynamics port infrastructures, and an historical stratification of urban fabrics. These conditions introduce discontinuities, conflicts in pedestrian and vehicular flows, as well as challenges of spatial continuity between infrastructure and the urban space. Within such contexts, uncertainty remains about which approaches to design offer the best value in terms of transport efficiency and urban integration.

A key question that authors try to reply in this paper is if multimodal interchange hubs should be mainly designed as transport infrastructures or as urban spaces that can bridge mobility systems and city. More specifically, the question can be finalised by considering spatial organisation strategies such as hierarchical distribution systems, flow separation, and multimodal articulation in a way that can secure operational efficiency as well as urban continuity. Added to this is the issue of active mobility, because contemporary interchange hubs are expected to connect rail, bus, and metro systems, and, at the same time, they have integrate cycling infrastructure within a coherent and legible spatial framework.

Indeed, existing literature highlights the importance of spatial hierarchy, central distribution spaces, and the separation of flows in improving the functionality of complex transport environments [10], but also the role of station forecourts, pedestrian continuity, and the relationship between infrastructure and public space [11–14]. However, these perspectives are often treated separately, without a comprehensive framework that connects internal spatial organisation with external urban integration, especially in coastal cities.

This paper aims to explore this particular issue through a design-oriented perspective, focusing on the relationship between spatial hierarchy, flow separation, and urban integration. The research is based on a comparative interpretation of European contexts and on the analysis of the Cagliari railway station area as a strategic coastal node between the metropolitan system, the historic city, and the waterfront. The objective is to identify recurring spatial principles and discuss their applicability in other coastal environments.

By doing so, the paper contributes to the broader debate on multimodal interchange design by addressing the gap between transport-oriented and urban-oriented approaches and it seeks to clarify how spatial and functional strategies can support the integration of infrastructure within the urban fabric, particularly in contexts characterised by strong environmental and spatial constraints.

In Sect. 2, the conceptual framework on spatial hierarchy, flow separation, and urban integration in multimodal interchange hubs are introduced. Section 3 describes the methodology and the analytical approach adopted in the study and Sect. 4 presents the case study of the Cagliari railway station. The main findings are underlined in Sect. 5 and the conclusions are summarised in Sect. 6, highlighting implications for future research and planning practices.

2 Conceptual Framework: Multimodal Interchange and Urban Integration

The concept of multimodal interchange has progressively evolved in response to broader transformations in urban mobility systems and in the role of transport infrastructures within contemporary cities [15, 16]. Initially associated with the notion of intermodality, a term rooted primarily in freight transport and in the efficient transfer of goods between transport modes, the concept has gradually been reinterpreted in relation to passenger mobility [17, 18]. In this shift, attention has moved beyond technical transfer efficiency measured only through transport indicators, towards the spatial, functional, and experiential organisation of movement, where the quality of public space and the degree of connectivity with urban life are also central to hub performance [8, 9].

In passenger transport contexts, the term multimodal interchange hub more accurately describes a node where different mobility systems, such as rail, metro, bus, cycling, and pedestrian networks, are connected through organised transfer conditions. This broader understanding is especially important because it frames cycling not as a residual mode, but as a potentially constitutive component of interchange hierarchy and station accessibility. This distinction is not only terminological, but it marks a clear shift from the optimisation of freight logistics to the design of environments that support passenger orientation, accessibility, continuity, and ease of movement. In this sense, the multimodal hub is both a transport device and a spatial system shaped around the experience of transition.

This evolution also reflects a broader change in the literature, where stations are increasingly understood not as isolated infrastructures, but as hybrid urban places: transport nodes embedded in the wider fabric of the city. Bertolini's node-place model was particularly influential in establishing this dual interpretation, later expanded by studies emphasising value creation around stations, user experience, and the role of stations in urban restructuring [19, 20]: the performance of interchange environments can be understood through transport indicators, as well as through spatial legibility, quality of public space, and the capacity to connect infrastructure with urban life.

Within this debate, a central issue is the relationship between the station and its ***urban frontage***. This should not be understood only as the architectural façade, but as the wider system of public spaces, access points, pedestrian routes, and transitional areas

through which the station connects with the city [21]. When this interface is accessible, permeable, and spatially well designed, it improves usability and strengthens the socio-spatial value of the station area, also supporting its potential role in urban regeneration [22].

A second focal point of research focuses on how interchange environments are organised internally. In complex transport nodes, where different modes and user flows coexist, a clear spatial structure becomes extremely important to consider and in particular the **hierarchy**, in terms of circulation and of the distribution of functions.

Large interchange systems often depend on central spaces, such as atria or main halls, which help users orient themselves and move through the hub, while secondary areas accommodate specific modes and services [9, 10]. The "atrium-satellite" logic is therefore relevant as a design diagram, and as a conceptual model for understanding how complexity is spatially ordered. As shown in Fig. 1, the atrium usually acts as the main distributive space, while satellites accommodate more specific functions, such as rail access, buses, taxis, car circulation, or pedestrian connections. As stations increase in scale, this logic does not necessarily change; rather, the number and articulation of satellites tend to grow. In larger metropolitan systems, more than one atrium may also be present, each connected to its own set of satellites. Their position and relationship with the main atrium influence not only internal circulation, but also the way the station connects with the surrounding city and shapes external public spaces. This organisational principle will be further discussed through the cases of Paris, Marseille, and Madrid.

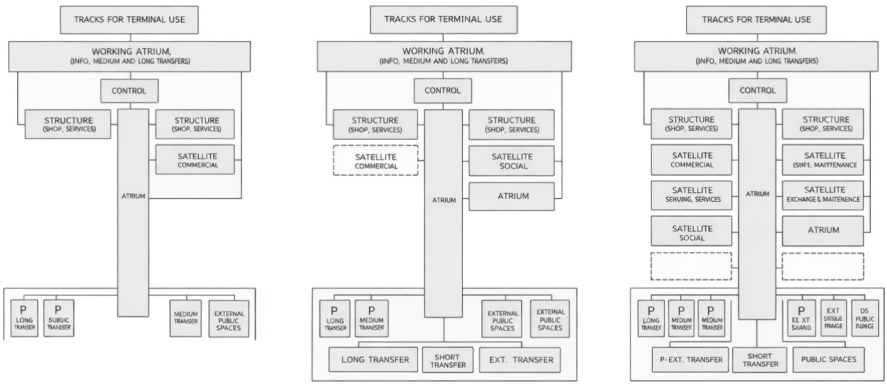


Fig. 1. Atrium–satellite hierarchy in multimodal interchange systems (Paris, Marseille, and Madrid). Source: elaboration by "LAURA PERETTI_architects"

A third important element of research is the **flow separation**. Studies on station design and interchange performance repeatedly show that the coexistence of pedestrian, vehicular, and rail-related movements generates friction when different speeds, directions, and access logics are forced into the same space [23, 24]. For this reason, the organisation of flows into differentiated levels or bands has become a recurrent strategy in contemporary multimodal hubs. Although often framed in technical terms, flow separation has strong spatial implications, since it conditions visibility, continuity, accessibility, and user perception.

A fourth issue is **urban integration**, indeed, stations perform better when they operate as extensions of the surrounding city rather than as autonomous enclaves [25–27]. This means that continuity of pedestrian space, public-space design, frontage permeability, and visual relationships with the urban context are part of interchange performance itself, particularly when passengers move within the hub, and the same hub becomes part of a broader urban system.

Building on these aforementioned statements, the present paper adopts a conceptual framework based on three interrelated analytical dimensions: **spatial hierarchy** (the differentiated organisation of interchange spaces according to role, centrality, and function, **flow separation** (the spatial and often vertical differentiation of pedestrian, vehicular, and rail-related movements), and **urban integration** (the extent to which the interchange hub establishes strong physical, functional, and visual relationships with the surrounding urban fabric). This last one includes the quality of the station frontage, the continuity of pedestrian systems, and the role of the hub in shaping public space and urban accessibility.

These three dimensions are treated in this paper as mutually dependent components of a single interpretative framework. Spatial hierarchy supports legibility, flow separation supports operational clarity and continuity and finally, urban integration supports the transformation of infrastructure into an urban interface. Their interaction provides the analytical basis for the comparative assessment developed in the following section.

3 Methodological Framework

This study adopts a qualitative comparative approach aimed at interpreting multimodal interchange hubs through the analytical dimensions defined in Sect. 2. The methodology is structured in two main components: the analysis of selected European precedents (paragraph 3.1) and the application of the resulting framework to a specific case study (paragraph 4). The objective is not to identify a universal model, but to understand why certain choices worked, as well as to recognise the recurring spatial logics and evaluate their applicability in complex urban contexts.

3.1 Comparative Analyses of Selected European Multimodal Interchange Hubs (Paris, Marseille, Groningen, and Madrid)

In this paragraph, selected case studies are analysed in order to understand different spatial responses to hierarchy, flow separation, and urban integration. The comparative analysis focuses on four European multimodal interchange hubs: Paris Gare de Lyon, Marseille Saint-Charles, Groningen, and Madrid Puerta de Atocha.

Paris Gare de Lyon offers a significant example of a multilayered terminal interchange, where spatial hierarchy, pedestrian continuity, and differentiated urban frontages are closely connected. The station is organised as a distributed system, with tracks located at an upper level, major access halls, and external public spaces that establish direct relationships with the urban fabric. As shown in the aerial views, the interchange is not concentrated in a single node, but articulated through a sequence of spatial devices linking the railway body, the atria, and the adjacent plazas (Fig. 2).

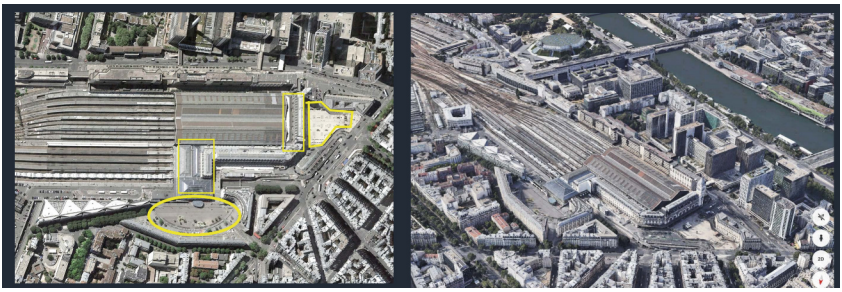


Fig. 2. Paris Gare de Lyon: aerial view of the terminal station, highlighting the two main atria and the principal external spaces of pedestrian access. Source: elaboration by "LAURA PERETTI_architects"

Fig. 3. Paris Gare de Lyon: interior views of the two main atria, showing their role in pedestrian distribution and vertical connection between station levels. Source: elaboration by "LAURA PERETTI_architects"

A central feature of the case is the role of the two main atria. These spaces function as the primary devices for pedestrian distribution and level transition, allowing users to move between the railway platforms, the city level, and the interchange services without compromising overall legibility. In this sense, the atria are not simply interior halls, but key elements in the hierarchical structure of the station, since they connect different levels while preserving continuity with the urban realm (Fig. 3). This case is also significant for the treatment of external public space. On the north-eastern side, pedestrian flows open onto a protected plaza system, while vehicular movement is canalised along dedicated and uninterrupted routes. This arrangement preserves the continuity of pedestrian space and avoids direct interference between pedestrians exiting the station and cars moving through the frontage, demonstrating how surface-level accessibility may be organised through a principle of dominant pedestrian continuity (Fig. 4).

On the south-western side, local traffic, bus services, cycling routes, and pedestrian areas coexist within the same urban edge. However, the case shows that coexistence does not necessarily mean spatial overlap. Each mobility system occupies a recognisable and distinct area, while the urban bus component is positioned laterally rather than directly in front of the main station frontage. This produces an interface that is more articulated than the north-eastern side, but still governed by clear separation between functions

Fig. 4. Paris Gare de Lyon: north-eastern station frontage, characterised by uninterrupted pedestrian and vehicular flows, organised through a clear spatial separation between welcoming pedestrian spaces and predominant, largely monofunctional car circulation and parking systems. Source: elaboration by "LAURA PERETTI_architects"

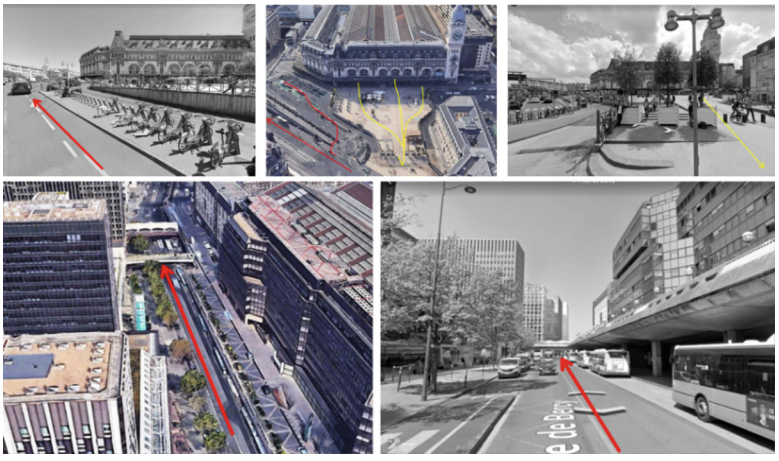


Fig. 5. Paris Gare de Lyon: south-western station frontage and right-hand side, characterised by cycle-pedestrian flows, welcoming public squares, and bus departure areas, with local neighbourhood traffic running longitudinally at city level and public space organised through clearly separated zones to avoid conflicts between vehicular circulation and pedestrians exiting the interchange hub. Source: elaboration by "LAURA PERETTI_architects"

and by readable transitions between modes (Fig. 5). The internal logic of the Paris case is further clarified by the schematic material representing the so-called "track model", where pedestrian, rail, and vehicular/bus flows are organised in distinct bands and across differentiated levels. In this configuration, flow separation is not a secondary technical solution, but the spatial principle that structures the station as a whole.

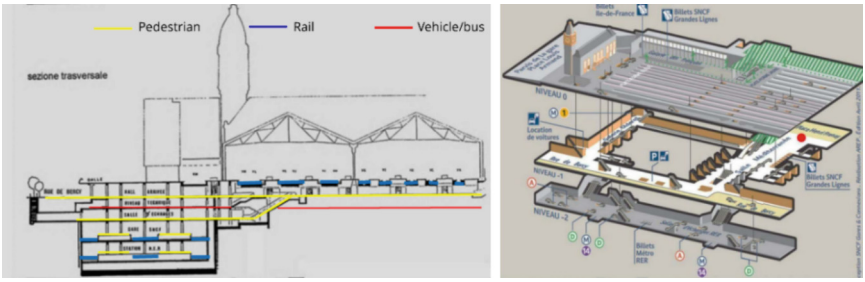


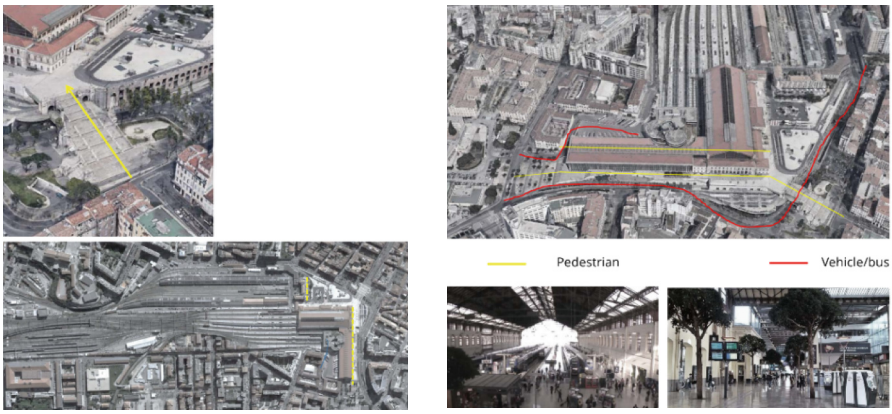
Fig. 6. Paris Gare de Lyon: a "track-based" model structures the entire station layout, with pedestrian, vehicular, and rail flows systematically ordered and separated into vertically organised, largely monofunctional bands, while the station halls play a fundamental role in reinforcing this hierarchy and mediating the relationship with the city. Source: elaboration by "LAURA PERETTI_architects"

The atria are essential to this system because they maintain hierarchical coherence and mediate between the different layers of movement (Fig. 6). A further aspect concerns the vertical allocation of parking and service functions. At Gare de Lyon, parking is positioned below the main station level, using the difference in height between the railway and the city to free the surface for predominantly pedestrian uses. This confirms that the quality of the station frontage depends not only on its formal design, but also on the capacity to move conflicting functions away from the main public interface. Paris Gare de Lyon is therefore significant because it shows how a large terminal station can work through a coordinated system of atria, differentiated frontages, layered circulation, and strong pedestrian continuity. In this case, spatial hierarchy and flow separation clearly support urban integration within a dense interchange environment.

Marseille Saint-Charles, instead, is especially relevant for understanding the relationship between interchange design and urban topography. Located above the city, the station has developed through successive phases of expansion and repositioning, combining historical and more recent components within a multilayered system. Rather than treating topographical difference as a barrier, the station transforms it into an organising principle through terraces, monumental stairs, vertical circulation devices, and distributed access spaces (Fig. 7.a).

A key feature of the Marseille case is that the principal atrium is located at the same level as the tracks, while a long lateral hall extends toward the city as a predominantly pedestrian space. The hall operates not merely as an internal corridor, but as an urbanised distribution environment, almost a protected boulevard, capable of managing both rail passengers and the arrival of extra-urban coach services. In this sense, the station frontage is not limited to an entrance façade, but unfolds as a linear public interface between the rail system and the city (Fig. 7.b).

The external terraces are central to this arrangement, as they absorb the height difference between the station and the city while creating visual and functional continuity with the urban fabric below. Together with ramps and vertical connections, they give Marseille Saint-Charles a strong landmark quality without compromising the legibility



a. Aerial view and its relationship with the surrounding urban fabric

b. Atrium at track level and long lateral hall as a pedestrian urban frontage.

Fig. 7. Marseille Saint-Charles: Multilevel terminal station. Source: elaboration by "LAURA PERETTI_architects"

of flows. The case also shows how an elevated terminal station can work both as a transport node and as an urban threshold. By placing parking and service functions below the public surface, the upper levels can remain largely dedicated to pedestrian continuity and the quality of public space. In this way, the Marseille case demonstrates that multilevel organisation can support both operational efficiency and urban integration, provided that the hierarchy of spaces remains clear and the pedestrian system remains dominant(Fig. 8).

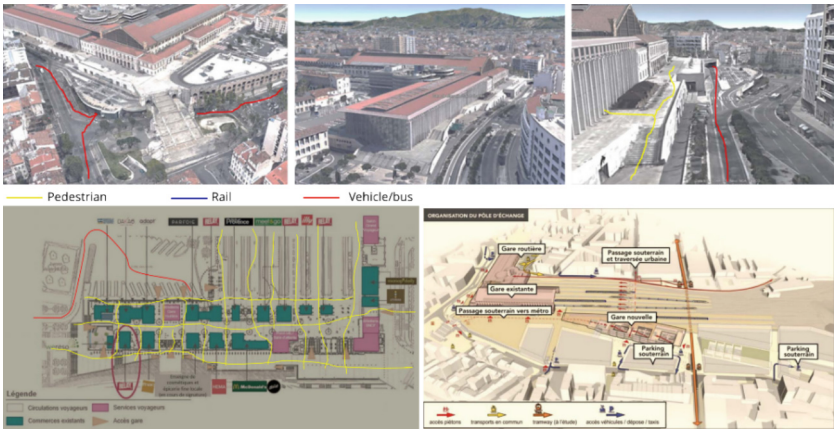


Fig. 8. Marseille Saint-Charles: terraces, vertical circulation, and sub-surface service organisation in the multilevel interchange system. Source: elaboration by "LAURA PERETTI_architects"

Analytically, Marseille is important because it demonstrates four interrelated conditions: the use of topography as an infrastructural resource; the effectiveness of an atrium

located at track level; the role of the hall as an urban frontage rather than a residual corridor; and the capacity of terraces and vertical circulation devices to transform level changes into a coherent public-space system.

Groningen offers a specific contribution with regard to cycling integration. Unlike the other cases, it foregrounds bicycle infrastructure not as a secondary or residual function, but as a structurally integrated component of the interchange system (Fig. 9).

The case is therefore especially relevant in extending the comparative framework beyond the conventional railway-bus-pedestrian triad and in demonstrating how non-motorised mobility can be incorporated into multimodal hubs through dedicated, recognisable, and autonomous spatial devices. In Groningen, cycling is not appended to the station as an accessory service, but spatially embedded within the overall interchange logic. Access, storage, and circulation related to bicycle mobility are organised through clearly identifiable areas that maintain direct connections with the main station system while avoiding interference with the principal pedestrian flows.

Fig. 9. Groningen station area: transformation of the surroundings into a dynamic urban zone centred on the 19th-century railway station (Source: [28]) Source: elaboration by "LAURA PERETTI_architects"

This makes the case particularly useful in showing that multimodal integration does not only concern the coexistence of motorised systems, but also the capacity to provide infrastructural dignity to active mobility. A second relevant aspect concerns the compactness of the configuration. Compared with larger and more monumental cases, Groningen shows that multimodal effectiveness can also depend on a compact but clearly organised spatial structure. Its value lies in the legibility of modal relationships and in the precise position assigned to each component within the overall hierarchy. In this sense, the cycling system can be read as a specialised satellite, directly connected to the station core but able to function autonomously. This broadens the idea of multimodal hierarchy beyond rail and bus systems and highlights the need to give active mobility a dedicated and recognisable role.

Analytically, Groningen is important because it demonstrates four interrelated conditions: the structural integration of cycling within the interchange system; the effectiveness of compact yet legible modal organisation; the role of dedicated bicycle infrastructure as a specialised satellite; and the capacity of non-motorised mobility to become a constitutive, rather than residual, component of multimodal hierarchy. In comparative terms, Groningen is important not because of monumental scale, but because it demonstrates that multimodal effectiveness may also depend on the integration of active mobility within a compact and highly legible interchange structure.

Madrid Puerta de Atocha represents a significant case of transformation and adaptive reuse. The redevelopment combines layered spatial organisation with the refunctionalisation of the former station building, which becomes a major public interior rather than an obsolete railway structure. The case is especially relevant for the way it distributes flows through sequences of spaces, satellites, and transitional devices, while maintaining the overall legibility of the interchange. A key aspect is the reuse of the former station as a large central public interior. Rather than being left at the margins of the new infrastructure, the historic building becomes a major pedestrian space, supporting movement, orientation, and waiting functions. This shows how adaptive reuse can strengthen the hierarchy of a multimodal hub instead of weakening it (Fig. 10a). A second important feature is the organisation of pedestrian systems across different levels. The material shows that Madrid does not rely on a single monumental connector, but on a distributed sequence of spaces and devices, including the circular interchange element that operates as a compact atrium-satellite. This relatively small but strategically positioned component resolves vertical transitions between subsurface levels and the city plane without compromising the separation between pedestrian and vehicular movement. In this respect, the case confirms the role of distributed hierarchy and compact connectors within large-scale interchange systems (Fig. 10b).

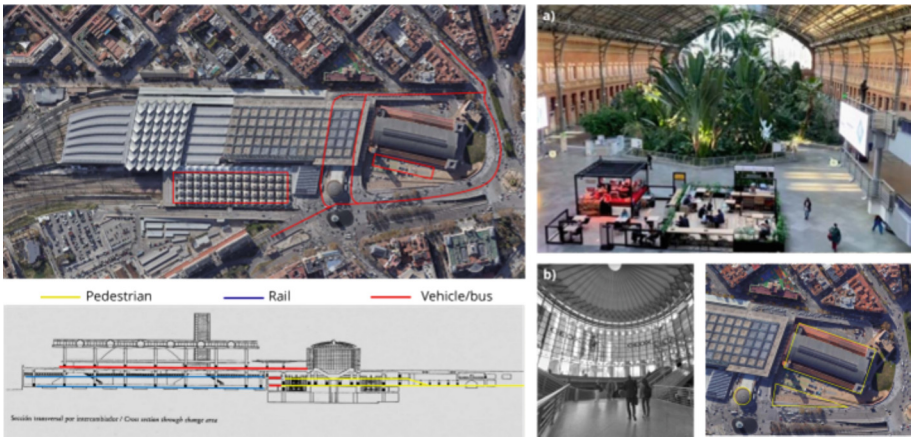


Fig. 10. Madrid Puerta de Atocha: (a) former station reused as a large public atrium and pedestrian interior; (b) circular atrium-satellite organising multilevel pedestrian movement and vertical transition between subsurface interchange spaces and the city plane. Source: elaboration by "LAURA PERETTI_architects"

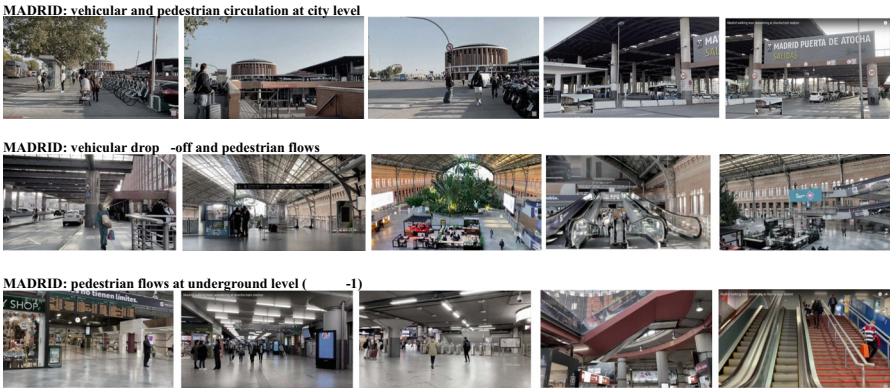


Fig. 11. Madrid Puerta de Atocha: differentiated pedestrian and vehicular systems across city level and subsurface interchange spaces. Source: elaboration by "LAURA PERETTI_architects"

The case is also particularly valuable for the clear differentiation between pedestrian and vehicular systems at city level and below it. Surface circulation, drop-off areas, and internal pedestrian sequences are organised so that overlap is minimised and transitions remain legible. At the same time, the coexistence of reused historical space and new transport infrastructure demonstrates that spatial continuity can be maintained even in highly transformed and enlarged station environments (Fig. 11).

Table 1. Multimodal Interchange Comparison

Case study	Rail level	Atrium / main distribution spaces	Pedestrian levels and connections	Cycling and micromobility	Parking system	Urban bus system	Regional / extra-urban bus system	Metro / rapid transit
Paris Gare de Lyon	+1 elevated	Multiple atria (multilevel)	0.00 city level; −1; (−2), (−3) functional	0.00 city level	Limited at grade; −1	0.00 city level (SW side, longitudinal)	Absorbed by RER and regional metro	−2; −3
Marseille Saint-Charles	+3 elevated	+3 (atrium at track level)	+3; +2	At grade	At grade; −1; −2	+2	+2	−2; −3
Madrid Puerta de Atocha	+1 elevated	−1 (tropical hall); 0.00 city level (bus atrium)	0.00 city level; −1	0.00 city level; −1	At grade; +1; −1	At grade	At grade	−2
Groningen	0.00 at grade	Main hall + cycling satellite	0.00 city level; direct connections	Dedicated cycling level and storage	Limited at grade; peripheral	At grade, integrated but separated	At grade	No metro

Madrid Puerta de Atocha is analytically relevant because it shows how adaptive reuse, distributed hierarchy, compact atrium-satellite devices, and layered circulation

can work together within a complex interchange environment. The case demonstrates that even a highly transformed station can preserve clarity and continuity when historic spaces, large passenger flows, vertical transitions, and modal connections are organised within a coherent spatial structure.

Taken together, the selected cases are interpreted through the three analytical dimensions introduced in Sect. 2: spatial hierarchy, flow separation, and urban integration. Rather than focusing on performance indicators, the comparative reading examines how each precedent organises circulation, structures relationships between modes, and defines its interface with the surrounding urban context.

Across the cases, a set of recurring spatial conditions emerges: the central role of atria or major halls in structuring hierarchy; the systematic separation of incompatible flows through levels and monofunctional bands; the use of vertical organisation to absorb complexity; and the transformation of the station frontage into an active urban interface. These conditions are not dependent on scale or form alone, but on the coherence between spatial organisation and modal articulation. At the same time, the comparison shows that these principles are not directly transferable as fixed solutions. Their effectiveness depends on the capacity to adapt them to specific urban conditions, including spatial constraints, topographical differences, and infrastructural discontinuities. Table 1 shows the comparison between the four stations analysed.

The relevance of the comparative analysis lies not in identifying ideal models, but in constructing an interpretative framework that can be tested in more complex and constrained environments. This is precisely the rationale for introducing, in the following section, a coastal case study characterised by strong spatial limitations and by a critical relationship between transport infrastructure and urban continuity.

4 Case Study: The Cagliari Station Area as a Coastal Interchange Node

Following the comparative analysis, the study focuses on the Cagliari railway station area to test the conceptual framework in a constrained coastal context. The site is located between the metropolitan mobility system, the historic city, and the port waterfront [29, 30], making it a particularly relevant case for examining spatial hierarchy, flow separation, and urban integration (Fig. 12). Its complexity derives from several overlapping conditions: limited space, proximity to the waterfront and port infrastructures, a historically stratified urban fabric, archaeological sensitivity, reclaimed land, and fragmented property arrangements. These factors create discontinuities between infrastructure and urban space and reduce the possibility of applying standardised interchange solutions.

For these reasons, the Cagliari station area is not used simply as an illustrative example, but as a critical test case. It allows to assess how the principles identified in the comparative analysis can be applied, adapted, or reinterpreted in a coastal environment marked by constraint, discontinuity, and strong infrastructural pressure.

From an analytical perspective, Cagliari is significant because it brings together, within a limited area, many of the tensions identified in the comparative framework: a weakly legible spatial hierarchy, partial overlap between pedestrian and vehicular flows, and discontinuity between the station frontage, Via Roma, and the waterfront. At the

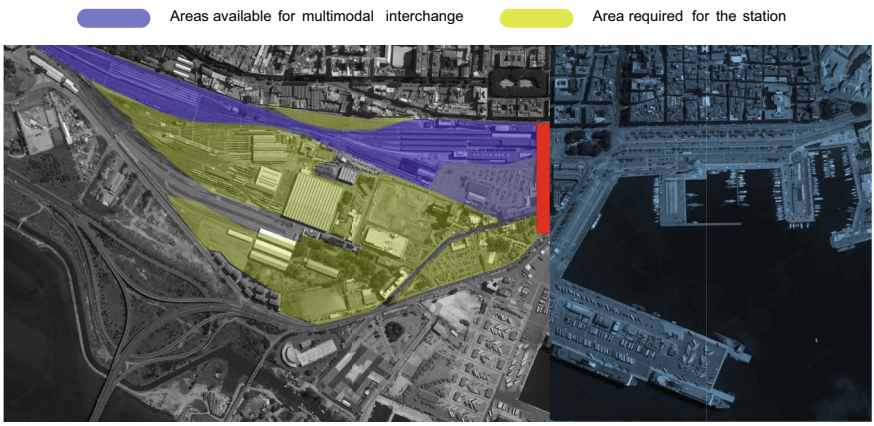


Fig. 12. The Cagliari station area between metropolitan access and historic urban structure. Source: elaboration by "LAURA PERETTI_architects"

same time, its position gives the station a strong latent potential as a gateway between metropolitan mobility, the historic fabric, and the seafront. This potential is limited by several site-specific constraints, including archaeological sensitivity, reclaimed land, the historical shoreline, and fragmented property and infrastructural arrangements. For this reason, Cagliari is not relevant because it replicates the international precedents, but because it tests how their principles can be adapted under more constrained coastal conditions.

The case suggests that an effective reorganisation would require a clearer hierarchical structure, centred on a dominant pedestrian interchange space at city level; a better redistribution of incompatible flows, possibly through differentiated or vertical arrangements; and stronger physical and visual continuity between the station, public space, and the waterfront. Cycling and micromobility should also be treated as dedicated and connected components of the interchange system, rather than as residual surface functions.

Seen in this way, the Cagliari station area does not yet fully operate as a multimodal interchange hub. However, its spatial position and structural conditions make it a critical site for redefinition. These analytical considerations may also be understood as preliminary to the broader study of the Cagliari station-port area, which in the Progetto-guida B.5 is framed as a strategic urban transformation zone aimed at reconnecting the historic city, the waterfront, and the intermodal node through a new covered atrium, improved permeability from Via Roma, reorganised bus facilities, and a wider transition toward a "15-min district".

Within the conceptual framework adopted in this paper, urban integration is interpreted as the capacity of the station to operate as a gateway between different urban systems. In this sense, the Cagliari case highlights the need to redefine the station not only as a transport node, but as a spatial interface capable of connecting metropolitan accessibility with local urban continuity and the waterfront.

This requires the construction of a continuous pedestrian system, the strengthening of the station frontage, and the establishment of clear visual and physical connections between the station and its surroundings.

When considered together, the three analytical dimensions reveal that the main issue is not the presence or absence of specific infrastructural elements, but the lack of an integrated spatial logic capable of coordinating them.

The Cagliari station area does not yet fully operate as a multimodal interchange hub in the sense defined in this paper. However, its spatial position and structural conditions offer a significant opportunity for redefinition. At the same time, the case acquires additional relevance because these analyses may be read as preliminary to a broader strategic reflection on the station-port area, where the intermodal node is already conceived, at the project-guide level, as a central device for reconnecting the historic city, the waterfront, and the wider metropolitan system.

The analysis suggests that the station can be interpreted as a **coastal gateway** if spatial hierarchy, flow separation, and urban integration are addressed simultaneously. This implies moving from a fragmented configuration to a coordinated system in which internal organisation and external relationships are conceived as part of the same spatial structure. This interpretation provides the basis for the discussion developed in the following section, where the implications of the analysis are generalised and related back to the research questions introduced at the beginning of the paper.

5 Discussion: Multimodal Interchange Between Spatial Organisation and Urban Interface

The comparative analysis and the Cagliari case study make it possible to return to the initial research questions, particularly the relationship between transport efficiency, spatial organisation, and urban integration. The findings show that multimodal interchange hubs cannot be understood only as transport infrastructures, nor simply as urban spaces. They work as hybrid systems, where operational performance and spatial quality are closely connected. In this sense, the node-place relationship should not be read as a contrast, but as a condition that needs to be spatially organised.

A central result concerns the combined role of **spatial hierarchy, flow separation, and urban integration**. In fact, hierarchy supports orientation and legibility, while flow separation helps manage pedestrian, vehicular, and rail movements more safely and efficiently. However, separation alone is not sufficient: if it is not supported by accessible and continuous connections, it can create new discontinuities and weaken integration. Urban integration is therefore essential, especially when stations are expected to work as extensions of the city rather than as isolated infrastructures.

The Cagliari case confirms this point in a particularly constrained coastal context. Unlike the comparative precedents, it operates within a dense system of spatial, historical, infrastructural, and environmental limitations. For this reason, the principles identified in the analysis cannot be applied as fixed models, but must be adapted as flexible strategies. The station can therefore be interpreted as a **gateway**, linking metropolitan accessibility, the historic urban fabric, and the waterfront.

The station can operate as a threshold between different urban systems, linking metropolitan accessibility, local urban structure, and the waterfront. This interpretation provides a more comprehensive understanding of interchange hubs, particularly in contexts where spatial discontinuities are more pronounced. These findings contribute to the ongoing debate on multimodal interchange design by emphasising the need for integrated analytical frameworks capable of bridging transport and urban perspectives.

6 Conclusions

This paper has analysed selected case studies of railway stations and has shown that multimodal interchange hubs cannot be understood only as transport infrastructures. The cases examined highlight three main aspects: spatial hierarchy is essential to make complex systems legible; flow separation helps organise pedestrian, vehicular, rail, bus, and cycling movements without unnecessary conflicts; and urban integration is what allows the station to work as part of the city rather than as an isolated node. Taken together, these elements show that the effectiveness of an interchange hub depends not only on transport performance, but on the way space is structured to support movement, orientation, and continuity with the surrounding urban fabric.

The Cagliari case confirms the relevance of this approach in a coastal context, where the station area is shaped by spatial constraints, historical layers, port-related infrastructures, and discontinuities between the city and the waterfront. In this sense, the station can be read as a gateway between metropolitan accessibility, the historic city, and the maritime edge. This work also operated as a preliminary analytical step for the broader reflection later developed in the Progetto-guida B.5, where the station-port area is framed as a strategic urban transformation zone aimed at reconnecting the historic city, the waterfront, and the intermodal node through a new covered atrium, improved permeability from Via Roma, reorganised bus facilities, and a wider transition toward a“15-min district”. Overall, the paper contributes to the debate on multimodal interchange design by emphasising the need for integrated and context-sensitive approaches. Future research may extend this framework through quantitative analyses and by testing its applicability across different urban conditions.

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Strategic Planning of Integrated Public Transport and Demand-Responsive Transport Systems Through PESTEL, SWOT, TOWS Analyses: The Case Study of Enna

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Abstract. Today, the planning of public transport systems must pay greater attention to growing and emerging contexts such as peri-urban areas, which are characterised by low demand, complex topography and socio-territorial fragility. Indeed, these areas require in-depth study, starting with the development of analytical tools capable of supporting evidence-based strategic decisions. Within this framework, this study analyses the potential for integration between local public transport (LPT) and demand-responsive transport (DRT) services through the combined application of three different types of analysis: PESTEL (Political, Economic, Social, Technological, Environmental, Legal), SWOT (Strengths, Weaknesses, Opportunities and Threats) and TOWS (Threats, Opportunities, Weaknesses and Strengths).

These techniques are adopted as a method for understanding the main external factors affecting a transport service (political, economic, social, technological, environmental and regulatory) and as tools to support strategic planning. The methodological approach is applied to the case study of the city of Enna, in southern Italy, an urban context representative of Italy's inland areas, characterised by significant topographical variation, discontinuous settlement patterns and marked inequalities in accessibility between different urban zones.

The results obtained from the three-step analytical process indicate an effective decision-support tool for various categories of stakeholders: indeed, for service operators, this approach provides operational guidance for optimising service provision and improving economic efficiency; for local authorities, it provides a structured basis for defining integrated mobility policies and for the effective allocation of public resources; for citizens, it translates into improved access to essential services, greater territorial equity and a higher overall quality of the public transport system. This research therefore contributes to the preliminary development of more inclusive, resilient and sustainable mobility models, particularly in urban contexts within inland areas.

Keywords: PESTEL · SWOT · TOWS · Integrated transport service PT-DRT · Accessibility · Mobility Plan and Design

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1 Introduction

The evolution of public transport in suburban and peri-urban areas is shifting away from a rigid traditional model, based on fixed timetables and infrequent services, towards more flexible, smart and sustainable systems, which are essential for ensuring accessibility and reducing social isolation [1–3].

In recent years, the integration of local public transport (LPT) and demand-responsive transport (DRT) services has been increasingly established as a key strategy for addressing the challenges faced by traditional transport systems, particularly in areas characterised by low demand, scattered settlements and a growing focus on accessibility and territorial equity [4, 5].

In Italy, DRT services have mainly developed as complementary solutions to conventional public transport, often serving as a substitute or supplement in outlying areas, small towns and at times of low demand [6, 7].

In the international context, particularly in the countries of Northern and Western Europe (Germany, the Netherlands, Scandinavia), DRT is, on the other hand, increasingly seen as a stable and integral part of the public transport system [8–11].

In such cases, integration with the PT takes place at the operational, tariff and information levels, with DRT services primarily acting as feeders to high-capacity lines, supported by advanced digital platforms and established governance models [12].

Outside Europe, particularly in North America and certain parts of Asia, DRT has also developed through public-private partnerships and MaaS (Mobility as a Service) solutions, with a greater focus on operational efficiency and service scalability [13].

Initiatives in Italy, generally promoted by local or regional authorities and funded through public funds, are characterised by a strong focus on social inclusion and access to essential services, but still show a limited degree of structural integration with the PT in terms of network planning, standardised pricing and digital platforms [14, 15].

Overall, whilst international experience shows a growing maturity in the integration of PT–DRT as part of a multimodal, data-driven transport system [16], the situation in Italy reveals a more gradual evolution, closely linked to local pilot schemes and temporary funding programmes.

However, the growing uptake of Sustainable Urban Mobility Plans (SUMPs), the focus of national policies on inland areas, and the availability of European funding are key factors enabling a gradual transition towards more structured models of PT–DRT integration, in line with international best practice [17–19].

To plan and implement complementary transport services, Table 1 provides a summary of the main benefits and challenges of integrating PT and DRT services.

To plan optimal services in island contexts and inland areas characterised by low transport demand and the absence of certain transport services, this paper outlines in paragraph 2 the development of analyses targeting different stages of the planning process, which are complementary to one another, particularly in the case of designing a DRT service in Enna, namely:

- A strategic (macro) PESTEL analysis to be carried out at the initial stage of planning to analyses the external environment and thus determine whether the conditions exist for developing the service and which factors may influence it [20, 21].

Table 1. Summary of the main benefits and challenges arising from the integration of PT-DRT services

Dimension	Pros (benefits)	Cons (drawbacks)
Geographical accessibility	Extension of the service to low-density areas with complex terrain	Uneven coverage if demand is very scattered
Social equity	Improved access for the elderly, students and vulnerable users	Risk of exclusion for non-digital users
Operational efficiency	Reduction in empty runs compared to fixed-route public transport	High unit costs if demand does not reach a minimum threshold
Service flexibility	Dynamic adaptation to timetables and routes	Less predictability compared to fixed timetables
Network integration	Feeder service to the main public transport network	Need for close coordination of timetables and hubs
User experience	Booking, information and integrated travel	Complexity of the interface if not well designed
Environmental sustainability	Reduction in unnecessary kilometres and potential modal shift	Limited environmental benefits if the average load is low
Governance	Flexible tool for policies in inland areas	High administrative and contractual complexity

- A SWOT analysis at the strategic-intermediate level – i.e. following the PESTEL analysis – to assess the system's positioning (internal strengths and weaknesses, external opportunities and threats) and thus establish an overall vision for the project [22–24].
- A TOWS analysis at the strategic-operational level to define a more advanced phase, in which action is taken by combining the results of the SWOT analysis to establish concrete strategies and courses of action for the implementation of the service [25, 26].

Section 3 applies the three analyses to the case study of Enna and the proposed implementation of the DRT-PT service, thereby offering a series of considerations aimed at translating the analysis into concrete strategies applicable to the Enna case study (Sicily). The discussion and conclusions section highlights the possible strategies and tools for implementing the integrated service, providing ideas for the various stakeholders involved.

2 The Use of PESTEL, SWOT and TOWS Analysis in the Planning of Integrated Transport Services

The use of PESTEL, SWOT and TOWS analyses in the planning of integrated transport services represents a structured methodological approach to systematically addressing the complexity of the mobility sector. PESTEL analysis enables an examination of the external context (macro-environment) in which the transport system operates, considering political, economic, social, social, social, technological, environmental and regulatory factors that may influence the feasibility and development of the service.

This allows decision-makers to identify opportunities and constraints as early as the preliminary stages of planning [27, 28].

Subsequently, the SWOT analysis complements this perspective through a situational analysis: it examines factors both within and outside the system – such as available resources, operational capabilities and organizational challenges – and relates them to the opportunities and threats arising from the external environment. In this way, it provides a comprehensive overview of the integrated transport service's positioning, which is useful for guiding strategic decisions [23, 29].

Finally, the TOWS analysis enables the results of the SWOT analysis to be translated into operational strategies, combining strengths, weaknesses, opportunities and threats to define concrete actions. This step is essential for moving from the analytical phase to the decision-making and planning phase, identifying effective solutions to improve integration between different transport services [25, 30].

Overall, the combined use of these three analyses enables the development of more informed, coherent and results-oriented planning, facilitating the creation of integrated transport systems that are more efficient, sustainable and responsive to local needs.

The main differences between the three methods are summarised in Fig. 1, namely the shift from PESTEL as an integrated analysis of external factors to an analysis of factors related to the service to be planned, via SWOT analysis, and from a planning approach to a strategic one through TOWS analysis.

The application of these three approaches in planning a DRT service offers several advantages but also presents certain challenges.

Among their main strengths, these methodologies provide a structured and comprehensive overview of the context (PESTEL), enable an integrated assessment of internal and external factors (SWOT), and translate the analysis into concrete operational strategies (TOWS), thereby supporting more informed and consistent decision-making. However, they also have certain limitations, as they are often based on qualitative and subjective assessments, can oversimplify the actual complexity, and do not directly provide definitive solutions, thus requiring further investigation and quantitative analysis for effective planning. The following section outlines the main features of the PESTEL, SWOT and TOWS analyses applied to the case study, whilst also considering the evaluation of composite indicators.

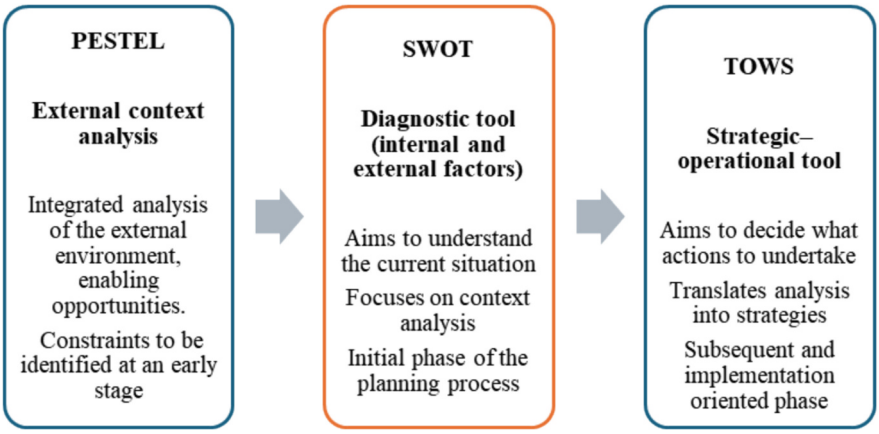

Fig. 1. Comparison of PESTEL (external analysis), SWOT (diagnosis), and TOWS (action) for the preliminary complementarity analysis between public and demand-responsive transport. The arrows indicate the evaluation process of factors, shifting from external analysis to potential actions to be implemented.

3 Methodology

The analysis begins with a brief description of the case study, before moving on to the structure of the PESTEL analysis, the identification of the four key elements of the SWOT analysis, and the identification and segmentation of the analysed context, to consider a range of parameters relevant to the strategic approach. Finally, the TOWS approach is outlined, which combines the SWOT factors to generate operational strategies.

3.1 Case Study Description

The study area analysed is the municipality of Enna, in Sicily (Italy), the location of which is shown in Fig. 2. The population living in the urban area of Enna is estimated at around 24,000–27,000, to which should be added around 10,000 commuters, comprising both workers and university students. The context of Enna is particularly well-suited to the introduction of a demand-responsive transport (DRT) service integrated with public transport, due to a combination of geographical, demographic and infrastructural factors.

The LPT in Enna is operated by a private company, providing connections between the various parts of the city, between Enna Alta (the historic centre) and Enna Bassa (the university and services area) via five urban routes. Route 3 is one of the main routes, offering a frequent service (approximately every 7–10 min). The routes cover key locations: the historic centre, Enna Bassa, the Tropea complex (Contrada Ferrante), and the Pergusa area.

Generally, the frequency of the other routes is approximately every 15–20 min on weekdays and roughly every hour on public holidays.

A free evening/night shuttle service has been in operation for about a year, connecting Enna Alta (Castello di Lombardia) with Pergusa area. It runs on certain evenings (Fridays and Saturdays) with services until 02:45, to facilitate safe travel during the nightlife. Currently, a single-journey ticket costs €1.20 and is valid for 60 min. The cost rises to €1.50 if the ticket is purchased on board. Monthly passes are available with discounts for specific groups (such as students and the elderly).

There is only one taxi service and a few private hire services, whose fares are significantly higher than those of public transport. Ultimately, public transport services today require a review and the introduction of additional systems and new timetables.

The introduction of a PT-DRT transport service can improve service provision, reduce costs and increase inclusivity, making the mobility system more effective and modern. In particular, the context of Enna offers ideal conditions for the implementation of such a service, as it is characterised by dispersed transport demand due to the complexity of its territory. It faces limitations regarding traditional transport and requires improved services in terms of accessibility.

Furthermore, as a town with a population of under 25,000 and approximately 12,000 commuters (e.g. workers and university students), it can be classified as a small-to-medium-sized town and is therefore a simpler case study to manage; where the potential integration of the service requires lower investment compared to metropolitan cities and allows for the creation of a pilot scheme that can be replicated elsewhere.

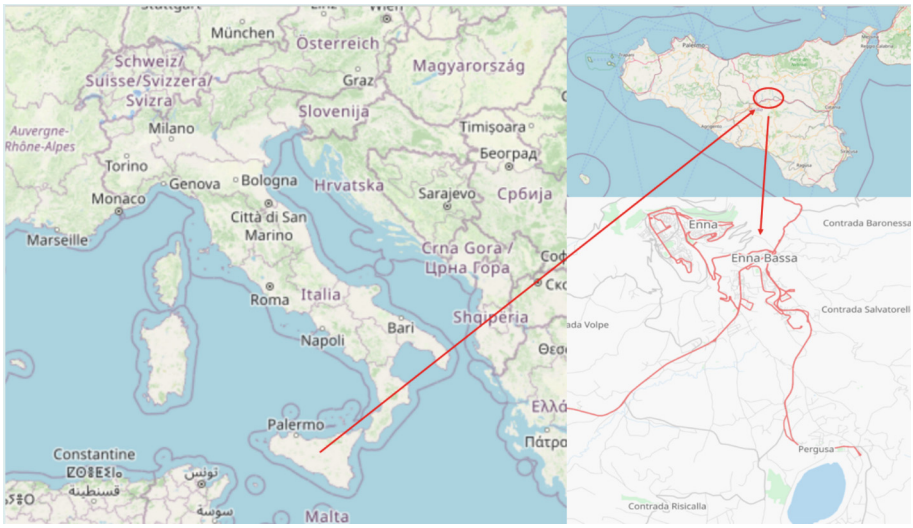

Fig. 2. Map of Italy highlighting Sicily with two zoomed-in insets of the Enna area (Enna Alta, Enna Bassa, and Pergusa). Red lines connect the main map to these detailed sections, showing the local road network and geographical context.

3.2 PESTEL Analysis

A PESTEL analysis can tangibly improve the planning of an integrated DRT–PT service in Enna because it enables stakeholders to anticipate constraints, capitalise on opportunities and adapt the project to the real-world context, thereby avoiding theoretical solutions that are difficult to implement. Its value is particularly evident when it is translated into operational decisions, as the following practical examples demonstrate.

From a political perspective, PESTEL enables the identification of existing funding instruments and strategic guidelines. For example, if Enna Council secures regional or European funding for sustainable mobility, it can design the DRT from the outset as an integrated and innovative service, thereby increasing the likelihood of obtaining resources. In practical terms, this could mean launching a funded pilot project, rather than an implementation entirely funded by the council budget.

From an economic perspective, the analysis helps to design a sustainable service. In a context such as Enna, where some bus routes are underused, PESTEL enables these inefficiencies to be identified and replaced with on-demand services. A concrete example is the reorganisation of evening or suburban routes, switching from fixed routes to DRT, resulting in reduced operating costs and better utilisation of vehicles.

As regards social aspects, the PESTEL analysis enables the service to be tailored to the actual needs of the population. In Enna, for example, the large number of elderly users suggests that the service should not rely exclusively on digital apps. A practical decision resulting from this analysis is the introduction of a dedicated telephone number for bookings, making the service accessible even to those who do not use smartphones.

On the technological front, the analysis helps to select solutions appropriate to the context. Rather than adopting complex and costly systems, Enna could initially implement a simple booking management platform, gradually integrating it with more advanced systems. This approach reduces the risk of technological failure and facilitates acceptance of the service.

From an environmental perspective, the PESTEL framework guides planning towards sustainable solutions. For example, DRT can be designed to reduce empty runs and limit the use of private cars in underserved areas, thereby helping to reduce emissions. In practice, low-demand zones can be identified where DRT completely replaces traditional services.

Finally, from a legal perspective, the analysis helps to prevent regulatory obstacles. For example, checking the constraints of public transport service contracts in advance allows conflicts between operators to be avoided by designing a coherent integration. A practical application is the definition of an integrated fare model, which allows users to use DRT and buses with a single ticket.

In summary, the PESTEL analysis improves planning by transforming contextual analysis into concrete decisions tailored to the local area, making the DRT service in Enna more realistic, accessible and sustainable from both an economic and social perspective. It therefore highlights how the integration of DRT in Enna is set within a context rich in opportunities but also characterised by certain structural challenges.

The results of the analysis are shown in Table 2.

Table 2. Identification of factors and implications for the implementation of an integrated PT-DRT transport service

Factors	Description	Implications for the DRT in Enna
Political (P)	European, national and regional policies focused on sustainable mobility and innovation	Access to public funding; need for coordination between local authorities and consistency in decision-making
Economic (E)	Local economic context and service implementation costs	Reduction in operating costs in the long term; high initial investment and need for financial sustainability
Social (S)	Demographic characteristics and mobility behaviour	Improved accessibility for outlying areas and older people; potential resistance to change and digital challenges
Technological (T)	Availability of digital technologies and service management systems	Improved service efficiency and flexibility; need for infrastructure and technological expertise
Environmental (E)	Environmental impacts and the sustainability of mobility	Reduction in emissions and private traffic; greater energy efficiency in transport
Legal (L)	Public transport legislation and regulations	Potential bureaucratic constraints; need for regulatory adjustments and integration into service contracts

The planning of an integrated DRT-PT transport service in Enna is therefore influenced by a variety of external factors: some strongly favour its implementation (such as public policy and technological innovation), whilst others require careful management (particularly regulatory, economic and social aspects).

3.3 SWOT Matrix

The SWOT analysis highlights how the integration of local public transport and on-demand transport represents a strategic solution for urban and peri-urban areas with low demand, such as the municipality of Enna [19].

However, the success of the model depends on the ability to maximise its strengths and opportunities, whilst mitigating structural weaknesses and threats related to economic sustainability and governance. The SWOT analysis is based on four categories: Strengths (positive internal factors), Weaknesses (negative internal factors), Opportunities (positive external factors) and Threats (negative external factors) [19, 31]. The SWOT analysis does not systematically cross-reference these elements: it lists, discusses and interprets them.

As regards strengths (S), Enna possesses geographical and demographic characteristics that make it particularly well-suited to a flexible transport model. The city's compact size facilitates the trailing and management of innovative services, allowing for more

direct control over operations and quicker adaptability. Furthermore, the presence of a distributed rather than concentrated demand for transport – typical of inland and hilly areas – makes on-demand transport an efficient solution compared to traditional fixed-route services, which are often underused. In this context, DRT can help optimise the use of resources, reducing empty runs and improving territorial coverage.

Alongside these positive aspects, however, several weaknesses (W) have emerged, primarily of an internal nature. Firstly, there is a limited uptake of digital skills among certain sections of the population, particularly the elderly, who may find it difficult to use the apps for booking the service. Added to this is the need to implement appropriate technological infrastructure, such as digital platforms and booking management systems, which require initial investment and specific expertise. Furthermore, the organisational complexity arising from the integration of traditional and on-demand services should not be overlooked, nor should the potential resistance to change from regular public transport users.

From the perspective of opportunities (O), the current context offers favourable conditions for the development of innovative mobility solutions. In particular, the availability of European and national funding – such as that linked to sustainability policies and the digital transition – represents a key lever for covering the start-up costs of the service. At the same time, technological advances, in terms of mobile applications and route-optimisation algorithms, make it possible to improve the efficiency and reliability of on-demand transport. Integration with public transport can also help reduce emissions and private car use, promoting more sustainable and inclusive mobility, particularly in outlying or underserved areas. Finally, it is necessary to consider certain threats arising from the external environment. These include potential regulatory and bureaucratic constraints, which could slow down the implementation of the service or limit its operational flexibility. A further risk factor is insufficient initial demand, which could compromise the economic sustainability of the system, at least during the start-up phase. Furthermore, the heavy reliance on private cars, typical of many areas like Enna, could reduce the appeal of the on-demand service. Finally, the initial implementation costs, linked both to the technology and to the reorganisation of the service, represent a critical factor that must be managed with care. Table 3 summarises the main points, describing in detail how the DRT service can bring benefits and challenges to the context analysed.

Table 3. SWOT analysis regarding the implementation of an integrated PT-DRT service in Enna

Strengths (S)	
Factor	Relevance
High flexibility and adaptability of the DRT service compared to public transport in low-density areas	Crucial for the context under analysis, and in particular for its outlying areas
Improved accessibility and equity through integrated services and reduced reliance on private cars	Consistent with the SNAI and inclusion policies

(*continued*)

Table 3. (*continued*)

Strengths (S)	
Factor	Relevance
Optimisation of the use of public resources (reduction in empty-run kilometres and replacement of inefficient services)	Important for the economic sustainability of the system
Alignment with European policies (i.e. Green Deal, development of SUMPs and MaaS)	Facilitates access to European funds
Weaknesses (W)	
Factor	Relevance
High operating costs per passenger (difficulty in economic self-sustainability)	Need for stable public funding
Management complexity (need for advanced ICT systems; coordination between operators; trained personnel.)	Need for professional development and the introduction of new roles
Digital barriers for users (exclusion of some groups such as the elderly)	Need for alternative channels (call centres)
Dependence on local governance	Improvement of administrative capacity and institutional coordination
Opportunities (O)	
Factor	Rilevance
European and national funding	Pilot schemes and scaling up
Technological innovation	Improving efficiency through the development of digital platforms, the introduction of electric vehicles and the use of AI
Combating depopulation	Improving quality of life; encouraging residents to stay; enhancing the area's appeal
Integration with social and health policies	Introduction of social and healthcare services and local welfare schemes
Threats (T)	
Uncertainty regarding funding	A lack of public funding can: jeopardise service continuity; undermine user confidence
Competition from private cars	In areas with low traffic congestion: cars remain a competitive option; demand-responsive transport (DRT) may be perceived as less convenient
Risk of fragmentation of the system	Without integrated fares and information: the system can become confusing; the user experience deteriorates

In summary, the SWOT analysis improves the planning of the DRT service in Enna because it enables a shift from a general approach to a design based on actual strengths,

specific challenges and external conditions, making the system more consistent with the needs of the local area and increasing the likelihood of successful integration with public transport. It highlights how the integration of on-demand transport into Enna's mobility system offers good potential for development but requires careful planning and targeted strategies to overcome the challenges and capitalise on the opportunities presented by the current context.

3.4 TOWS Matrix

As for the TOWS Matrix, it enables a transition from analysis (SWOT) to the formulation of strategies. The TOWS Matrix highlights how the integration of local public transport and on-demand transport can be structured through a coherent set of strategies for development, consolidation and risk mitigation. The TOWS Matrix evolved from SWOT analysis and introduced a framework for strategic cross-referencing [26]. These planning tools can help identify a range of approaches depending on who will be using them – whether administrators, technicians, service managers, or those responsible for funding the services. The TOWS analysis enables the elements identified in the SWOT analysis to be translated into operational strategies for integrating on-demand transport with local public transport in the city of Enna. In this sense, it represents a fundamental tool for guiding decision-making and defining concrete methods for implementing the service.

Firstly, SO (Strengths–Opportunities) strategies aim to capitalise on the strengths of the local context to seize the opportunities offered by the external environment. In the case of Enna, the compact size of the area and the widespread demand for mobility represent ideal conditions for launching on-demand transport pilot projects, supported by public funding allocated to sustainable mobility and innovation. Integration with advanced digital technologies can be facilitated precisely by the small scale of the urban system, allowing for more controlled and effective experimentation. Furthermore, the possibility of replacing or integrating underused traditional routes with flexible services makes it possible to improve the overall efficiency of the system. WO (Weaknesses–Opportunities) strategies, on the other hand, focus on reducing internal weaknesses by capitalising on external opportunities. In this context, the challenges associated with limited digital literacy can be addressed through training and awareness-raising programmes aimed at the public, potentially funded by public money. At the same time, the available financial resources can be used to develop appropriate technological infrastructure, thereby reducing the burden of initial investment. A particularly important factor is the introduction of alternative methods of accessing the service to digital apps, such as telephone booking, which allows for a wider user base and makes the service more inclusive. As regards ST (Strengths–Threats) strategies, these aim to use the system's strengths to counter external threats. The inherent flexibility of on-demand transport, for example, makes it possible to adapt supply to actual demand, thereby reducing the risk of economic inefficiency when demand levels are uncertain. Furthermore, greater operational efficiency can help to contain costs and make the service more competitive compared to the use of private cars. In a context characterised by potential regulatory or bureaucratic constraints, small-scale trials can represent an effective strategy for demonstrating the validity of the model and promoting its gradual institutionalisation. Finally,

WT (Weaknesses–Threats) strategies take on a defensive character and aim to minimise both internal weaknesses and external threats. From this perspective, it is advisable to plan for a gradual introduction of the service, through successive phases of trialling and expansion, to limit risks and address any critical issues as the project progress. Continuous monitoring of demand and service performance is essential to ensure a balance between costs and benefits. Furthermore, fare and operational integration with existing public transport can encourage user acceptance and improve overall accessibility. Finally, collaboration between local authorities, operators and institutions is key to overcoming regulatory obstacles and ensuring the coordinated and effective management of the system. Overall, the TOWS analysis highlights that the integration of on-demand transport in Enna should not be viewed merely as a technological innovation, but as a complex strategic process requiring a careful combination of resources, expertise and public policies to be successfully implemented. In particular, the use of European funds and policies for inland areas makes it possible to overcome the main weaknesses of DRT, whilst the flexibility of the service is a key factor in countering threats related to economic sustainability and social acceptability. In other words, by considering the S–O aspects, it is possible to highlight the strengths to seize the opportunities, as shown in Table 4.

Table 4. Analysis of S-O Strategies, i.e. Development and Growth Strategies

S–O Strategies (Strengths + Opportunities)		
Strengths (S)	Opportunities (O)	S–O Strategies
Flexibility of the DRT	EU funds / PNRR	Develop funded pilot DRT services
Equity and inclusion	SNAI policies	Position DRT as an essential service
Alignment with the SUMP	Technological innovation	Integrate DRT into MaaS frameworks
Operational efficiency	Local welfare	DRT as a social and healthcare service

About the case study, the potential of the Canalicchio and Enna Alta areas as SNAI pilot zones is highlighted, along with the possible implementation of strategies to access PNRR funds for digitalisation and electric vehicles. This translates into the planning of strategies for the expansion of the integrated service and innovation. By considering the W–O framework to overcome weaknesses by exploiting opportunities, the results shown in Table 5 below are obtained.

Table 5. W-O Strategy Analysis, i.e. Strategies for Improvement and Consolidation

W–O Strategies (Weaknesses + Opportunities)		
Weaknesses (W)	Opportunities (O)	Opportunities (O)
High costs	EU funding	EU funding
Management complexity	ICT innovation	ICT innovation
Digital barriers	Social inclusion	Social inclusion

(*continued*)

Table 5. (*continued*)

W–O Strategies (Weaknesses + Opportunities)		
Weaknesses (W)	Opportunities (O)	Opportunities (O)
Weak governance	Interreg programmes	Interreg programmes

These considerations could, for example, encourage the implementation of strategies for using ERDF funds for DRT platforms and the creation of dedicated call centres for elderly users. This therefore highlights the need for measures aimed at structural strengthening. Regarding the S–T combination, however, it is worth noting the value of leveraging strengths to mitigate threats, as shown in Table 6.

Table 6. Analysis of S-T Strategies or Active Defense Strategies

S–T Strategies (Strengths + Threats)		
Strengths (S)	Threats (T)	S–T Strategies
Flexibility	Competition from cars	Improving reliability and journey times
Integration of public transport and on-demand transport	Fragmentation	Integrated ticketing
Accessibility	Low uptake	Targeted information campaigns
Efficiency	Funding instability	Demonstrating results (e.g. calculating indices such as CSI composite indices)

Finally, about the W–T combination, the aim is to minimise the impact of weaknesses and threats (defensive strategies). The analysis of the W–T combination is shown in Table 7.

Table 7. Analysis of Mitigation and Control Strategies

W–T Strategies (Weaknesses + Threats)		
Weaknesses (W)	Threats (T)	W–T Strategies
High costs	Ground instability	Gradual roll-out of the service
Complexity	Fragmentation	Single public authority
Digital divide	Low participation	User support
Weak governance	Discontinuity	Multi-year service agreements

In summary, SO (Strengths–Opportunities) strategies make it possible to capitalise on the region's strengths (its compact size and dispersed demand) to seize available opportunities, such as launching a publicly funded pilot project focused on outlying

areas. One resulting measure, for example, is to replace a low-passenger-volume route with a DRT service, testing its effectiveness at a low cost. WO (Weaknesses–Opportunities) strategies enable weaknesses to be overcome by exploiting external opportunities; for instance, the limited digital literacy of the elderly population can be addressed by using funding to develop an inclusive access system. For example, one could envisage the creation of a multi-channel booking service (app + telephone) accompanied by user training campaigns, thereby improving the service's accessibility. ST (Strengths–Threats) strategies enable the use of strengths to counter threats; this means, for example, being able to implement a system that operates journeys by booking only, reducing waste and making the service more economically sustainable. Finally, WT (Weaknesses–Threats) strategies are defensive in nature and aim to reduce risks and critical issues; they may propose, as a concrete solution, the launch of a pilot phase limited in time and scope, with continuous performance monitoring and the possibility of adaptation prior to large-scale implementation. In summary, the TOWS analysis improves DRT planning in Enna because it enables a transition from analysis to strategy, translating the information gathered into concrete, targeted and realistic actions, thereby increasing the effectiveness and sustainability of integration with public transport.

4 Discussion

The implementation of flexible services presents an opportunity for the environmental, economic and social sustainability of transport systems. Their characteristics – flexibility, variable routes, door-to-door service and reduced capacity – make them particularly well-suited to contexts with low demand, where traditional scheduled services may prove inefficient. On-demand services, however, present significant implementation challenges. Key implementation challenges include fare coordination (single ticket), multi-stakeholder governance (different operators for the two sectors) and data sharing; these are complex issues that require time and investment. Furthermore, financial sustainability remains a central issue, particularly in the initial roll-out phases of integrated services.

This article discusses the possibility of integrating on-demand transport with local public transport in the city of Enna. SWOT, TOWS and PESTEL analyses were conducted; the three analyses differ in terms of their role and level of detail, whilst being complementary to one another. Given the various stakeholders involved in implementing a DRT service integrated with public transport in Enna, the PESTEL, SWOT and TOWS analyses offer specific benefits for each role. For public authorities, the PESTEL analysis is essential for understanding the regulatory, political and social framework within which they operate, whilst the SWOT analysis enables them to assess the local context, and the TOWS analysis supports the formulation of mobility policies and strategies. For transport operators, the SWOT analysis is particularly useful for analysing their operational capabilities and critical issues, whilst the TOWS analysis helps to translate these assessments into concrete management decisions; PESTEL, on the other hand, provides insights into external constraints and market opportunities. Planners use PESTEL to analyse the territorial and socio-economic context, SWOT to structure a concise overview of the system's conditions, and TOWS to develop scenarios and project strategies.

Finally, those involved in financing find PESTEL a useful tool for assessing macroeconomic and regulatory risks and opportunities, SWOT a means of understanding the project's soundness, and TOWS a reference for verifying the consistency and feasibility of the proposed strategies. With regard to the specific application to PT–DRT systems, it should be noted that PESTEL analysis enables the identification of constraints and risks (for example, those related to legislation, implementation costs or the social characteristics of the population) and supports strategic planning, making it possible to design a service that is consistent with the local context and easier to implement. The SWOT analysis highlights why traditional PT does not work on its own but demonstrates the potential of DRT and identifies territorial constraints (gradient, dispersion). As regards the TOWS analysis, it is worth noting that it indicates where to introduce DRT and how to integrate it with PT; it supports roadmaps and quantitative targets and is a tool consistent with SUMP and EU calls for proposals. Therefore, the SWOT analysis represents an indispensable phase of strategic diagnosis, but it is through the TOWS Matrix that the elements identified are translated into operational and territorialised strategies, making the approach particularly suitable for the planning of integrated PT–DRT public transport systems.

5 Conclusion

The results obtained through the sequential application of the three methodologies highlight the potential of the approach developed as a decision-support tool for a wide range of stakeholders involved in the planning and management of transport systems. There are various stakeholders who stand to benefit from this work.

Firstly, transport service operators, for whom the proposed framework enables the identification of operational guidelines useful for defining the characteristics of the service offering, thereby promoting a better match between demand and service capacity; in this way, it contributes to improving economic and operational efficiency.

The analysis enables the identification of spatial and temporal criticalities in the distribution of mobility demand, allowing for more effective targeting of any service redesign interventions. Secondly, public administrations and local authorities. For them, the research findings provide a structured analytical basis to support decision-making processes in the fields of mobility policy and spatial planning.

The proposed approach can contribute to the definition of integrated transport and accessibility strategies, as well as to a more efficient allocation of public resources, facilitating targeted interventions in areas characterised by greater challenges in terms of access to essential services.

As this is an initial stage of the investigation, the authors emphasise that future research in this field will need to establish a more robust methodological framework for the integrated application of PESTEL, SWOT and TOWS analyses in the case study concerning the integration of public transport (PT) and demand-responsive transport (DRT) in the city of Enna.

Future research steps will aim to define a structured, reproducible and valid protocol, avoiding a simple sequential use of the three models (such as steps involving the collection of territorial and transport data, classification and selection processes for

the identification of enabling and critical factors; identification of structural constraints and strategic opportunities). Finally, a quantitative analysis will be carried out using a multi-criteria weighting system (such as AHP or a weighted evaluation matrix) and the definition of specific quantitative indicators of accessibility and performance, useful both for ex-ante evaluation and for monitoring the service.

Finally, the article is of interest to the public, for whom a planning system supported by analytical tools of this kind can translate into tangible benefits in terms of improved access to services, a reduction in regional inequalities, and an overall improvement in the quality of the public transport system.

Focusing on the mobility needs of potentially vulnerable groups helps to promote a more equitable and inclusive transport system. Overall, this research contributes to the preliminary analysis and development of more inclusive, resilient and sustainable mobility models, with reference to peri-urban contexts in inland areas, where the combination of dispersed demand, limited availability of services and socio-demographic fragility makes the adoption of innovative approaches to mobility planning particularly relevant.

From this perspective, the proposed framework represents a step towards integrating accessibility analysis, service optimisation and territorial development policies, whilst opening the way for future research developments aimed at expanding the scope of application and integrating further dimensions of sustainable mobility.

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Exploring MaaS–DRT Integration Through a Systematic Literature Review: Methodological Insights for Rural Mobility Planning

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Abstract. Today's mobility is evolving toward the smarter paradigm, rapidly introducing new technologies (such as IoT, AI, and 5G) and designing increasingly connected, sustainable, and autonomous transport systems to improve urban efficiency. This evolution is lagging in rural areas, where transportation demand is low, mobility trends are inconsistent, modal choice is limited, and a significant percentage of users are affected by the digital divide. In these areas, it is necessary to evaluate the implementation of flexible transport services complementary to public transport, such as dial-up services (DRT). These services are also evolving as integrated components of the Mobility as a Service (MaaS) system, representing a significant opportunity to encourage users to adopt more sustainable mobility behaviors. This study presents a comprehensive literature review aimed at identifying key trends, research directions and scientific developments in the field of MaaS, with particular attention to the enabling technologies, platform architectures and operational models adopted in practice. The systematic literature review allows for the analysis of sector research from the last twenty years using keywords and Boolean variables that can link them. The study, specifically focused on rural areas and the combination of MaaS and DRT, reveals an uneven spatial and temporal distribution. The research examines not only the correlation between the themes but also focuses on social inclusion and gender equity to assess the impact of these integrated transport solutions. The results of this research demonstrate how the integration of MaaS and DRT represents a fundamental pillar of modern sustainable mobility policies in Italy and Europe. This integration also represents a fundamental strategy in rural and inland areas to combat depopulation, improve accessibility to essential services, and reduce private car use. In this context, current and future policies must aim to transform and integrate local public transport with flexible services based on dedicated digital platforms and MaaS systems to ensure territorial coverage (last mile) and social inclusion.

Keywords: Mobility as a Service (MaaS) · Demand Responsive Transit (DRT) · Rural Mobility · Low-Demand Transport Systems · Accessibility and Social Inclusion

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1 Introduction

The evolution of transport systems currently shows a different distribution across urban, semi-urban and rural areas. Numerous studies have highlighted this disparity on the basis of territorial factors [1], economic [2] and social [3, 4].

Data from 2020 [5, 6] shows that 29% of European citizens and 17.33% of US citizens live in rural areas. Demographic factors, the presence of underdeveloped infrastructure, limited public transport and longer travel distances are significant obstacles for areas with low demand, making it difficult for both public transport and innovative mobility systems to achieve viability and user acceptance [7].

While causality is difficult to establish, numerous studies report an association between rural depopulation and reduced public transport provision. Limited access to services and opportunities, often linked to a lack of transport infrastructure and services, is one of the factors contributing to the marginalisation of rural areas and their depopulation [8].

The last decade has been marked by numerous disasters and pandemics, which have led to an increase in low demand areas because of a lack of transport services and the depopulation of cities [9, 10]. Rural and sparsely populated areas represent one of the main challenges facing modern transport systems [11, 12].

The scattered nature of settlements, reduced demand for transport and an ageing population making it difficult to organise traditional public transport services that are both efficient and economically viable. There is a need to reverse this trend and improve connections between urban areas and outlying regions [13].

In non-urban areas, there is also a high level of private car use, leading to an increase in the negative externalities of the transport system in terms of pollution, accident rates and CO_2 emissions. It is necessary to make public transport services more attractive, so that they can better meet the needs and expectations of users, thereby encouraging a modal shift towards more sustainable modes of transport [14, 15].

Among the most promising solutions, Demand-Responsive Transit (DRT) is is highly adaptable in low-demand areas [16]. By responding exclusively to actual user demand, it offers a flexible and customisable service, often serving users without access to private transport [17].

In this context, the analysis of integrated transport systems plays a central role in safeguarding the right to mobility and combating social and territorial isolation.

The demand for mobility in rural areas is characterised by certain structural features: low travel volumes, high temporal variability, heavy reliance on private cars, and a prevalence of journeys linked to work, healthcare, education and access to essential services.

Beyond these factors, there are often more vulnerable groups, such as the elderly, young people and individuals with limited financial resources [18–20].

These factors make public transport models based on fixed routes and rigid timetables ineffective, highlighting the need for flexible solutions that can be adapted to actual demand.

It is therefore beneficial to roll out integrated PT-DRT transport services, promoting the concept of integration not only in organisational terms but also in operational and fare-related aspects, so as to optimise all available resources and extend service

coverage across the region. DRT enables operators to tailor service provision to user demand, thereby reducing operating costs and expanding regional coverage. However, these services are most effective when integrated into a coordinated system rather than operating as stand-alone solutions.

In the current urban mobility landscape, Mobility as a Service (MaaS), based on the integration of multiple transport services, represents an emerging development. Through a unified digital platform supported by Information and Communication Technology (ICT) tools, it allows users to plan, book and pay for various transport options. By placing the user and the fulfilment of their needs at the heart of their primary objectives, these platforms promote multimodal mobility, increasingly establishing themselves as a strategy for urban mobility that is ever more efficient, inclusive and sustainable from an environmental, social and economic perspective [21–24].

This study presents a systematic review of the literature on the diffusion of PT-DRT integrated transport systems, and at the same time examining the integration of these services into MaaS digital platforms with a view to improving user experience.

Section 2 analyses the state of the art on-demand transport systems over the past decade and their integration with public and shared transport services but also analyses the evolution of MaaS digital platforms.

Section 3 defines a methodology for the systematic literature review using the main scientific databases.

Section 4 discusses the results from the previous section and outlines strategies for improving the integration of transport services with the technologies for mode choice.

2 Literature Review

2.1 The Development of DRT Services

The spread of DRT services has made it possible in recent years to implement sustainable transport services [25, 26].

The development of these services within an integrated transport system has led to improvements in social inclusion (for example, through the introduction of services tailored to the most vulnerable groups) and better accessibility in underserved areas, thus becoming a valuable service for covering the first and last mile [27–29].

Several studies have shown that DRT services using fleets of minibuses (both electric and non-electric) have been introduced, and an increased number of studies also focus on autonomous vehicles [30–33].

It is important to emphasise that whilst scheduled public transport, particularly sub-urban and regional rail services, acts as the backbone of the system, flexible transport services with a feeder and distribution role.

Therefore, through integrated planning, on-demand services could be used as links to transport hubs, stations or main stops, ensuring journey continuity and reducing travel times to essential services.

This approach helps to overcome the divide between urban areas with good transport links and marginalised rural areas, promoting greater territorial equity [34, 35].

Other studies, however, have highlighted the uneven distribution of these services due to regulatory restrictions [27], a lack of technical consultation between service providers and issues related to the digital divide [36, 37].

In recent years, there has been a lack of clarity and consistency in the policy framework within which the public sector plays a strategic and coordinating role. It is therefore necessary to develop an integrated mobility plan that explicitly includes rural areas within catchment area plans, SUMPs and territorial development strategies [38]. It must be borne in mind that, unlike in urban areas where transport demand allows for a greater number of market operators, in areas with low demand these dynamics are often absent, and public intervention is essential to ensure the continuity, fairness and quality of services.

Another critical issue relates to the question of public funding for the sustainability of such services in areas with low demand. Funding models must recognise the social value of transport, going beyond an assessment based solely on economic efficiency.

Targeted subsidies, flexible service contracts and compensation mechanisms can enable the integration of on-demand services into the public transport system, preventing them from remaining experimental or temporary solutions.

In this regard, the development of MaaS platforms can ensure the implementation and improvement of multiple services, or rather the improvement of the entire mobility ecosystem, by supporting interoperable digital platforms, integrated fare systems and subscription models that also include rural services. This approach makes it possible to ensure the economic sustainability of services which, taken individually, would not be viable, but which are essential for guaranteeing the right to mobility [39, 40].

According to the literature, the adoption of modern technologies could significantly enhance the integration and flexibility of public transport, but above all its coverage in areas with low demand; it could also balance and contain operating costs and support principles of social, economic and environmental sustainability [41, 42].

Digital integration makes it possible to coordinate these services with public transport networks, reducing overlaps and improving the overall efficiency of the system.

In this sense, the integration of DRT and MaaS emerges as a promising strategy for improving the efficiency and coverage of transport systems, indeed data from 2024 relating to the eighth National Report on Sharing Mobility confirms this growth, with a 40% increase already in the first few months of 2024, with 41 active services: 24 operating in urban areas and 12 in rural areas [43, 44, 45].

Among the advances in integrated transport solutions, Mobility as a Service (MaaS) is playing an increasingly central role because it ensures integration between different modes of transport, promoting greater flexibility, access to real-time travel information and efficiency [46, 47].

Ensuring a greater availability of transport services in areas with low demand means facilitating access to work, education and healthcare, thereby combating depopulation and strengthening territorial cohesion.

Furthermore, by improving the synergistic integration between public transport and on-demand services, a significant contribution can be made to reducing private vehicle use.

Finally, governance represents a further critical element. Integrated transport systems in rural areas require multi-level governance models, in which regions, local authorities and transport authorities collaborate with public and private operators. In this context, public authorities must retain control over service objectives, quality standards and territorial equity, whilst operators are responsible for operational and technological implementation. MaaS platforms can become tools for governance as well as service delivery, facilitating data sharing and performance monitoring [40, 48] as discussed.

2.2 The Development of MaaS

The concept of MaaS is relatively recent in academic circles; the first publications date back to 2018 and focus on the main characteristics of the service.

There is not yet a single definition of the MaaS concept, but it is generally understood as a model for the provision of transport services that includes both public and on-demand transport, which, by converging on a single platform, optimises multimodality.

The research of [47, 49] summarises the key features of the MaaS model in three main elements relating to the integration of:

- mobility, enabling access for different transport operators within the same area
- ticketing and bookings consolidated into a single platform
- information technologies capable of providing real-time information on transport services.

An analysis of the spatial and temporal distribution of scientific contributions reveals that the number of publications has risen rapidly in recent years and that they originate predominantly from Europe, with the Netherlands leading the way, followed by Sweden, Finland, and then the United Kingdom and the USA. The latter region represents the area with the most significant growth, particularly for MaaS users [50].

However, research highlights significant gaps in the assessment of the impact of MaaS on existing transport systems, as well as in the design and pricing of services to make them more attractive to users. Ultimately, however, it appears that the widespread adoption of these models, by improving last-mile coverage, will significantly reduce the use of private vehicles [51]. In Italy, thanks to the National Recovery and Resilience Plan (PNRR), a portion of the funding has been allocated to MaaS projects, thereby contributing to the large-scale development of these models. The aim of streamlining the relationship between public and private transport, making it more sustainable, efficient and accessible, includes Mobility as a Service among its key initiatives. Indeed, among the pilot schemes launched in Italy are three metropolitan cities: Milan, Naples and Rome [52].

From literature review [50] it appears that multi-level approaches to cooperation and organisation among the stakeholders involved have been defined, highlighting how public and private entities can integrate and work in synergy. However, several issues have been identified that pose substantive challenges to the roll-out of these MaaS systems. Specifically, these concern to the management of sensitive data, including its secure processing, and storage, while ensuring privacy is respected.

It also refers to the qualitative and quantitative impact of MaaS on the use of different modes of transport, and on service design, planning and pricing strategies, so as to

make the service attractive to users. The adoption of such services is, in fact, closely linked to users' socio-economic and behavioural factors, as user satisfaction significantly influences the adoption of the service.

MaaS represents the new trend in smart mobility, as these platforms are able to provide integrated urban transport solutions, including buses, underground, car sharing and micro mobility services, thereby ensuring that users can plan their journey using a single platform and choose the most appropriate mode of transport for each leg of the journey [53].

MaaS also represents an innovation in the planning and use of transport systems.

Stemming from the fundamental need to overcome the fragmentation of mobility and the idea of unifying both public and private transport services within a single digital platform, the concept of MaaS was born, a way of offering users a travel experience centred on a personalised and seamless service.

By promoting the combined use of public transport and shared mobility services, MaaS offers an interesting approach to sustainable mobility, tailoring transport solutions to users' needs and ensuring accessibility in rural areas where demand for transport is low [51].

Consequently, the integration of MaaS platforms into rural areas represents a significant development in the literature, as these platforms were initially strongly geared towards predominantly urban contexts. Numerous studies [54] highlight that although MaaS models originated predominantly in urban settings, they can be adapted to rural contexts, as these approaches represent a promising solution to the structural challenges faced by areas with low transport demand. Indeed, MaaS models can make areas with low transport demand accessible, enabling the integration of public transport, on-demand services and other forms of mobility into journey planning. This integration and multimodality helps reduce barriers to the use of public transport and increases user confidence in the system. In the MaaS context, on-demand transport serves a complementary and connecting role, covering the so-called 'last mile' or serving areas and times when a scheduled service would be inefficient.

The integration of PT and DRT can therefore be considered at several levels [25, 55]:

- Information level: through MaaS platforms that display travel solutions that combine, for example, a regular bus service with an on-demand service for the final leg
- Operational level: the on-demand transport system can be designed to act as a feeder service for local public transport

The evolution of MaaS systems and the integration of public transport with on-demand services have a significant impact on environmental and social sustainability [46, 56].

A well-designed system can reduce private car use, emissions and congestion, whilst improving accessibility for older people, people with disabilities and residents in outlying areas [54]. In particular, on-demand services integrated into MaaS can ensure a minimum level of access to transport even where traditional public transport is not economically viable, helping to reduce regional inequalities.

Furthermore, when discussing integration, it is possible to propose a further perspective in this regard because, in some models, the on-demand system can be integrated, even

if only partially, into the public transport fare system, making journey costs transparent for the user and fostering collaboration between public and private bodies [39].

Despite its potential, the implementation of MaaS and the integration of transport services still present several challenges, including the development of sustainable business models, the definition of public authorities' roles in coordination, and the management and archiving of data held.

Looking ahead, strengthening policies, governance and public funding models could facilitate the full integration of rural areas into MaaS systems. This requires a paradigm shift, in which mobility is not viewed merely as a cost, but as a strategic investment in territorial cohesion, local development and the overall sustainability of the transport system.

The integration of public transport, flexible services and MaaS, supported by a strong role for the public sector, therefore represents one of the main levers for ensuring a greater presence of mobility services even in areas with low demand, reducing territorial inequalities and improving the quality of life in rural areas.

2.3 Research Gaps, Objectives, and Contribution

The purpose of this document is to understand the benefits and challenges associated with these digital solutions, which are of considerable importance not only for service providers but, above all, for users, who are guaranteed a flexible and sustainable transport service. The literature highlights the role of MaaS systems integrated with DRT systems; it is noted that on-demand transport systems improve accessibility, reduce territorial marginalisation in rural areas, and demonstrate economic and operational benefits compared to public transport.

Despite this, there are gaps in the literature, identified primarily in the scarcity of concrete case studies, the limited actual integration between public and private service operators, the risk of digital exclusion in rural areas, and the lack of effective policies to integrate MaaS and DRT.

The primary objective, therefore, would be to attempt to integrate future policies aimed at transforming and integrating local public transport with flexible services based on dedicated digital platforms and MaaS systems, in order to ensure territorial coverage (last mile) and social inclusion. In this way, it would be possible to ensure the development of operational models adapted to the diverse needs of users, guaranteeing well-being, accessibility and efficiency.

3 Methodology

The literature review, conducted using a Systematic Literature Review (SLR) approach, began with the definition of specific keywords and a search of the main scientific search engines such as Scopus, ScienceDirect and WOS. The document examines the topic based on scientific literature from the past decade, from 2016 to 2026.

The search was conducted using Boolean combinations applied to titles, abstracts, and keywords, as follows:

- [(“Mobility as a Service”) AND (“demand responsive transit”) OR (“DRT”) OR (“demand responsive transport”)]
- [(“Mobility as a Service”) AND (“demand responsive transit”) OR (“DRT”) OR (“demand responsive transport”) AND (“rural areas”)]
- [(“Mobility as a Service”) AND (“demand responsive transit”) OR (“DRT”) OR (“demand responsive transport”) AND (“policy”) AND (“public transport”)]
- [(“Mobility as a Service”) AND (“demand responsive transit”) OR (“DRT”) OR (“demand responsive transport”) AND (“policy”) AND (“social inclusion”) AND (“social exclusion”)]

A rigorous selection process was conducted based on clearly defined inclusion and exclusion criteria. Specifically, the review considered journals and conference proceedings written in English, covering subject areas relevant to the research, and available via open access. Contributions that did not meet these criteria were excluded.

4 Results and Discussion

The results consist of a total of 91 papers: 52 relating to the first combination, 11 to the second, 20 to the third and 8 to the fourth. Following a process of selection and removal of duplicate papers, only 21 were included in the final analysis.

The selection criteria included papers published over the last twenty years, encompassing both journal articles and conference proceedings.

Excluded, however, were all duplicates, papers belonging to different subject areas, non-open-access papers and book chapters, non-English papers and non-peer-reviewed papers.

The literature highlights how the promotion of MaaS systems in synergy with integrated transport systems proves to be a significant strategy in the structural transformation of transport systems and, above all, in improving accessibility conditions in contexts with low transport demand.

Table 1 summarises how each contribution relates to the proposed MaaS model.

The 21 contributions are classified by their primary theme: impacts on accessibility and territorial cohesion; policy, governance, and public funding; impacts on sustainability and inclusion; and technological evolution and related impacts.

As shown in Table 1, the 21 selected papers generally address specific issues that converge on the relevance of the MaaS model and the prospect of integration with on-demand transport services. However, a significant gap emergence in the literature. Most of the studies analyse integrated transport systems and advocate the adoption of MaaS as a tool capable of ensuring more efficient, personalised and technologically advanced services. A smaller subset examines applications in rural areas; however, it is observed that structural problems linked to socio-demographic factors complicate the implementation and roll-out of new smart mobility strategies. These findings, which focus on rural areas, highlight obstacles to implementation and underscore the difficulty of transferring results obtained from broader contexts to areas with low demand. Overall, most of the contributions take a predominantly theoretical and descriptive approach, presenting MaaS models as a viable and desirable strategy. This highlights a methodological gap in the literature, as the limited number of case studies identified in this systematic review

Table 1. MaaS Literature Review Table

Reference	Theoretical (T)/Application (A)	Impacts on accessibility and territorial cohesion	Policy, governance and public funding	Impacts on sustainability and inclusion	Technological evolution and related impacts
[57]	T	x	x		x
[58]	T	x	x	x	x
[59]	T	x		x	
[60]	T	x	x	x	
[61]	A	x		x	x
[62]	A	x		x	x
[63]	T	x		x	
[63]	T/A		x	x	x
[64]	A	x		x	
[65]	A	x	x	x	
[66]	T	x	x	x	
[67]	T	x		x	
[68]	T	x		x	x
[69]	T	x	x	x	
[70]	A	x	x	x	
[71]	T	x		x	
[72]	T	x	x	x	
[60]	T	x	x	x	
[17]	T	x		x	
[73]	A	x		x	x
[74]	A	x		x	x

restricts the ability to verify the information and theoretical approaches that prevail in the literature. While theopretical contributions emphasise all the potential benefits of MaaS, the pilot case studies remain too context-dependent and although they demonstrate a more practical approach, they cannot be applied too generally. Although the literature presents well-established findings, there are still few practical case studies from which to derive reliable and well-founded data.

The two most frequently addressed topics relate to the impact that MaaS integrated with DRT may have on territorial cohesion, and the impacts on sustainability and social inclusion.

Therefore, whilst on the one hand, with regard to purely theoretical contributions, it is not possible to provide clear evidence of the long-term objective benefits that may be derived from the adoption of MaaS-DRT in terms of economic, social and environmental

sustainability and the improvement of transport systems in areas with low demand; on the other hand, the awareness and consistency regarding issues of territorial accessibility, social inclusion and environmental impact are significant and highlight the confidence placed in these innovative mobility systems for marginalised areas.

From another perspective, the results of pilot projects in small towns demonstrate not only the effectiveness of DRT services but, also how these systems, when integrated into MaaS models, are evolving significantly, providing services increasingly tailored to users' needs and improving connections to public transport networks that can enhance accessibility and territorial connectivity.

The integration of DRT services within MaaS platforms, as the research suggests, would offer a range of benefits to both users and service operators, thanks to a dynamic balance between transport supply and demand. These benefits are also evident in terms of optimising and reducing journey times, operating costs and kilometres travelled. All of this is considered, according to the literature, to be among the most significant factors in users' perceived quality of service [57].

It is also becoming clear that these on-demand systems, when properly integrated into MaaS, represent an effective tool capable of complementing local public transport in areas with low demand, thus proving not to be a niche service but rather one that complements and integrates the wider transport network. When properly integrated into MaaS, on-demand systems effectively complement local public transport in low-demand areas. Mobility hubs are extremely useful in this regard because they manage to simultaneously integrate coherent strategic planning objectives, synchronising timetables, waiting times, journey times and routes to ensure increasingly comprehensive door-to-door services [60, 62].

Some contributions, however, focus on different aspects, highlighting other potential applications of MaaS. Indeed, when tailored to specific user groups, these services can better support the first/last mile function and provide connections to the main public transport network. However, this same concept, in trials already established in contexts with low demand, shows that when technological, operational and fare integration exists not only between MaaS and DRT platforms, but also includes integration with local public transport, it is possible to guarantee flexibility for users and sustainability over time [58].

Consequently, the multidimensional analysis proposed by Butler et al. clearly shows that integrated MaaS-DRT solutions can have a positive impact on tackling transport disadvantage and inequalities in access. Improvements are therefore evident in terms of territorial accessibility and social inclusion, particularly in contexts such as areas with low demand where public transport is often insufficient. From this perspective, another potential of MaaS is highlighted: it can serve as a policy tool capable of supporting and enhancing social and territorial cohesion objectives, particularly for rural projects with a dual public-private nature [70, 66].

Evidence from Japan highlights persistent challenges alongside the general potential: long-standing structural constraints, such as population ageing and shortages of operational staff, have limited the impact of smart-mobility innovations and MaaS pilot projects, leaving transport-demand issues unresolved. Compared with European case

studies, Japanese case studies demonstrate clear long-term results. It is also worth noting that different demographic factors, across various global contexts, have a significant influence on the success of services and outcomes.Therefore, based on this rural evidence, it would appear that the success of these platforms integrated with DRT systems does not depend so much on an increase in passenger numbers but rather on much more precise and specific assessments for each context with low demand. The success and positive benefits of these models can only emerge if there is a bespoke design of MaaS-DRT services for areas with low, rather than generalised, demand [65, 66].

In fact, solutions such as MaaS Lite, simpler solutions focused on local areas and a limited number of transport modes, can often bring immediate benefits and success [64].

This final point, in line with the European and Japanese case studies, lays the groundwork for a concept we believe to be significant, the importance of adapting these technologies, on-demand services and governance models to local circumstances, their specific characteristics and, above all, the mobility needs of these areas with low demand, thereby avoiding a standardised approach [68, 69].

5 Conclusions

This paper assesses, on the basis of scientific literature from the last decade, the direction of scientific development in the MaaS sector, paying particular attention to the integration of these platforms with DRT systems in areas with low transport demand, such as rural and suburban areas. Unlike traditional fixed-route systems, Demand-Responsive Transport (DRT) systems offer dynamic and customisable routes, thereby improving access to essential services and reducing territorial marginalisation. This analysis has shown that the integration of new MaaS technologies with DRT systems represents, particularly in theory, a fundamental pillar of modern sustainable mobility policies, presenting itself as a virtuous strategy in inland and rural areas. The systematic literature review revealed that many existing studies are purely theoretical in nature, highlighting the benefits of using on-demand systems and demonstrating a solid foundation in the literature, emphasising their crucial role particularly in areas with low demand and low population density, where a reduction in operating costs compared to traditional transport is necessary. They analyse how the roll-out and subsequent integration of MaaS systems would ensure real-time management of bookings, facilitating digital integration in these rural areas between public transport, both road and rail, DRT systems and shared mobility schemes. It is therefore noted that some papers, which also present pilot projects, emphasise the need to raise awareness of the issue. The results of the pilot projects highlight how MaaS platforms are expanding rapidly and developing their system architecture to provide high-performance, personalised services tailored to users' diverse needs. This undoubtedly improves connections to public transport networks and, consequently, territorial connectivity and continuity; however, we must also take into account improvements to the platforms' fare systems. The aim should be to create a single system, not only for ticketing but also for payment, as this is the only way to make bookings via a single interface in an even simpler and more accessible manner.

There are also a number of challenges that require attention, such as the importance of developing policies and improvement strategies to ensure that DRT-MaaS integration

has a meaningful impact; or the need for connectivity between mountainous and rural areas whilst avoiding digital exclusion; the need to integrate data from public and private sources, where dialogue and data sharing would facilitate the management of integrated services; the need to assess the impact of these services on citizens' well-being in these areas with low transport demand.

However, few studies analyse this aspect of policy and feasible strategies for integrating DRT systems in rural areas; rather, recommendations regarding differentiated policies for flexible services based on user clusters are becoming more common. Specifically, following a review of the existing literature, this paper proposes policy strategies to facilitate the integration of DRTs in these areas with low transport demand. In this context, flexible, reservation-based services that adapt to actual demand should be developed, alongside service models that experiment with 'Last Mile' approaches such as Route and Point Deviation.

It is also suggested that the regional regulatory framework be amended so that these on-demand transport systems can operate together with local public transport, ensuring a single fare system. It would indeed be effective to consider integrated ticketing and single-fare systems for journeys combining on-demand transport (DRT) with traditional transport services; this would ensure better accessibility at interchange hubs whilst minimising waiting times. This can be achieved through the development of apps, websites and call centres via which users can view and book both on-demand and fixed-route transport services.

In terms of funding and governance, this is a crucial point: in areas with low demand, transport services often face serious financial difficulties; consequently, long-term public support strategies and regional and local partnerships are essential in order to jointly define routes, timetables and fares, as is the case in inland areas. From this perspective, transport services are optimised, and educational, health and social services are also involved in a co-design approach. It follows that the economic sustainability of these services, particularly in areas with low demand, must be pursued through integrated governance models, so as to ensure balanced operating costs, operational sustainability and improved effectiveness over time.

To conclude from a technological perspective, the adoption of smart systems enables the implementation of dynamic and intelligent solutions that can optimise routes, journey times and waiting times. Indeed, the introduction of MaaS solutions integrated with Demand-Responsive Transit systems, particularly in low-demand areas, clearly emerges as a key recommendation. This would undoubtedly represent a radical change and a new perspective, but would simultaneously ensure the widespread adoption and establishment of equitable mobility, accessible to all, thereby reducing regional inequalities.

In light of the discussion so far, the findings highlight how the integration of MaaS and DRT represents a promising solution for ensuring better accessibility and efficiency of services in areas with low demand. It is possible to outline future lines of research to be directed towards medium and long-term analyses aimed at evaluating the MaaS-DRT integration in qualitative and quantitative terms, exploring how these can play a significant role in sustainable mobility solutions for areas with low demand. This research, conducted using a systematic literature review (SLR) approach, has yielded limited empirical results when compared with the wide range of theoretical studies. Therefore,

the main limitation of this research lies in the nature of the studies analysed, the majority of which are theoretical, with a relatively small number of pilot projects capable of validating the benefits of DRT-MaaS integration. Among future research objectives, the primary goal is undoubtedly to bridge this gap, focusing on more empirical contributions and on the effectiveness of integrated DRT-MaaS services in real-world contexts, and more specifically in rural settings. To refine and expand the theoretical hypotheses widely discussed in the literature, future research must prioritise experimentation and empirical evidence, which are the only means of supporting this transition from conceptual models to integrated DRT-MaaS solutions. This contribution could be useful to the scientific community as it summarises the main elements found in the literature, providing a knowledge base on the application of these platforms in rural areas, and also to service operators in terms of the guidance provided for the development of increasingly sustainable models.

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Economic Impact of Digital Payments on SMEs in Emerging Markets: A Bibliometric Systematic Literature Review (2016–2025)

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Abstract. Digital payments have fundamentally transformed modern financial systems and have been reshaping the operations of Small and medium-sized enterprises in emerging markets; nevertheless, prior studies indicate that there are fragments and limited empirical findings on the impact of economic factors on digital payments on SMEs in developing economies, as well as the absence of up-to-date bibliometric evidence. This study applies a bibliometric systematic literature review (B-SLR) of Scopus-indexed peer-reviewed articles published from 2016 to 2025 to identify the intellectual structure, thematic development, and highly cited literature in the field. Applying VOSviewer for Bibliographic coupling and keyword co-occurrence, and Biblioshiny for analytical structure and thematic evaluation, the study identifies five key thematic clusters: fintech, technology uptake and SME-driven entrepreneurial activity; access to finance and resilience against shocks; digital finance and economic development; and financial literacy, capacity and financial inclusion. Citation and coupling emphasize the increasing importance of financial technology-enabled credit access, the digital shift, and technological innovations, including digital currencies, blockchain, and crowdfunding. The findings highlight growing academic attention to the role of digital payments in lowering transaction costs, easing financing constraints, and strengthening SME competitiveness.

Keywords: Digital payments · SMEs · VOSviewer · Financial technology · Digital transformation · B-SLR

1 Introduction

Digitalization plays a major role as a driver of economic development, changing the way businesses operate, customer engagement, and access to financial services. The diffusion of mobile technologies and digital financial systems has enabled firms to overcome transactional obstacles, such as high transaction costs and restricted access to formal banking services [1]. Digital payment systems, mobile money, and IoT-integrated systems

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emerged as major innovations, enabling safer, faster, and more transparent transactions while improving financial inclusion and economic growth [2]; [3] The adoption of digital payments enhances SMEs' access to finance by reducing information asymmetry and encouraging effective utilization of financial services. In addition, financial literacy and organizational understanding allow small-scale enterprises to better manage financial challenges and improve business performance. Enhanced financial knowledge fosters positive attitudes toward electronic payments, guides payment behavior, and ultimately leads to improved economic outcomes for SMEs.

Digital financial inclusion initiatives further enhance SMEs' financial efficiency and capacity for innovation by alleviating financial bottlenecks and facilitating technological programs [4]. Despite these advancements, SMEs continue to face gaps in understanding how digital transformation, fintech adoption, and organizational capacities affect performance and the mechanisms connecting them [5]. Digital payment systems have a positive, statistically significant impact on MSME profitability; however, they explain only a limited proportion of profit variation, underscoring the contribution of other factors that also play a significant role [6, 7]. Empirical evidence on the broader impact of digital payments on production, enterprise performance, and long-term growth remains limited [8–10]. Although research on digital payments has expanded significantly, no bibliometric review has systematically mapped the field's intellectual structure between 2016 and 2025, a period marked by accelerated financial technology adoption in emerging markets. This research contributes to existing studies by conducting a bibliometric systematic literature review (B-SLR) focused on the economic implications of digital payments on small and medium-sized enterprises in developing economies, and by uncovering, examining, and tracing thematic focus within the field.

Previous reviews have focused on fintech in general, rather than specifically addressing the economic impact of digital payments on small and medium-sized enterprises (SMEs). To address this gap, the present study applies a Bibliometric Systematic Literature Review (B-SLR), a methodology well-suited to rapidly evolving and fragmented research domains such as digital payments and SME development in emerging markets. The Bibliometric systematic literature review enables systematic identification, screening, and analysis of relevant literature; visualization of publication patterns; identification of influential authors and journals; and derivation of policy-relevant insights, while also highlighting knowledge gaps. Accordingly, this research is driven by the following research questions.

What are the leading research themes and thematic clusters in studies on digital payment adoption among SMEs in emerging markets?

Which articles are most influential in driving the growth of digital payments and SMEs in emerging markets? Which countries and institutions contribute most to the literature?

This study is restricted to peer-reviewed English-language articles published from 2016 to 2025 and examines the economic impact of digital payments on small and medium-sized enterprises (SMEs) in emerging economies. Book chapters, conference papers, and editorials are excluded from the analysis.

2 Theatrical Perspective

The theoretical foundations of the previous literature on digital payments in SMEs are based (in order from greatest to least) on a combination of four theories: Technology Acceptance Model (TAM), Diffusion of Innovation Theory, Financial Inclusion Theory and Institutional theory; and secondarily, Resource-Based View (RBV). These foundations, relating, on the one hand, to each route through which SMEs adopt digital financial technologies and to the diffusion of innovations across markets, and, on the other, to their downstream effects in terms of inclusion, resilience, or competitiveness for a specific economy. A large share of previous studies has discussed theories of innovation adoption, particularly the diffusion of innovations (DOI), from a technology acceptance perspective. Some studies examine the role of credit technology in enabling banks to lend more easily to small and medium-sized enterprises (SMEs), a value chain that explains industrialization dynamics, especially in China.

This research indicates the use of financial technologies in conventional systems and increases access to financing for small- and medium-sized firms. Moreover, [1] analyzes technology-driven entrepreneurship and demonstrate how technological innovations disrupt innovation ecosystems, thereby supporting diffusion-of-innovation theory. [11] complement previous studies by offering perspectives on how Industry 4.0 solutions and financial technology can improve green supply chain finance in small- to medium-sized enterprises. Literature Review: How digitalization accelerates sustainability transitions [12] Digital Waivers Stimulate Entrepreneurship in a Crisis [5] However, collectively these provide support for relevance of Diffusion of Innovation theory in context of digital transformation process within SMEs.

3 Methodological Approach

3.1 Research Design

A bibliometric systematic literature review (B-SLR) was implemented to identify, screen, and visualize relevant data. Keyword co-occurrence frequencies were analyzed using VOSviewer, which groups terms based on their co-occurrence within the dataset. Only keywords with a minimum of five occurrences were included in cluster formation. Full counting determined the total number of occurrences for each keyword, while normalization based on association strength generated accurate proximity values. This approach facilitated the identification of the most highly cited studies on digital payments and small and medium-sized enterprises (SMEs). The eight articles with the highest citation count and strongest link strengths were selected. On 23 December 2025, a Boolean search was performed in the TITLE-ABS-KEY fields using the following query: (“digital payment” OR “mobile payments” OR “e-payments”) AND (“small businesses” OR SME OR microenterprises) AND (“emerging market” OR “developing countries”) AND (“economic impact” OR growth).

A bibliometric systematic literature review (B-SLR) was carried out to identify and analyses pertinent studies. The initial Scopus database search identified 530 publications. Following this, a preliminary screening process was implemented through the Academic Journal Guide rankings (4* to 1) to identify peer-reviewed journal articles that met quality

and reliability standards. The study used VOSviewer to analyses keyword co-occurrence frequencies, and clusters were based on their dataset. Only keywords with a minimum of five occurrences were included in cluster formation. Full counting determined the total number of occurrences of each keyword, while normalization accounted for the association between accurate proximity values. Co-authorship analysis was conducted at the organizational level using a minimum occurrence threshold of 2, and a bibliographic coupling network of influential articles was generated from documents with at least 1 shared reference. This approach helped identify the highly cited studies on digital payments and small and medium-sized enterprises (SMEs). The eight top-cited articles and the strongest link strengths were selected.

Alongside VOSviewer, the study used the Biblioshiny interface of the Bibliometrix R package, accessed locally in the browser at http://127.0.0.1:3838/ after running the biblioshiny () command to conduct conceptual structure analysis, including the generation of a thematic map and a thematic evaluation. The thematic visualization was produced by navigating to the conceptual structure and applying the following parameters: field equal to author keywords, data paramedics equal to 250 papers, minimum cluster occurrence equal to 5 per thousand documents, α equal to 0.5, number of labels equal to 3, label size equal to 0.3, community equal to 0,5 and the Louvain grouping algorithm.

Similarly, thematic evaluation was implemented in Biblioshiny using author keywords, three times slides (2023–2019,2020–2022, 2023,2025), and a minimum frequency threshold of 2 to capture emerging themes. And finally, the geographic map was developed in QGIS to show the most productive countries by merging Scopus country-by-document data with a world shapefile. Data started from 2016 to 2025; a Boolean search was conducted in the TITLE-ABS-KEY within the field area identified using following query: (“digital payment*” OR “electronic payment*” OR fintech OR “digital finance” OR “mobile money”)) AND TITLE-ABS-KEY ((“small business*” OR SME* OR microenterprise* OR entrepreneurship)). Scopus was chosen as the sole data source due to its comprehensive coverage of peer-reviewed literature in finance, economics, financial technology, social science, and business. Inclusion criteria were: peer-reviewed journal articles and reviews written in English and published from 2016 to 2025. Excluded were conference papers, editorials, and book chapters.

This method works well for new and rapidly evolving research areas, as it finds links between articles based on shared references rather than on citation frequency. As a result, bibliographic coupling is particularly useful for showing the intellectual structure of current digital payment research. Following Donthu et al., 2021 bibliographic coupling at the article level and keyword co-occurrence analysis were used to map the intellectual and thematic structure of the literature. The integrated application of PRISMA screening procedures, VOSviewer visualization, Bibliophagy conceptual and evaluation analyses, and QGIS spatial mapping enables a comprehensive, holistic assessment of the field.

4 PRISMA Screening

Figure 1 shows the Identification, eligibility, and inclusion procedures were implemented in accordance with PRISMA 2020 guidelines to ensure transparency and reproducibility. The first-stage search in Scopus showed 530 papers from 2016 to 2025. After removing

duplicates and implementing ABS journal ranking filters, 336 papers were retained for screening. Screening of titles and abstracts resulted in the exclusion of 134 papers that failed to meet the eligibility criteria. After the eligibility assessment, 202 studies qualified for inclusion in the analysis.

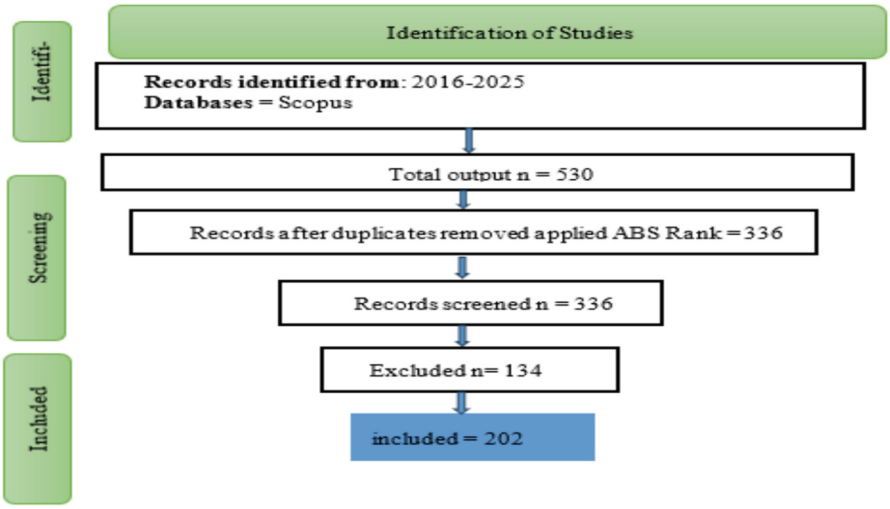

Fig. 1. PRISMA 2020 diagram depicting the identification, screening, eligibility, and inclusion of studies

4.1 Limitation of the Search Strategy

The search strategy is subject to several limitations. Restricting the dataset to Scopus may exclude relevant studies indexed in Web of Science or other databases. Limiting the search to English-language publications introduces linguistic bias, especially in emerging markets where research is frequently published in local languages. Additionally, bibliometric approaches reveal structural patterns but do not establish causal relationships between digital payments and SME performance.

4.2 Publication Trends

Figure 2 shows the annual distribution of publications from 2026 to 2025. Research productivity increased gradually from 2016 to 2023, followed by a small downward trend in 2024 and a significant increase in 2025, reflecting growing academic interest in research focused on digital payments and Small and medium-sized enterprises in emerging markets.

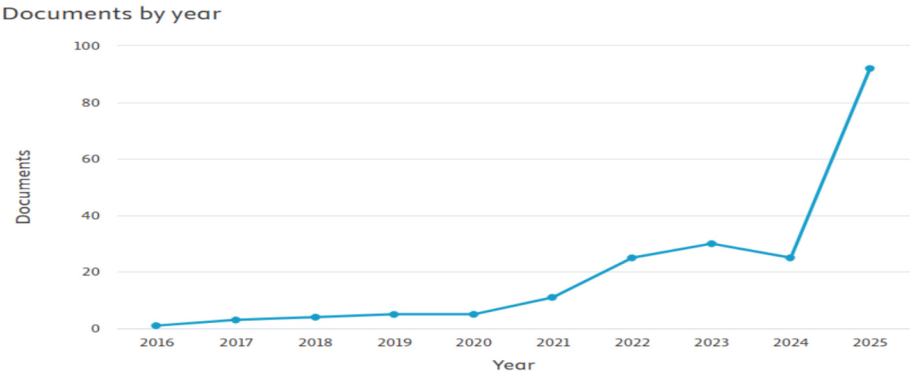

Fig. 2. Shows annual distribution of publications 2016–2025

4.3 Thematic Clusters

The five main thematic clusters found through keyword co-occurrence analysis. These clusters highlight the main areas of research in digital payments and small- and medium-sized enterprises (SMEs). The top keywords in each group point to the main topics covered. Together, these clusters show changing trends in SME performance, fintech adoption, financial inclusion, and the increasing influence of new technologies, including blockchain and crowdfunding.

Table1 illustrates the primary thematic clusters identified through keyword co-occurrence analysis. The cluster identifies five major research streams in prior literature. Cluster 1 explores digital financial services and technology adoption, including mobile payments, financial innovation, and the digitalization of small and medium-sized enterprises. Cluster 2. Focus on financial technology and SME business development, underlining fintech upgrading, crowdfunding, and sustainability. Cluster 3 draws on research of financial inclusion and the ability to withstand crisis, particularly during the COVID-19 period, funding limitations, and the fragility of small enterprises. Cluster 4 captures studies on digital finance and economic development, with considerable representation of research related to China. Finally, Cluster 5 investigates issue of financial capability and inclusive finance, exploring the interplay among financial literacy, financial technology adoption, and SME performance outcomes. Overall, these clusters reveal the field's transition from early fintech adoption toward inclusive development themes of innovation and SME development.

Figure 3 presents the network visualization illustrates a well-organized structure composed of five groups that are clearly distinct yet interrelated. Core nodes such as "Financial technology," digital finance," "financial inclusion," "small and medium-sized enterprises," and "entrepreneurship" show the leading themes in the prior studies. The closeness and concentration of nodes indicate a strong association between Small and medium-sized enterprises, digital fintech, and economic performance in developing economies. The use of expressions such as COVID-19, Mobile money, innovation, and blockchain reflects changes in research focus from 2015 to 2025.

Table 1. Summary of keyword Clusters (Occurrence = 5)

Cluster	No keywords	Representative keywords	Theme
Cluster 1	11	Banking, digitization, financial innovation, financial services, financial system, innovation, investment, mobile money, mobile payment, small and medium-sized enterprise, technology adoption	Digital financial service and technology adoption
Cluster 2	7	Crowdfunding, entrepreneurship, financial technology, fintech, SMEs, sustainability	Fintech innovation and SME Entrepreneurship
Cluster 3	7	COVID-19. Digital financial inclusion, financing constraints, Indonesia, information asymmetry, small business, SME	Financial inclusion and Crisis resilience
Cluster 4	6	China, digital finance, digital inclusive finance, economic development, entrepreneur, finance	Digital finance and economic development
Cluster 5	4	Financial inclusion, financial literacy, fintech adoption, SMEs,	inclusive finance and financial capability

4.4 Influential Articles

This section examines the most influential articles shaping the field through citation-based analysis, coupling strength, and intellectual linkages among seminal studies. The analysis determines the most influential works that anchor the research area and illustrates how foundational contributions affect discrete thematic clusters in the field.

Table 2 displays the findings from the bibliographic coupling analysis, determining the most cited publications in the field. The studies characterised by the strongest linkage coupling and citation effect, such as Sheng (2021), Son (2022), Hiang (2022), and Liu (2022), occupy major positions in the intellectual structure of existing studies. This research focuses on themes such as the impact of financial technology on SME credit access, Industry 4.0 technologies, investment efficiency, and digital finance for enterprise development. Several recent works, including Xie (2024) and Trianto (2025), also indicate stronger connections, emphasising emerging research fronts associated with SME survival, electronic payment adoption, and financial inclusion. Overall, the coupling trends demonstrate a Coherent body of influential studies that frame the development of research on digital finance SMEs.

Figure 4 shows a bibliometric network visualization of main studies and authors. The 8 most influential articles, as listed in Table 1, are highlighted in the network to

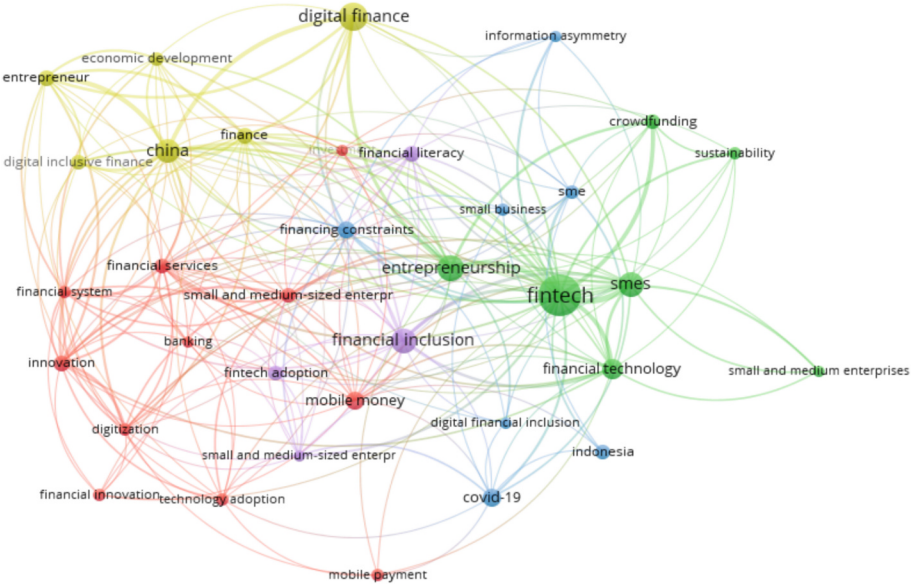

Fig. 3. Keyword Co-Occurrence Network (VOSviewer, Occurrence = 5) using VOS Viewer

demonstrate their interconnections, shared references, and the structure of intellectual influence in research on digital payments and SMEs.

4.5 Co-auorthrship Analysis (Institutions)

Figure 5 presents the institutional co-authorship analysis based on the Scopus dataset utilized in this study. The diagram illustrates that research on digital payments and small businesses spans multiple disciplines, including business, accounting, finance, and development studies. The diagram highlights the multidisciplinary nature of research on digital payments and SMEs, including business, accounting, finance, and development studies. The distribution of nodes reveals that a wide range of universities contribute to this field, rather than a single dominant institution, highlighting the field's broad, decentralized nature.

Figure 6 presents the classification of documents across different subject areas. Most publications fall under Business, Management, and Accounting (39.1%) and Economics and Econometrics (36.6%); after that, the social sciences (8.2%), followed by Decision Science (6.9%) and computer science (4.1%), emphasizing the role of technology and the analytical characteristics of digital payments. This result confirms that, despite being largely based on economic and business perspectives, it is expanding to include technological and social dimensions, indicating the impact of digital payments on Small and Medium-sized enterprises in emerging markets.

Table 2. Bibliographic coupling of influential articles

Authors	Title	Citations	Links	TLS	NC
Sheng (2021)	The effect of fintech on banks' credit provision to SMEs	238	19	41	2.7328
Yin (2019)	What drives entrepreneurship in digital economy?	245	5	7	2.2560
Son (2022)	Industry 4.0 technology implementation: fintech & supply chain finance	257	22	27	3.7311
Chen (2023)	Low-carbon development & digital transformation	111	19	22	2.8881
Wu (2023)	Digital inclusive finance & household entrepreneurship	83	1	1	3.4778
Frimpong (2022)	Financial literacy, digital finance & SME performance	69	25	29	1.0017
Rosavina (2019)	P2P lending adoption by SMEs	93	15	16	0.8564
Huang (2022)	Fintech & investment efficiency	87	61	112	1.2631
Liu (2022)	Digital finance & migrant entrepreneurship	99	39	50	1.4373
Xie (2024)	Digital finance & SME survival	11	54	75	0.5839
Yang (2023)	Digital penetration & entrepreneurial decision	6	10	11	0.1561
Trianto (2025)	e-payment adoption among micro-entrepreneurs	18	44	72	4.1608
Ranabahu(2024)	Fintech and liability of poorness	9	29	34	0.4777
Mutamimah(2023)	Fintech, financial literacy and inclusion	17	48	56	0.4423
Liu (2023)	Lean inventory, fintech & SME financing	18	72	120	0.4683

4.6 Thematic Map (Conceptual Structure Analysis)

The thematic visualization provides a well-organized view of the field's conceptual structure. The horizontal axis indicates centrality, showing the significance of each theme in the research area, while the density on the y-axis displays the internal evolution of

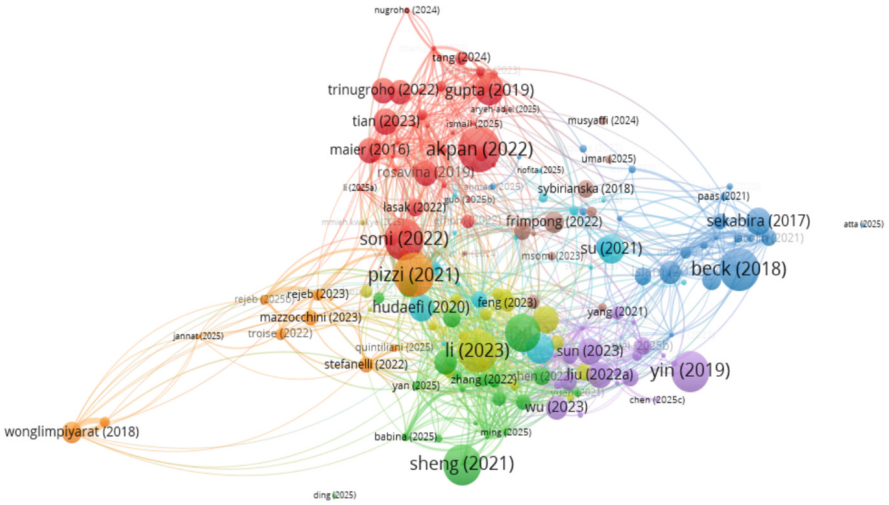

Fig. 4. Highlights Bibliographic coupling network of influential articles

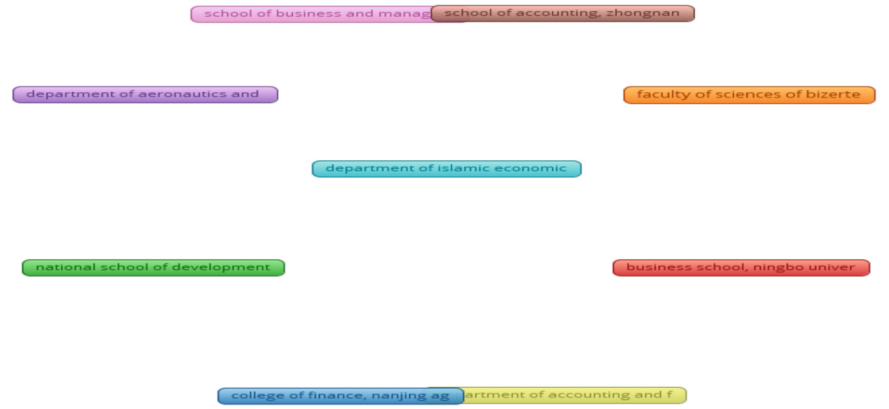

Fig. 5. Institutional co-authorship network (minimum occurrence = 2)

each theme. According to these two dimensions, themes are clustered into four divisions: niche themes, motor themes, emerging and basic themes.

Figure 7 shows that the thematic map identifies financial technology, financial inclusion, and financial innovation as motor themes, all of which are strongly pertinent and well established in the literature. Basic themes such as Small and medium-sized enterprises and financial technology are identified within the discipline's basic framework and encompass widely studied concepts. Niche themes, encompassing access to finance and financial literacy, denote specialized but relatively less central areas of the study, often investigated in a given context or sub-field. Emerging themes, including mobile payments, digital finance, COVID-19, and entrepreneurship, suggest an increasing interest in technology-enabled SMEs.

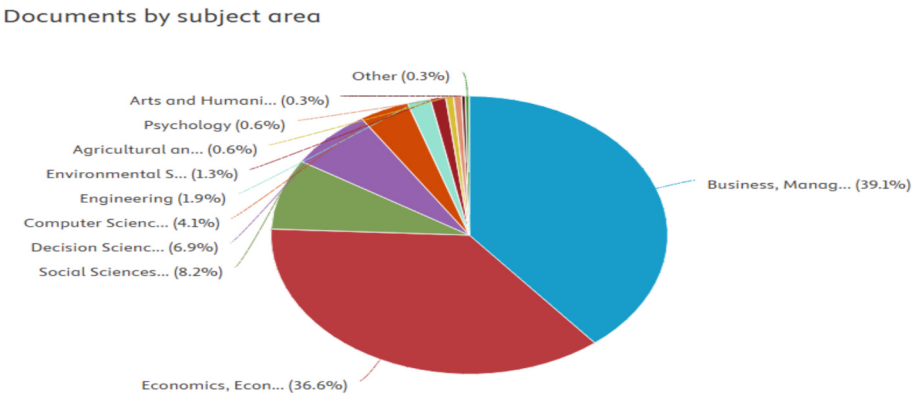

Fig. 6. Geographic distribution of documents on digital payments and SMEs in emerging markets

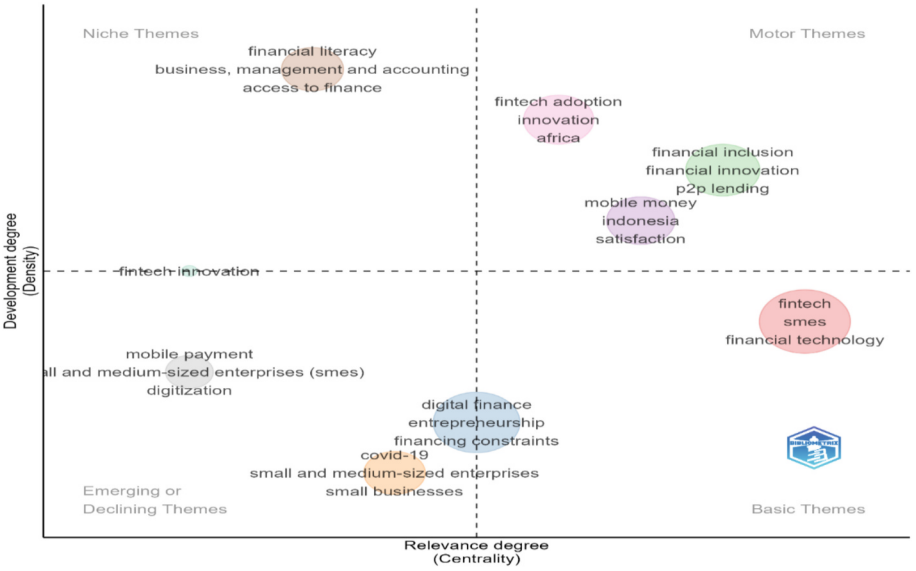

Fig. 7. Presents the thematic map using Biblioshiny with author keywords

4.7 Thematic Evaluation

Thematic evaluation displays how core research shifts over time. The analysis was conducted using Biblioshiny, with a minimum frequency of 2, to support the development of emerging themes in each time segment.

Figure 8 indicates the evolution of research themes across three distinct periods. In the initial phase (2016–2019), financial technology, crowdfunding, and Africa were identified as central topics. Between 2020 and 2022, research placed greater emphasis on financial inclusion, mobile money, entrepreneurship, and COVID-19, reflecting the accelerated digital transformation resulting from the pandemic. From 2023 to 2025,

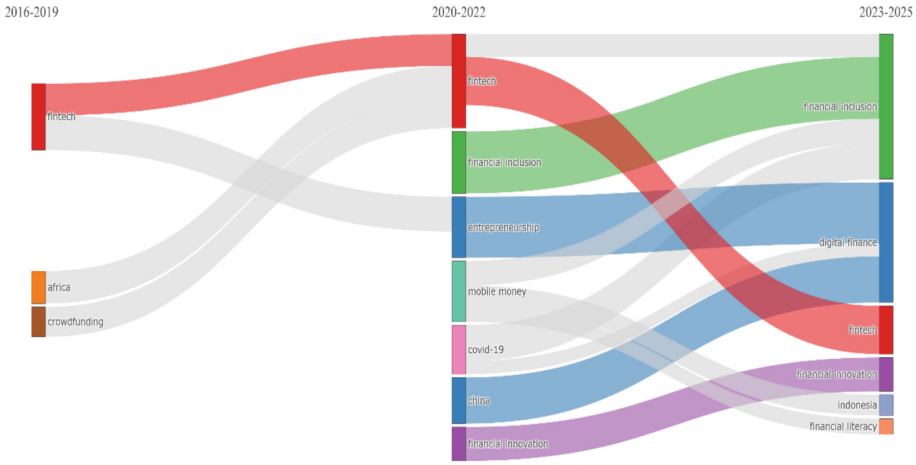

Fig. 8. Thematic Evolution of Author Keywords (2016–2025): Visualization of how main r search themes developed across three distinct stages.

the thematic focus shifted toward advanced topics such as financial innovation, digital finance, and financial literacy, signifying a transition from early financial adoption to the development of comprehensive financial ecosystems driven by innovation.

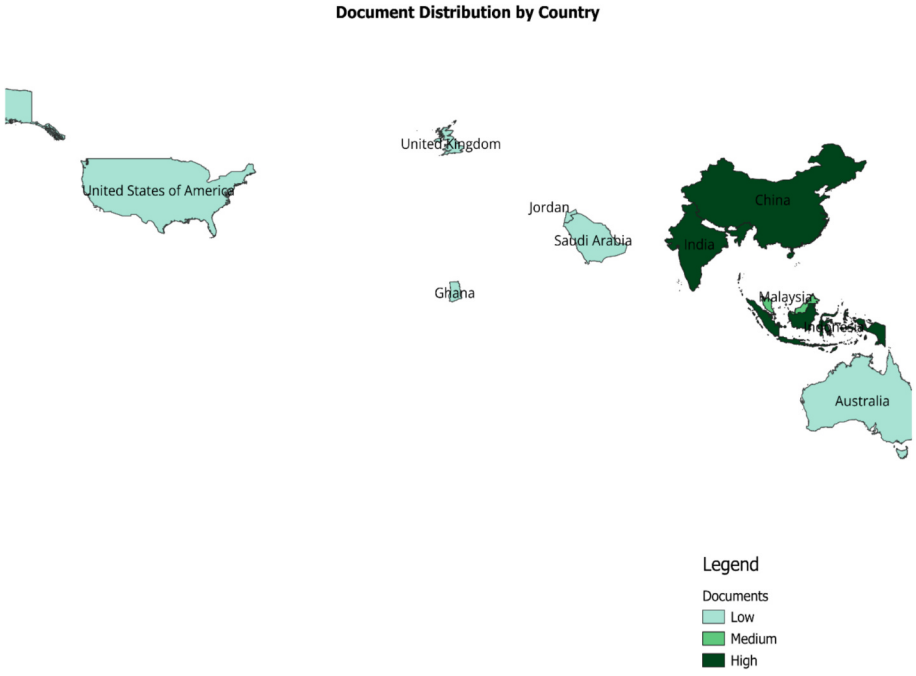

Fig. 9. Shows the distribution of literature on digital payments and SMEs

Figure 9 illustrates the geographic distribution of the included studies shows significant clustering in emerging Asian economies, particularly China and India, which together account for the majority of published research. This pattern reflects the rapid growth of digital payment ecosystems and their considerable influence on small and medium enterprises (SMEs) in these countries. Moderate contributions from Southeast Asian nations, including Indonesia and Malaysia, further underline the region's increasing significance. Conversely, the limited representation of studies from Africa and the Middle East indicates major gaps in the current literature.

5 Discussion

The results demonstrate a structural transformation of digital payment within developing economies. Earlier studies mainly focused on digital banking and mobile payment services, while literature from 2023 to 2025 increasingly integrates blockchain, crowdfunding, and digital currencies. This trend aligns with international financial developments, where platform-based financial ecosystems and decentralized financing models are becoming more prominent. The widespread use of financial technology and financial inclusion themes indicates that digital payments are widely regarded as mechanisms for mitigating financial challenges and enhancing the performance of small and medium-sized enterprises (SMEs). This perspective is consistent with global evidence indicating that digital financial services reduce information asymmetry, decrease transaction costs, and increase access to credit.

These findings present important considerations for policymakers in emerging markets. Strengthening digital infrastructure, improving regulatory frameworks, and advancing financial literacy are likely to accelerate the adoption of digital payments by small and medium-sized enterprises (SMEs). Furthermore, facilitating interoperability among payment platforms, expanding digital identity systems, and incentivizing fintech innovation can enhance SME financing. Future research should clarify the causal mechanisms linking digital payments to SME performance, identify adoption barriers in underrepresented regions such as Africa and the Middle East, and assess the influence of emerging technologies on SME financing. Longitudinal studies are necessary to evaluate the long-term economic effects of digital payment adoption.

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Conflict of Interest. Ther authors declare no conflict of interest.

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Process-Oriented Digitalization in Port Systems: Evidence from the Port of Trieste

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Abstract. This paper analyses the role of digitalisation in port systems within the context of the major transformations currently affecting the contemporary port sector, including technological, energy and geopolitical transitions. The study presented here stems from a research project that, starting with an analysis of existing processes related to port digitization, sought to develop a digital tool that would serve as an orchestrator, with the aim of simplifying a particularly fragmented and complex process: the procedure for semi-trailers to obtain port access permits.

The analysis was based on an applied qualitative approach, in which, in an initial phase, a series of unstructured interviews were conducted with key stakeholders to understand the operational processes that could be implemented, identifying a systemic gap attributable to the fragmentation of information flows and limited interoperability between the Port Community System (Sinfomar) and Terminal Operating Systems. This gap is particularly evident in truck access management processes, characterized by duplication of tasks, the use of parallel tools and a high incidence of manual operations. In a second phase the development of a digital process orchestration tool was implemented, designed as an intermediate layer of integration between existing systems. The application of the solution to the access process for departing lorries has yielded significant results, with operational times reduced from several minutes to a few seconds, accompanied by a decrease in errors and smoother flows.

Keywords: Port Digital Transition · Smart Port · Port Community System · PCS · Port of Trieste

1 Introduction

The digital transition represents one of the main drivers of innovation and change within the port sector. It is embedded in and develops as part of a broader reconfiguration of ports, characterized by the interaction between at least three major evolutionary trajectories: the digital transition, the environmental and energy transition, and the resurgence of geopolitics as a defining factor in global logistics chains [1].

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The digitalization of port processes, supported by the adoption of technologies associated with the Industry 4.0 paradigm – such as the Internet of Things, artificial intelligence, blockchain and digital twins – has profoundly altered the way operations are managed, promoting automation, data sharing and information integration among stakeholders in the port community [2]. Port Community Systems (PCS), in particular, have established themselves as key digital infrastructures for the coordination of information flows, helping to improve operational efficiency and process transparency [3].

Despite the growing attention in the literature towards port digitalization, analysis of the concrete processes and the ways in which digital innovations translate into actual improvements in operational efficiency remains limited. In particular, there remains a persistent gap between the adoption of digital infrastructure – such as PCS – and the actual integration of processes, which often continue to be characterized by fragmentation, duplication and poor interoperability between stakeholders, particularly given the multitude of software and tools commonly in use [4].

This study fits within this framework, proposing to reflect on which digital solutions we can adopt to improve operational efficiency in the port sector. To address this issue, the analysis focuses on the case of the Port of Trieste, chosen as a case study due to its strategic importance and the already advanced level of digitalization achieved. Through a qualitative approach based on desk research, analysis of existing systems and interviews with operators, the study identified specific operational processes currently managed in an ad hoc manner, characterized by duplication of information and the presence of multiple, non-integrated solutions. Starting, therefore, with a mapping of processes, this paper proposes the development of a digital solution geared towards process orchestration, capable of addressing an operational bottleneck by seeking to improve coordination between the various stakeholders involved [5].

The work contributes to the debate on port digitalization by proposing a process-oriented approach, which moves beyond the emphasis on individual technologies to focus on operational integration and the reduction of systemic inefficiencies, adopting the following structure: the second section presents a review of the literature on port digitalization, with particular reference to Port Community Systems and key European best practices; the third section introduces the case study of the Port of Trieste; the fourth section presents the methodological framework; the fifth section presents the results obtained; and the final section is devoted to the conclusions.

2 Literature Review – Digitization and Interoperability of Port Systems

In recent years, the digitalization of ports has become one of the most significant themes in the transformation of maritime logistics systems. The modern port is increasingly characterised by the interplay of physical and information flows. Ships, lorries, trains, goods, documents, permits, customs data, operational requests and administrative procedures all move in tandem [6]. It is in this space, between the movement of goods and the circulation of information, that the digitalisation of port systems is increasingly taking on a central role [4, 7].

In the past, ports were viewed primarily in terms of their physical infrastructure: quays, water depths, cranes, yards, warehouses, and rail and road connections. This perspective remains essential to ensure that port environments continue to function as efficient infrastructure, but a port's competitive capacity increasingly depends on the quality of its information systems: in this sense, a port must be able to manage not only goods but also information flows, circulating them among the various stakeholders, making them available at the right time, avoiding duplication, reducing errors and facilitating coordination between operators [8].

The literature on smart ports and Port 4.0 emphasises precisely this point: the port is progressively becoming a connected system, in which automation, sustainability and the dematerialisation of information flows represent three fundamental directions of digital transformation [9, 10].

Port digitalisation can be analysed at several levels. A first level concerns the conversion of paper documents into electronic documents. This is the most immediate step: files, forms, requests, authorisations and communications are managed through IT systems. This saves time and improves the traceability of operations. A second level concerns the organisation of processes, influencing the way in which stakeholders work, communicate and make decisions. A procedure may be uploaded to a digital platform, but if the operator then has to re-enter the same data into another management system, the benefit is reduced. Digitalisation produces more substantial effects when it allows the operational flow to be rethought as a whole. A third level concerns the transformation of port governance, where digital platforms change the way information is produced, controlled and shared [11]. This affects relations between Port System Authorities, terminal operators, freight forwarders, shipping agents, customs, road hauliers, rail companies and other parties involved in the logistics chain. In this sense, the port is a collective system. No single stakeholder governs the entire process alone. Every operation depends on a sequence of steps, and each step requires a multitude of data [12].

In the literature, numerous authors have examined port evolution processes, and recently, the topic of digitalisation has come to the fore in discussions on the subject: ports are, in fact, evolving from simple infrastructure hubs into integrated logistics platforms. In this sense, the latest generations of ports are characterised by real-time connectivity, data exchange, collaboration between stakeholders, a focus on sustainability and the use of advanced technologies. This evolution responds to various pressures. There are economic pressures, linked to competition between ports and the need to reduce times and costs. There are logistical pressures, connected to the growth in volumes, the complexity of supply chains and the demand for greater reliability. There are environmental pressures, as ports must manage emissions, energy consumption, congestion and their impact on the local area. And there are institutional pressures, particularly regarding security, customs, traceability and the regulation of cargo flows.

In this context, the Port Community System (PCS) plays a central role [13]. The PCS is a digital platform designed to enable the interoperable exchange of information between stakeholders in the port community. Its main function is to connect parties that use different languages, procedures and information systems. Shipping agents, freight forwarders, terminal operators, hauliers, customs authorities, the Harbour Master's Office, the Guardia di Finanza, maritime health authorities, freight villages and rail

operators all play a part in the port process [14]. The PCS aims to establish a common platform for exchange. The Port Community Systems can be describe as digital platforms capable of facilitating information exchange, coordination and collaboration among port community stakeholders. Their usefulness is linked to the ability to simplify communication, automate data exchange, and enhance efficiency, transparency and security within maritime trade systems [15]. Interoperability therefore becomes the central issue. Systems must be able to connect and exchange data via compatible interfaces, protocols and architectures. This concerns the relationship between PCS, Terminal Operating Systems (TOS), customs systems, rail platforms, access systems, public databases and private management systems. The interoperability of a PCS with the entire port community is certainly a critical aspect to take into account. One need only consider the breadth of interfaces a Port Community System must handle: whilst the TOS simply concerns the port terminal and its internal operations—yard, gates, vehicles, cargo units, operational sequences, equipment, and handling planning—the PCS must be able to view port operations holistically, whilst also communicating with the various IT systems used by different operators [16, 17]. When the PCS and TOS communicate effectively, the transition between document, authorisation and physical operation becomes smoother. When communication is incomplete, operators must intervene manually. They re-enter data, check across multiple screens, use reference sheets, and send requests via email. The process remains digital, but its continuity is weak.

Interoperability affects the port's ability to function as a unified system. A port may have good physical infrastructure yet suffer from information bottlenecks. It may have adequate draughts, major rail connections and specialised terminals, but lose efficiency in certain document or authorisation stages. Bottlenecks in transport systems can therefore be found as much in logistics yards, at entry gates, during customs checks, and in the interface between ship and train, as in the communication between different digital and IT architectures. This is why digitalisation must be analysed at the micro-operational level. Recent literature on smart ports often emphasises the technological dimension: automation, sensors, artificial intelligence, cloud platforms, and digital twins. Whilst all these elements are particularly relevant to day-to-day port operations, the success of digitalisation often depends on more minute details: a screen that communicates with another, a field filled in just once, a list that can be selected in bulk, a document priority correctly read by the system, an authorisation that passes from the PCS to the terminal without further steps: it is these details that determine a significant increase in efficiency in the field of port digitalisation [18].

The digital tools a port can adopt also include GPS systems, OCR, RFID, automated gates, PCS modules, access control systems and management platforms. The presence of these tools indicates a path towards modernisation. Their coordination, however, indicates a deeper capability: that of making the parts of the system work together. Digitalisation, then, becomes a matter of synchronisation, that is, the ability to share data and information when it is needed [19]. Too late, and the data loses its operational value. Too early, and it may still be incomplete. If incorrect, it generates additional checks. If duplicated, it increases the administrative burden. The digital port works when data is timely, reliable and shared according to clear rules.

3 Methods

3.1 Understanding Digital Port Processes

The core of this project lies in a methodological approach designed to combine qualitative research with empirical applications, aimed, in the first instance, at identifying certain systemic issues within port processes and, in a second phase, at developing a digital solution capable of addressing one of these inefficiencies in an effective manner. The first phase of the research was exploratory in nature and focused on establishing a comprehensive understanding of digital port processes. During this phase, desk research was conducted, along with an analysis of the main best practices at European and international level regarding port digitalization, Port Community Systems (PCS) and tools geared towards the integrated management of logistics flows.

This analysis was then applied to the port of Trieste through a study of the Sinfomar PCS, considered the central digital infrastructure for coordinating a significant portion of port processes: in this context, the functional modules and its digital architecture were examined to understand the functionalities involved in managing information relating to ships, cargo, vehicles and rail traffic, as well as to understand the nature of the interactions between the port system as a whole and individual operators. This preliminary phase therefore provided an initial mapping of existing digital processes and identified areas where digitalization was already well-established and those where, conversely, signs of critical issues were emerging.

3.2 Identification of System Gaps

The second phase forms the core of the methodology adopted and was carried out through unstructured interviews with key stakeholders at the Port of Trieste, including terminal operators, logistics operators and rail operators. The decision to use unstructured interviews was driven by the need to capture the actual operational dynamics without imposing an overly rigid framework of observation from the outset. This approach made it possible to highlight not only the functions formally assigned to digital systems, but above all the limitations, inconsistencies and informal solutions that characterize day-to-day operations.

The evidence gathered showed that the port's digitalization is developing in layers that are only partially integrated. In particular, the Port Community System Sinfomar primarily serves as a document and institutional liaison, whilst the internal management of terminal operations falls to the Terminal Operating Systems, which each operator adopts independently in accordance with their own organizational needs.

It is precisely in the relationship between Sinfomar and the terminal systems that a systemic weakness requiring intervention has been identified. The interviews highlighted how, in various areas, the lack of interoperability between the PCS and TOS leads to a duplication of processes and a fragmentation of information flows, particularly regarding the authorization of lorries' pre-entry to the terminal via the digital traffic light system linked to Sinfomar, the overview of this system is presented into the Fig. 1.

The Ro-Ro access management process, as currently structured requires a series of manual steps often in a rather laborious manner. The control room operator logs

into Sinfomar PCS, searches for the truck's license plate among the registered vehicles, matches it to the correct booking, and only then can they authorize the green light at the Ferretti traffic signal. An operation that, taken individually, seems manageable. The problem is that it must be repeated every time, for every single vehicle, one at a time.

Once access is granted, the event must be recorded in an external Excel file, a parallel tool, manually updated by the control room, which serves as a log of authorized trucks. That data is then imported into the Terminal Operating System to synchronize the information in the terminal's management system. Three different environments, essentially to record the same thing.

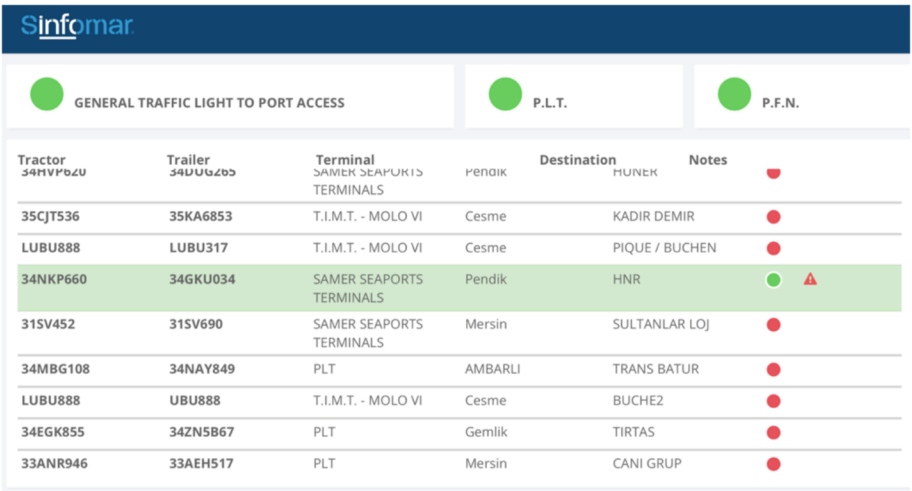

Fig. 1. Traffic light system for access to the new free zone on the Sinfomar website of the Port System Authority of the Eastern Adriatic Sea. Source: https://sinfomar.porto.trieste.it/GPF/mezzifermifernetti.jsp last access: 07/05/2026

Further complicating the picture are emails: the requests for terminal access, infact, often arrive via email, while bookings are generated directly by the TOS. The operator is therefore forced to manually transfer the information from the terminal management system to PCS and then back to Excel. Every transfer is an extra step, a moment when something can go wrong—a wrong license plate, an outdated booking, a mismatch between systems.

The result is a fragmented information flow, in which the same data is rewritten and rechecked multiple times, in different contexts, without any of the systems involved ever having an up-to-date and complete view of the situation in real time. Those working in the control room must piece together the operational picture bit by bit, cross-referencing different sources, with all that this entails in terms of time and margin for error.

3.3 Development of the Digital Solution

Once the system gap requiring intervention had been identified, the third phase of the research focused on designing and implementing a digital solution aimed at resolving

that specific problem. The approach adopted was problem-driven, in the sense that the technological tool was not developed prior to the analysis but rather after identifying the vulnerable process requiring intervention. In this regard, the tool was conceived as what could be defined as a process innovation designed to address an operational problem that clearly emerged from discussions with port stakeholders [20]. The analysis of port processes, highlighted in the previous phase, thus identified a particularly significant bottleneck in the duplication of access operations to the multipurpose terminal, and, on this basis, a prototype orchestrator was developed, designed as an intermediate layer between the Port Community System (PCS) and the Terminal Operating Systems (TOS). The function of the orchestrator developed in this project is to reduce the manual steps that the terminal control room is required to perform, thereby also reducing information fragmentation and eliminating the duplication of activities, creating an interface capable of direct communication between IT systems through a tool that enables platforms currently operating separately to communicate with one another.

The development of the orchestrator therefore aims to create an automated flow of information between the PCS and the TOS, eliminating the need for external manual interventions such as the use of Excel files or email communications for operational monitoring. In the specific application regarding truck access to the terminal, the tool was designed to address the most rigid aspects of the process, leading to fully automated management of access authorizations, in which the digital tool serves as the interface between the various platforms, completely reorganizing the process for semi-trailers to request pre-entry into the port terminal.

The result achieved through the development of the orchestrator is to transform a system based on various redundant and complicated steps into a continuous flow of information, where physical terminal operators are required only to perform a document verification role, while the task of entering information is delegated to an automated system.

4 Case Study: The Digitalisation of Port Processes at the Port of Trieste

The case study presented in this paper focuses on the Port of Trieste, an infrastructure with a complex logistics structure in which maritime traffic, rail freight, road transport, customs procedures, document management, and terminal operations are all intertwined. The volume of goods transported by rail annually (with over 8,000 trains handled in 2025) and the free port regime make this port a unique port ecosystem on a national scale [4]. It is precisely this exceptional nature that makes digitization a crucial step, because, as mentioned earlier, the port's operations increasingly depend on the ability to circulate accurate information in a timely manner to meet operational needs.

At the heart of the port digitization process in Trieste is Sinfomar, the Port Community System of the Port of Trieste, adopted in 2014. Its introduction marked the start of the most structured phase of the port's digitization, following earlier initiatives—such as the Black Box system—which were primarily focused on collecting statistical and commercial data related to the Free Port. Sinfomar was thus created with a specific purpose: to establish a common platform through which the various stakeholders in the port

community could communicate while coordinating information flows. Even today, this platform serves as a link between the Port System Authority, terminal operators, customs, freight forwarders, carriers, rail operators, and other entities involved in logistics activities; its modular architecture allows it to cover various operational areas: management of ships, cargo, vehicles, trains, people, and statistics [16]. Sinfomar thus builds a shared information base, useful both for administrative procedures and for monitoring the physical flows passing through the port. A schematic representation of the operations managed by Sinfomar is shown in Fig. 2. From a functional standpoint, Sinfomar has helped improve certain aspects of port management, with a particular focus on the digitization of information flows and the streamlining of document processing, thereby enhancing the traceability of operations. The presence of a common platform thus helps reduce some of the document fragmentation that traditionally characterizes port environments. One of the most concrete and immediate results has been the digitization of customs documentation. Ship arrival and departure manifests, summary declarations for incoming and outgoing goods, and advance notices for road traffic: procedures that previously existed on paper—often in duplicate—are now managed electronically through the system. Each shipment of goods is identified by unique codes that link logistics data to customs data, ensuring precise matching and the automatic generation of reliable statistics. This is no minor detail in a port where the Free Port regime requires particularly strict customs control [21].

Over time, other technological solutions have developed around Sinfomar, with varying degrees of integration. One of the most visible concerns the management of semi-trailer traffic, a particularly significant issue given that hundreds of thousands of trucks pass through the port each year (360,000 in 2025), causing congestion problems both within the port area and on urban roads [20].

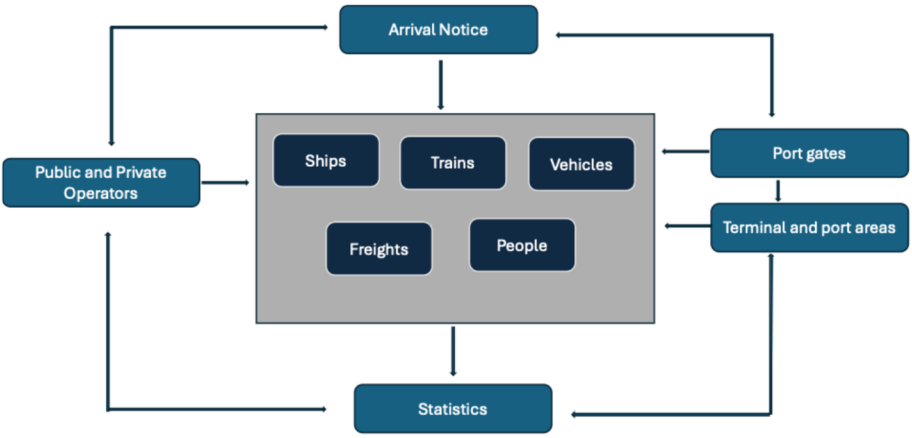

Fig. 2. Schematic representation of the operations managed by the Port Community System of the port of Trieste – Sinfomar. Source: Author's Elaboration

5 Results and Discussion

As highlighted above, this paper stems from a research and development project, in which the most significant findings relate to the process of managing port access for departing lorries, identified during the qualitative analysis as one of the most critical issues in terms of operational integration. Indeed, under the traditional operational setup, this process relied on a highly manual and fragmented sequence, where the operator was required to identify the vehicle waiting within the Sinfomar interface, manually retrieve essential data, separately consult the Terminal Operating System to extract the information needed for the booking, prepare and submit the pre-entry request, retrieve the confirmation data, log back into Sinfomar to fill in the required fields and, finally, manually update the vehicle's status to authorize its progression [18]. The information flow generated by requests for access to the port terminal required manual intervention to coordinate various systems, ranging from reading emails containing terminal access requests, to identifying the booking via the TOS, to entering the various data obtained into Sinfomar, which involved manually filling out all the fields shown in the interface presented in Fig. 3. The estimated time required to process this procedure was approximately 7 min per unit entering the terminal. The introduction of the orchestrator—developed as an intermediate layer between the PCS, the TOS, and other IT tools such as email and Excel files—led to a substantial process innovation. The digital orchestrator was in fact designed to automatically read data from various information sources, retrieving the necessary data from the TOS and the email system, and then autonomously generating the pre-entry request to the terminal for the waiting truck, filling in the required fields within Sinfomar and simultaneously updating the terminal control room's operational report managed via an Excel file. In this way, this process—which previously consisted of several manual operations—has been reorganized into a continuous and integrated workflow, managed autonomously by an automated solution, while maintaining operator control, with the operator now performing only a supervisory role.

In terms of performance, the most striking result is the drastic reduction in the time required to complete the entire procedure. Whereas in the previous configuration the workflow could take an average of 7 min, with the new tool the same process is completed in around 12 s: the efficiency gain is therefore extremely significant, both in absolute and relative terms, and demonstrates how the intervention has redesigned the entire access authorizations process, eliminating most of the redundant activities and interruptions that characterized the original workflow[1].

In addition to the reduction in processing times, the results show a qualitative improvement in the process. Automation significantly reduces the risk of human error, particularly during data transcription between different systems and in the management of booking confirmations. At the same time, the operational centralization of the workflow helps to overcome the issue of parallel information channels, which was one of the main critical issues highlighted in the interviews. The process thus becomes more linear, more transparent and more controllable, with positive knock-on effects on the standardization of procedures and the ability to monitor their progress over time.

[1] An explanatory video about the digital orchestrator developed as part of the project can be found at the following link: https://bit.ly/Orchestrator_Port_Trieste.

The result achieved is the development of an efficient and functional technological solution, whilst also demonstrating how a system gap—linked to the lack of integration between platforms and the duplication of activities—can be addressed through an orchestration tool capable of intervening directly in the process.

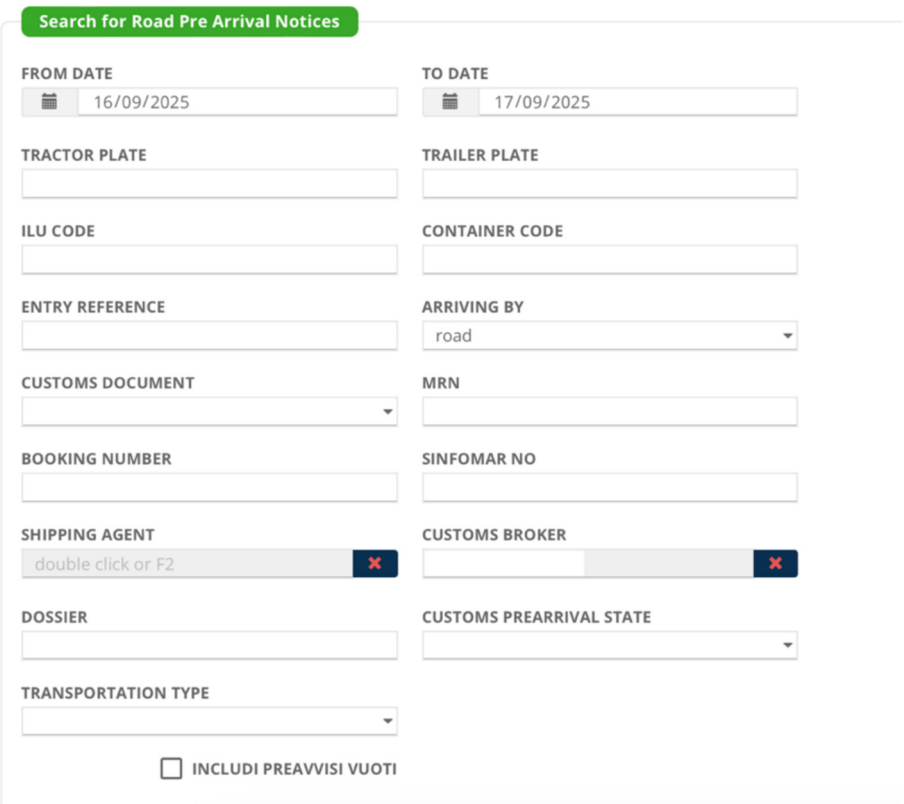

Fig. 3. Form for reporting pre-arrival at the port terminal, to be completed in order to receive approval. Source: Sinfomar

6 Conclusions

The paper analyzed the digitalization of port processes, placing it within a broader context of transformations that are redefining the role of modern ports, amidst technological, energy and geopolitical transitions. This study aims to highlight the importance of interoperability in operational processes, demonstrating that efficiency depends as much on the presence of an advanced digital infrastructure as on that infrastructure's ability to interact with the entire port ecosystem. The results show that one of the main limitations of port digitalisation lies in the fragmentation of information systems and the separation between the documentary level and the more explicitly operational level. In this regard, we have observed since the literature review that document dematerialisation can represent the first fundamental step towards highly digitalized smart ports; however, to also

improve the efficiency of the operational component, we need to take a step further and thus create an interoperable ecosystem. This is made even more complicated when one considers how many different operational systems can coexist within a single port community, where each terminal will use a different terminal operating system, and every logistics, rail, MTO and other operator will utilise different information systems: the challenge of port digitalisation lies precisely in the ability to integrate all these different components into a single system, in order to minimise duplication of procedures, manual steps that are particularly prone to error, and the disjointed management of information flows.

Specifically, in this paper we have focused on the process by which lorries request access to the terminal; in this particular case study, it was clear to see that there are inefficiencies within the process which result in long processing times, procedural rigidity and a risk of human error on the part of operators. All these factors led us to identify this process as an interesting area of application for developing a digital tool capable of offering a solution tailored to this specific operational process. The orchestrator developed has demonstrated that integration between the various existing systems is not only feasible but can also lead to effective implementations, drastically reducing operational times—which can drop from the 7 min mentioned earlier to a matter of seconds—whilst simultaneously improving the quality and reliability of the process, thanks to a reduction in potential human errors.

The approach adopted in this study, based on identifying a system gap through qualitative analysis and the subsequent design of a targeted solution, has highlighted how it is possible to take concrete action to address these critical issues. The development of a process orchestration tool has demonstrated how the integration of existing systems can yield significant improvements, drastically reducing operational times—from several minutes to a few seconds—whilst simultaneously enhancing the quality and reliability of the process [21].

From this perspective, the value of digitalization lies not so much in the proliferation of platforms, but in their ability to communicate with one another and effectively support day-to-day operations. The results indicate that targeted interventions aimed at integrating existing systems can generate significant benefits without necessarily requiring the replacement of existing digital infrastructure. This implies a greater focus on interface design, the standardization of information flows, and the development of solutions capable of reducing dependence on manual tasks and parallel tools.

Acknowledgments. This work is the result of reflections and perspectives shared by both authors; however, specifically, paragraph 6 (conclusions) is to be attributed to G. Borruso, paragraph 1 (introduction) is to be attributed to both authors, whilst the remaining content of the contribution is to be attributed to A. Gallo. This study was carried out as part of the iNEST project, PNRR CUP J43C22000320006 “Digital Twin and BI for the Advanced Digitalisation of Port Processes in the Port of Trieste” in collaboration with Prodigys Technology S.R.L.

Disclosure of Interests. The authors declare any competing interests.

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Cities and Sport. Proximity Planning Among Green Networks and Commons

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Abstract. This paper discusses the relationship between sport, health and urban form within the perspective of proximity planning, focusing on the role of green networks and urban commons. Starting from the growing relevance of outdoor physical activity after the Covid-19 pandemic and from the effects of climate change on urban environments, the contribution interprets sport as a driver of sustainable urban development and public health. The paper reviews the evolution of the relationship among sport, urban greenery and health, highlights current conditions in Italian cities, and argues for a planning approach that integrates walkability, green infrastructure and informal sports practices. Particular attention is devoted to large mono-functional urban enclaves and disused compounds, which can hinder proximity networks but also become strategic spaces for regeneration. Using previous research on Cagliari and Trieste, the paper recalls the use of GIS tools, community data and the Walkability in Big Buildings Index to support the interpretation of urban space as a network for health-oriented and inclusive sports practices. The contribution concludes that sport should be recognized as an urban common good and as a key component of the resilient city within the ecological transition.

Keywords: Sport City · Health Geography · Urban Greenery · Proximity Planning · Commons · Walkability

1 Introduction: Sport, Health and Urban Form

The interconnection between sport, health, and urban form is increasingly evident as a consequence of urbanization processes, such as the growing prevalence of sedentary lifestyles, air pollution, and climate change, as well as epidemiological aspects related to the spread of viruses and diseases. The Covid-19 pandemic marked a moment in which outdoor activities experienced a significant grassroots-driven upsurge, characterized by both organized and informal practices taking place in spaces not necessarily designated for sporting purposes. This trend led, albeit still timidly, to the development of urban policies aimed at assigning areas to sports practices (gyms, swimming pools, playing

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fields, etc.) and at the reappropriation of urban spaces not originally intended for sporting use.

At the same time, the increasing frequency of perceived extreme climatic events, associated with rising temperatures in urban areas, has highlighted the crucial role of green spaces in mitigating the effects of these phenomena, making them an increasingly essential component of urban regeneration strategies.

The statement that "sport is an important enabler of sustainable development" [1] prompts a rethinking of urban policies from a health geography perspective, linking urban morphology to the spatial distribution of diseases. Within this framework, the arrangement of open spaces, green networks, and sports facilities assumes a structural role in shaping cities oriented toward health, influencing socio-geographical factors of access to well-being and the capacity for prevention with respect to major risk factors by structuring everyday opportunities for active mobility, social interaction, and exposure to restorative environments, these spatial configurations operate as "health-promoting" urban devices that can either reduce or exacerbate inequalities in morbidity and mortality [2, 3]. Recent contributions in urban health and epidemiology have shown how landscape morphology, connectivity, and the distribution of activities condition patterns of exposure to airborne diseases, with more "patchy" and heterogeneous urban fabrics often associated with higher contact rates and vulnerability [4, 5]. In this sense, the design of green and sport infrastructures intersects with debates on the 15-min city and chrono-urbanism, which advocate for proximity-based access to everyday services and physical activity as a way to advance health equity, particularly for socially and spatially disadvantaged groups [6, 7]. Such perspectives reinforce the idea that integrating sport, greenery, and walkable public spaces into ordinary planning is not merely a matter of amenities, but a core public health strategy embedded in the spatial organization of the contemporary city.

2 Sport, Health, City, and Urban Green: Evolution of the Approach

The relationship among city, health, sport, and urban greenery has become a well-established connection, understood as a multidimensional system in which geographic space acts as a multiplier and diffuser of well-being, rather than as a mere container. Sport is viewed as a "total social fact," capable of both reflecting and influencing the structures of contemporary society, engaging aspects of medical and health geography [8, 9], where the quality of urban life is intrinsically linked to the equilibrium between the environment and the human body.

Physical and sporting activities also serve as a driving force for local and territorial development [10, 11], producing new geographies and processes of rewriting the urban space. Urban sporting events have become a consolidated practice [3], materializing the interaction among economic, social, environmental, and territorial marketing benefits [12]. Historically, stadiums, arenas, and large sports facilities have represented emblematic spaces of the "public city"—a space that is identity-building, spectacularized, and often politically symbolic. The current transition toward widespread forms of everyday sporting practice marks a shift from a nodal and centripetal model—based on specific facilities for dedicated sports activities—to a diffuse, networked configuration in which

streets, waterfronts, squares, and parks collectively function as a "distributed stadium" designed from the bottom up [13].

Alternative sporting practices [14] reveal how citizens "rewrite" the urban territory, transforming marginal areas into spaces of well-being and reclaiming a healthier and more inclusive city. This shift moves the focus away from traditional, institutionalized sports (such as football, tennis, and athletics) toward so-called "Lifestyle Sports" or "action sports" [15].

From a geographical perspective, new functional networks emerge, overlapping those of mobility and following temporal and spatial logics often unforeseen by traditional planning tools. Within the planning domain, however, this vision translates into a growing critique of functionalist standards. According to Boeri [16], urban forestry represents vital infrastructure for public health, while Castagnoli [17] argues that urban green areas should not be confined to a purely conservationist dimension. The link between sport and green space [18] becomes a central issue: outdoor recreational activity transforms urban greenery into a "territorial health service." Yet coherence in policy implementation often remains weak. Lindsey and Darby [19] warn of the fragmentation between sustainable development goals (SDGs) and actual practices.

From a social standpoint, the right to health and sport within green spaces acquires a distinct political value. Harvey [20] conceptualizes these spaces as essential *commons* for the "right to the city," while Corburn [21] emphasizes that urban planning must incorporate the claims and experiences of local communities to achieve genuine effectiveness.

3 Sport, Health, City, Urban Green. The State of the Art in Italian Cities

Recent analyses on Italian cities confirm the interdependence among sport, green infrastructure, and public health, outlining a "Sport City" model conceptualized as an integrated ecosystem, generally associated with high levels of urban quality of life [22, 23]. According to the Green White Paper 2025 [24], urban greenery is no longer seen as a mere decorative feature but as a functional "lung" structured around three core pillars: economic and managerial integration, social cohesion, and environmental resilience. This approach directly addresses the climate emergency identified in ISPRA reports [25, 26], complemented by Copernicus data, which indicate a critical temperature increase of + 1.33 °C in Italy in 2024 as a peak year if compared to the trend recorded from 1961. Within this scenario, green spaces act as mitigators of "urban heat islands," providing essential ecosystem services that foster psycho-physical well-being and protect socially vulnerable groups.

The *2025 Sports Index* [23, 27, 28] highlights how sports participation serves as a key determinant in balancing quality of life and economic development, while still reflecting marked geographic disparities. Northern and Central Italy retain their leading positions: Trento confirms its top ranking by combining outstanding sports performance with exceptional environmental indicators (over 100 m^2 of green space per capita). Bolzano follows for its high per capita green endowment, alongside major urban centers such as Milan, Bologna, and Florence—the latter ranking first for women's sports.

Among metropolitan areas, Venice (35.5 m^2/inhabitant) and Turin (22.7 m^2/inhabitant) stand out for green space accessibility. Structural weaknesses persist in Southern Italy, where cities such as Reggio Calabria, Vibo Valentia, and Crotone consistently occupy the lower end of national rankings. In Catania, Messina, and Bari, accessible green space falls below the legal threshold of 9 m^2 per inhabitant, exacerbating urban vulnerability.

Environmental emergencies continue to affect the Po Valley's urban areas, which, despite slight improvements in emission trends, still record harmful concentrations of fine particulate matter (PM2.5) and ozone—making urban afforestation an urgent public health necessity. Data analyses reveal encouraging signs of progress: urban afforestation projects increased by 6.7% over the past year. The regulatory framework, influenced by the *Nature Restoration Law* [29], is steering local administrations toward the "no net loss" goal for natural land, promoting a qualitative and adaptive management of open spaces.

4 The Role of Urban Planning in Sports Practices

The emergence of new urban forms of outdoor physical activity highlights how the city serves as the territorial framework for the daily production of health and well-being. International literature on sport, green spaces, and urban environments underscores that the coexistence of ecological infrastructures and facilities for active mobility can reduce psychosomatic stress, influence metabolic risk factors, and enhance perceived quality of life—thus confirming the interconnection between urban form, social capital, and health. In recent years sport-equipped urban green spaces have become part of urban regeneration projects and initiatives. Green areas are currently integrated and structural parts of redevelopment projects in urban areas, while the inclusion of publicly available sport equipment is integrating urban green particularly along scenic footpaths and strolling streets.

Within this framework, the authors have investigated the concept of the "Sport City" as an integrated planning device capable of guiding community movement practices in a democratic and non-extractive manner, in some cases fostering the urban transition toward "street sport."

Recent reflections inspired by the "15-min city" model, aimed at enhancing proximity-based activities and services, now demand a reconfiguration of ordinary planning processes—placing walkability and other movement practices at the center as indicators of health and as modes of sustainable transport. This often intersects with the presence of "urban voids" and large mono-functional complexes—typically industrial, military, or infrastructural—which generate spatial fragmentation, perceptual discontinuity, and barriers to walkability. These enclaves, characterized by underuse and selective accessibility, can be interpreted as "anti-common goods," subtracting significant portions of land from collective enjoyment and limiting the potential for building proximity networks.

4.1 Materials

Trieste and Cagliari—mid-sized Italian port and regional capitals located respectively on the Northern Adriatic and in Southern Sardinia, respectively hosting 198,388 and 146,692 in 2025—can be framed as comparable Mediterranean "sportscapes" in which sport, walking, and outdoor physical activity have become elements of the urban environment and important key points for interpreting contemporary urban transformations and changes.

Both cities combine their relatively compact historical cores – the two municipalities span from around 80 km^2, with nearly half of such surface hosting citizens and urban activities - with a relevant and dominant maritime interface, where seafront promenades, waterfronts, and linear parks function as everyday "sport corridors" supporting running, walking, and non-motorised mobility. Trieste waterfronts are in the city centre and in the Barcola suburb, this latter a key promenade enabling year-round outdoor practices. Cagliari presents its waterfronts as the city centre and the Poetto urban beach (≈8 km) and its backshore, provide a continuous infrastructure for jogging and cycling. This spatial configuration aligns with recent national rankings, where the PTS/Il Sole 24 Ore Sportiveness Index [23] places Trieste 7th and Cagliari 10th among Italian provinces, and is further reinforced by their designation as European Cities of Sport (Trieste 2011; Cagliari 2017), reflecting a growing emphasis on the accessibility and diffusion of spaces for grassroots and outdoor activities rather than elite performance alone. Such a geographical and morphological configuration offers the roots for analysing how different groups of inhabitants and temporary users appropriate, traverse, and reconfigure these urban spaces through everyday sport practices, thereby informing sport-oriented planning strategies for public space regeneration and the redefinition of the relationship between city, health, and citizenship.

4.2 Methods

In this context, the authors have focused on indicators of regeneration of large urban complexes [13, 30–32], expressed, for instance, through the Walkability in Big Buildings Index (WBBI). This composite index measures the effectiveness of interventions across three pillars: Porosity (PI), understood as the capacity to create spatial relationships; Crossability (CI), referring to the quality of pedestrian and cycling connections; and Attractiveness (AI), linked to the diversity of proximity functions (sports, health, social interaction).

Building on this, the authors define the Walkable Big Buildings Index (WBBI), a composite indicator that integrates three components—PI, CI, and AI—through a weighted sum. Each component is assigned a weight (pk) reflecting both the characteristics of the buildings and the conditions of the surrounding urban context, with all weights summing to 1. The index is normalized on a 0–100 scale using the formula:

$$WBBI = \sum_{i=1}^{n} (I_i \cdot p_k) \cdot 100 \quad (1)$$

The weighting system is informed by the spatial and functional features of historic urban centers, which serve as the primary reference for evaluating context. Overall, the WBBI captures the potential walkability of large abandoned buildings by combining building-specific attributes with broader urban conditions.

The use of GIS technologies and community data enables the mapping of "physical activity landscapes," turning static spatial readings into dynamic analyses of usage flows.

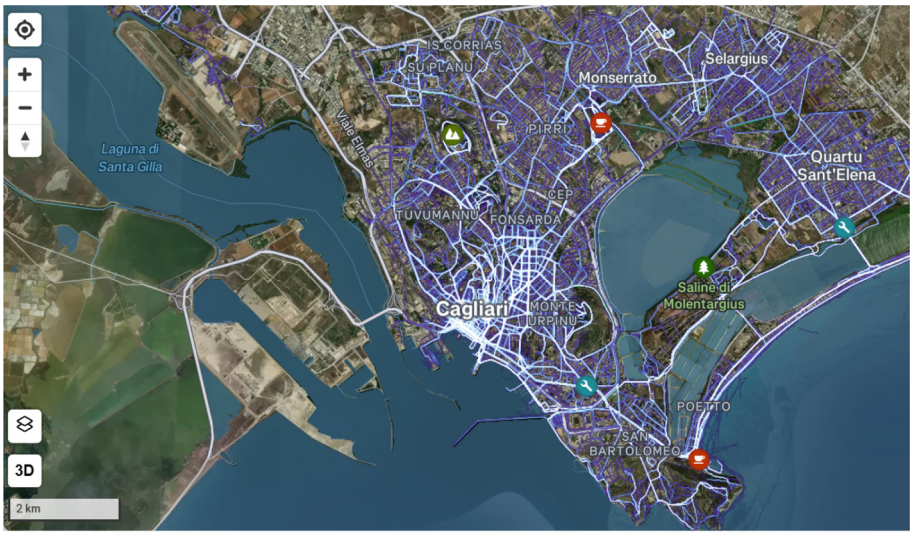
4.3 Results and Discussion

Focusing on the cities examined in the research (Cagliari and Trieste), GPS tracks of "urban athletes" using the walking mode were organized into density maps that highlight the most frequented streets and routes (shades ranging from light to dark blue based on their intensity of use). The resulting representation of the "sportively lived network" traces paths across both traditional and newly created networks - often non-pedestrian or vehicular -, while also revealing urban enclaves—blocks effectively closed to public access (Fig. 1 *a* and *b*; Fig. 2 *a* and *b*).

Reasoning about the patterns drawn by user-generated digital sport tracks leads to identifying most chosen areas for leisure and outdoor activities, as well as highlighting urban enclaves, therefore presenting a map of accessible and non-accessible areas within the different urban environments considered.

The overview of the two cities considered presents some similarity in patterns, where more dense areas, as highlighted in Fig. 1 and Fig. 2, tend to concentrate in central parts of the city. Nonetheless, denser and most frequented areas appear to be located in linear orientation along major walkable pathways, often located in close proximity to urban and peri-urban amenities.

Zooming onto selected parts of the cities examined reveals some interesting and relevant elements related to two aspects of the relationship among active citizens and urban fabrics. The comparative reading of training-app traces across the two cities highlights how digital mobility footprints can function simultaneously as urban portraits and as diagnostic instruments of spatial inequality. In the first case – Fig. 3a and b -, the aggregation of individual workouts produces a legible "drawing effect": repeated trajectories thicken into luminous corridors that effectively map the city's preferred and performative spaces—waterfronts, parks, scenic footpaths and roads, and central districts—where perceived safety, environmental quality, and symbolic attractiveness converge. These patterned concentrations should not be interpreted merely as the sum of personal choices, but as an emergent representation of how the city invites movement through continuity of public realm, aesthetic cues, and accessible infrastructures. In the second case, as it by contrast, the traces are fragmented, abruptly interrupted, and forced into detours, making visible the presence of urban "enclaves": fenced, circumscribed, and functionally exclusionary areas that constrain permeability and reduce route diversity – Fig. 3a and b, bounded polygons.



(a)

(b)

Fig. 1. **a.** Heatmap of pedestrian urban traces in cities. City of Cagliari. 2D view. Source: Authors' elaboration from Strava Heatmap (https://www.strava.com/maps/global-heatmap). **b.** Heatmap of pedestrian urban traces in cities. City of Cagliari. 3D view. Source: Authors' elaboration from Strava Heatmap (https://www.strava.com/maps/global-heatmap).

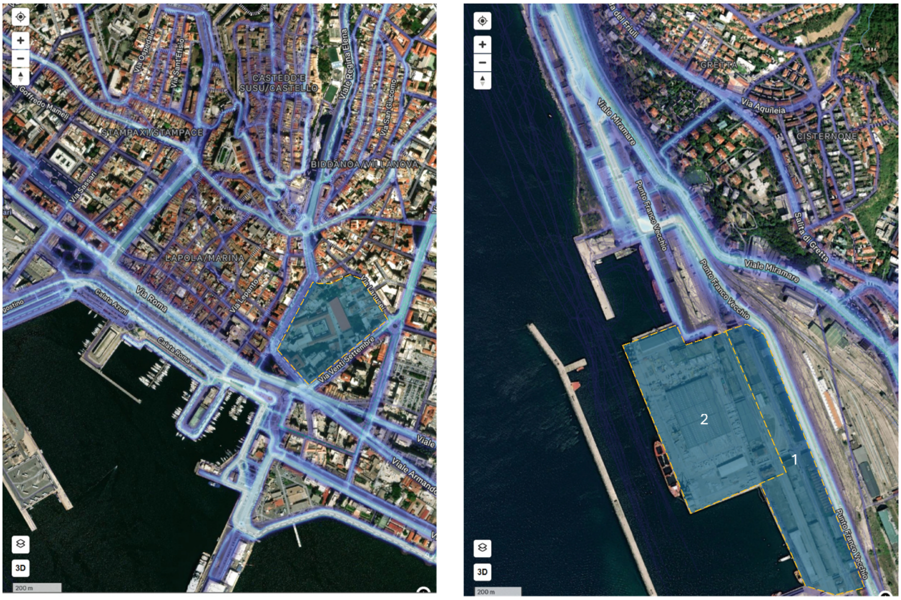
In the case of Cagliari – Fig. 3a -, the bounded area corresponds to the former Tobacco factory, now a cultural centre, reconverted from industrial to urban uses and purposes, but at the same time representing a non-permeable enclave to pedestrians. On the contrary, even major boulevards and traffic bypass in the central part of the city, as well as the waterfront pedestrian area – now under a relevant process of urban renewal and reconversion, appear densely traced by sport traces.

(a)

(b)

Fig. 2. **a.** Heatmap of pedestrian urban traces in cities. City of Trieste 2D view. Source: Authors' elaboration from Strava Heatmap (https://www.strava.com/maps/global-heatmap). **b.** Heatmap of pedestrian urban traces in cities. City of Trieste 3D view. Source: Authors' elaboration from Strava Heatmap (https://www.strava.com/maps/global-heatmap).

In the case of Trieste – Fig. 3b - a focus is on the former Old Port, now at the centre of a major urban regeneration process. The denser traces present part of the area widely and intensively used by active citizens, the two bounded polygons represent two areas earmarked for urban conversion in different times. No 1 is expected to be rapidly assigned to urban functions, while No 2 is still hosting terminal port operations and still separated by the rest of the urban fabric.



(a) (b)

Fig. 3. Zoomed heatmaps of a) Cagliari and b) Trieste (same scale).

5 Conclusions

The analysis of sports mobility trajectories makes it possible to interpret street sport as a practice of re-territorializing public goods, foregrounding the value of collective space over land rent. In this perspective, the city no longer serves as a mere backdrop for athletic performance, but becomes part of the performative dispositive itself, shaping differentiated conditions of accessibility, safety, inclusion, and environmental comfort. This calls for rethinking the "Sport City" as a field of negotiation between institutional uses and spontaneous practices, between event-based economies and rights to bodily citizenship, in line with recent debates on policies for sport, including informal activities and non-conventional practices, in which urban green spaces, urban voids, and enclaves can together give shape to an extensive urban ecological and sports network.

Trieste and Cagliari can act as laboratories in which urban morphology (density, central compactness, coastal location) and the spatial distribution of sport facilities and open spaces co-evolve with emerging patterns of urban health, well-being and social inclusion. The work operationalises geolocated fitness-platform traces (e.g., running and swimming) via GIS processing and heatmaps, revealing marked spatial clustering along seafront linearities and within compact, walkable central fabrics, thereby offering an empirical basis for accessibility- and well-being–oriented planning agendas.

In conclusion, sport must be recognized as a social fact [33] and an urban common good and as a cornerstone of the resilient city. The key challenge for future planning is to ensure that the landscape quality and accessibility of sports networks are genuinely inclusive—with particular attention to vulnerable groups—thereby elevating the right

to health and outdoor physical activity to fully-fledged new rights of urban citizenship within the broader framework of ecological transition.

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Authorship Contribution Statement. Conceptualization, methodology, formal analysis, materials and resources, data curation and validation: all authors. In particular: Borruso realized Sects. 2 and 4, and Balletto wrote Sects. 1 and 3. Abstract and conclusions have been realized by both authors.

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Predictive Modeling of the Activation Energy of Petroleum Sludge Pyrolysis Using Artificial Intelligence Approaches

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Abstract. This study is about using a hybrid artificial intelligence approach to predict the activation energy (Ea) of petroleum sludge pyrolysis. Three modeling techniques were compared: Artificial Neural Networks (ANN), Radial Basis Functions (RBF), and a new hybrid model that combines Radial Basis Functions with a Genetic Algorithm (RBF-GA). Models were trained using physicochemical parameters (elemental composition, proximate analysis) curated from peer-reviewed literature.

In this study, RBF-GA demonstrated superior performance by achieving an determination coefficient (R^2) value of 0.79, having a root mean square error (RMSE) of 21.37 kJ/mol, while the independent ANN model produced an R^2 value of 0.26, and RBF received an R^2 of 0.50. This research highlights how AI-developed meta-models can be utilized as a feasible alternative to traditional isostatic methods for kinetic analysis of pyrolysis, and will serve as a powerful computational tool to support optimizing the valorization of petroleum waste products.

Keywords: Modelisation · Pyrolysis · Waste valorisation · Genetic algorithm

1 Introduction

Petroluem Sludge (PS) is one of the more challenging forms of hazardous waste created throughout the process of producing petroleum, including drilling, transport, storage, and refining. It crisis produce between 60 and 80 million tons of sludge every year worldwide [1]. Due to its complex physicochemical composition, petroleum sludge is known to cause serious environmental and health hazards if not handled appropriately. The conventional methods of disposal include landfills and incineration. These methods are still widely practiced but are associated with significant operating costs, as they may cause soil and groundwater contamination, greenhouse emissions, as well as secondary pollution Environmental Science and Pollution Research [2].

Recently, processes like thermochemical conversion processes (pyrolysis) have proven to be very promising as alternatives to the conversion of petroleum sludge.

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Pyrolysis is the process of breaking down organic matter using heat in the absence of oxygen; this generates useful products, including pyrolytic oil, syngas, and char. This method produces much more environmentally friendly disposal options than do conventional practices and results in 70–80% recovery of biomass as potential energy sources. However, the efficiency of this process depends on the knowledge of its reaction kinetics [3]. Among the kinetic parameters that govern pyrolysis, activation energy (Ea) is c is the most important one. It reflects the amount of energy required to initiate thermal decomposition, as well as providing insight into the level of reactivity and stability of the sludge components. Determining Ea accurately is important for reactor design, process optimization, and large-scale implementation [4]. Traditionally, Ea is estimated using thermogravimetric analysis (TGA) together with isoconversional methods like Flynn-Wall-Ozawa (FWO) and Kissinger-Akahira-Sunose (KAS). While these model methods are commonly used, they have limitations when applied to materials like petroleum sludge, which are highly heterogeneous. Specifically, they have difficulty capturing nonlinear interactions between various influencing factors, such as elemental composition, proximate properties, catalytic effects, and temperature-controlled heating rates.

To overcome these issues, AI based approaches have begun to be used in the area of kinetics modelling, and especially with use of machine learning techniques that have demonstrated their value in working with nonlinear, multivariate and dimensionally large datasets. Artificial Neural Networks (ANN) have been shown to have tremendous potential in solving complex thermochemical problems. However, the basic ANN are generally associated with the following problems: overfitting, slow convergence, and local minima traps, especially when dealing with relatively small data sets [5].

The present investigation seeks to develop and establish a hybrid artificial intelligence approach for the prediction of the activation energy of petroleum sludge pyrolysis. The intended design of this hybrid approach would be the application of a Radial Basis Function (RBF) networks coupled with a Genetic Algorithm (GA) for optimized parameter selection, unlike the conventional RBF network that has limited flexibility associated with having fixed parameters [6].

The originality of this work lies in three main aspects:

- A comprehensive dataset has been built from the peer-reviewed literature, which combines both elemental and proximate analyses.
- The development of an optimized hybrid RBF-GA architecture specifically tailored for activation energy prediction.
- A systematic comparative evaluation between ANN, RBF, and RBF-GA models using rigorous cross-validation procedures.

By suggesting the application of an artificial intelligence-based metamodel as an auxiliary tool to the conventional isoconversional methods, the present study makes an important contribution to the development of predictive modeling in the thermochemical valorization of wastes, as well as the development of an efficient computational tool for optimizing petroleum sludge pyrolysis processes.

2 Materials and Methods

Through both Elemental and Proximate analyses, all PS samples were subjected to extensive characterization. Elemental analysis measured the content of carbon (C), hydrogen (H), oxygen (O), and nitrogen (N), while proximate analysis included the determination of volatile matter (VM), ash content (A), fixed carbon (FC), and moisture (M). In addition, the samples were analyzed for their biochemical composition in terms of cellulose, hemicellulose, and lignin contents. These physicochemical characteristics collectively form the set of input variables for modeling, denoted as X:

X = [M, VM, FC, A, C, H, N, O, cellulose, hemicellulose, lignin, catalytic ratio].

The Ea, expressed in kJ/mol, was estimated from TGA using isoconversional methods, specifically FWO and KAS. The output of the modeling approach is the activation energy and therefore it is represented by as Y = Ea.

Three different AI techniques were evaluated to predict Ea from the input parameters: ANN, Support Vector Regression (SVR), and Random Forest Regression (RFR). Each method was assessed for its ability to accurately model the complex nonlinear relationships between the physicochemical properties of the PS samples and their corresponding activation energies.

In order to ensure the accuracy of the metamodels during their construction and to eliminate the impact of the nature of the training data on the result, the leave one out cross validation technique (LOOCV), which has been shown to be very effective in the literature [7], is applied. This technique is based on excluding a portion of the data used to create the model for validation purposes.

2.1 Artificial Neural Networks (ANN)

The ANN is a computational model based on the human brain structure and is composed of interconnected nodes referred to as artificial neurons. The artificial neurons exist in layers and interact with each other via weighted connections. The architecture is defined by the number and types of layers and neurons in those layers, the training algorithm used to create the ANN, along with its activation function [8]. The ANN model adopted in this work is based on the multilayer ANN as depicted in Fig. 1 with nonlinear activation functions [9]. The output is determined by Eq. (1).

$$\hat{Y} = f(W_2 \cdot f(W_1 \cdot X + b_1) + b_2) \tag{1}$$

where W_1 and W_2 are the weight matrices, b_1 and b_2 are the biases, and f(.) is an activation function.

Figure 1 illustrates the overall workflow of the proposed approach. It highlights the interaction between the RBF model and the optimization process, providing a global view of the methodology.

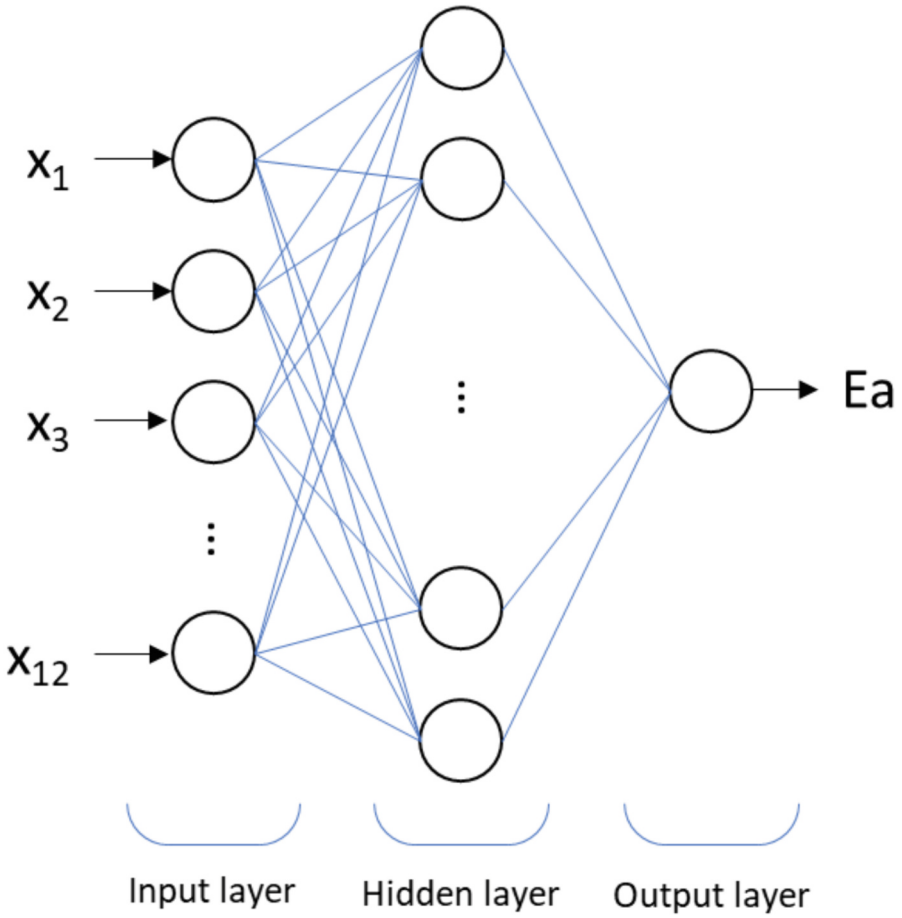

Fig. 1. ANN model architecture.

2.2 Radial Basis Function Networks (RBF)

The RBF uses a set of Gaussian functions, with each function centered around a certain point, ci [10]. These functions are used as activation functions that react to the distance between input vectors and centers.

In this work, the RBF method proposed in [7] has been used. As it has been shown in many comparative studies, RBF is one of the best approximations for problems in a high dimension space. The RBF approximation is given by Eq. (2).

$$f(x) = \sum_{i=1}^{N} \lambda_i \phi(\varepsilon_i x - x_i) \tag{2}$$

where the vector $x_1,\ldots,x_n \in \Re d$ is the set of Design of Experiments (DoE) points; φ is a user-defined radial function; λ is the vector of interpolation coefficients; and ε is the vector of shape factors.

2.3 Genetic Algorithm-Optimized Hybrid RBF Model (RBF-GA)

This model enhances the traditional RBF network by employing a GA to optimize its key parameters: the centers ci, widths σi, and weights wi [9]. In this study, ci represents the center of the radial basis function, σi denotes its spread (width), and wi is the associated weight parameter. Unlike fixed-parameter approaches, this evolutionary method allows the network to dynamically adapt its architecture and parameters based on the underlying data complexity. As a result, it significantly improves the model's flexibility, accuracy, and ability to generalize to nonlinear and high-dimensional problems.

As shown in Fig. 2, the parameters of the RBF are initialized in the first step. The model is constructed according to the experimental data with the RBF tool. According to the technique presented in this work, an error evaluation is performed to measure the convergence (Err_Conv = 1 for convergence achieved, Err_Conv = 0 for convergence not achieved). If convergence is not achieved, while respecting a maximum cost (Cos_Max), the RBF parameters will be optimised based on the genetic algorithm.

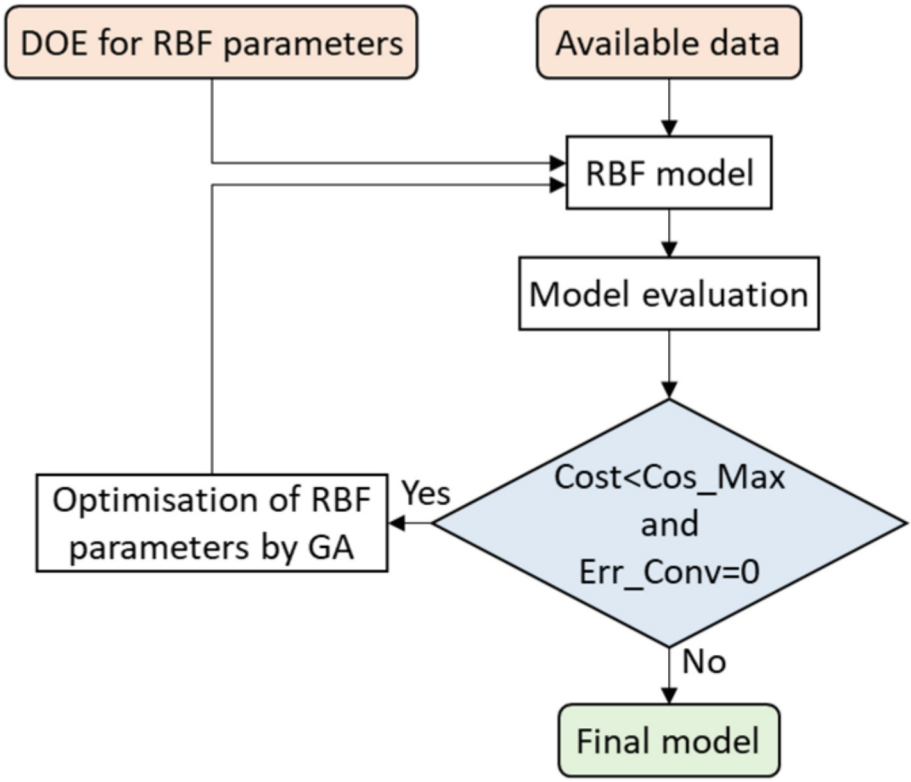

Fig. 2. Organisation chart for the RBF-GA model.

3 Results and Discussion

The comparison between predicted and experimental values showed a noticeable difference, with the model failing to accurately reflect the real data trends; this was quantitatively confirmed by the low coefficient of determination value of $R^2 = 0.26$, which indicates a poor correlation and low prediction ability. Such a result suggests that the ANN, in its current configuration, is not well adapted to the complexity of the input data. To enhance its performance, several improvements could be considered, including hyperparameter tuning (e.g., learning rate, number of hidden layers, activation functions) or the exploration of alternative ANN structures. Implementing some of these changes could potentially help capture non-linear relationships and increase generalization capability (Fig. 3). Cross-validation was used to ensure the reliability of the evaluation. This technique is based primarily on setting aside 5% of the data for validation and training the model using the remainder. This step is repeated several times, selecting different subsets for validation.

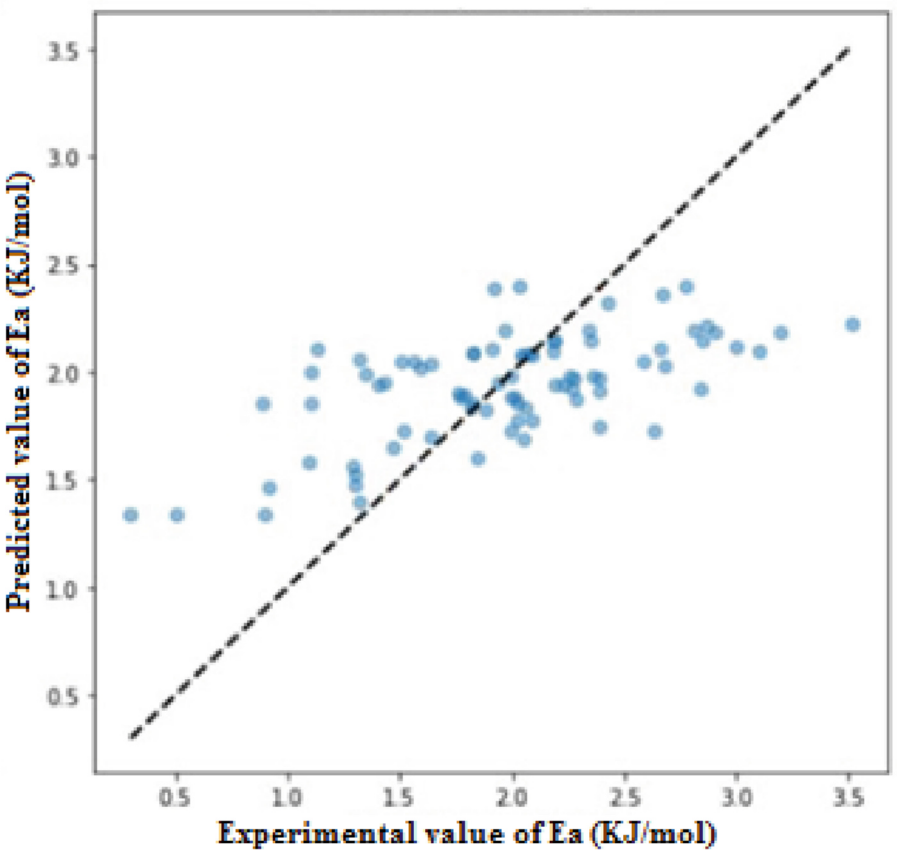

Fig. 3. Activation energy prediction using ANN.

In response to the limitations observed with the ANN model, a RBF model was tested. This approach led to a noticeable improvement, with a coefficient of determination value of $R^2 = 0.5$, reflecting a better correlation with the experimental activation energy values (Fig. 4). Despite this enhanced performance, the RBF model alone was still inadequate for achieving high predictive accuracy, indicating the need for further refinement or the integration of more advanced modeling techniques.

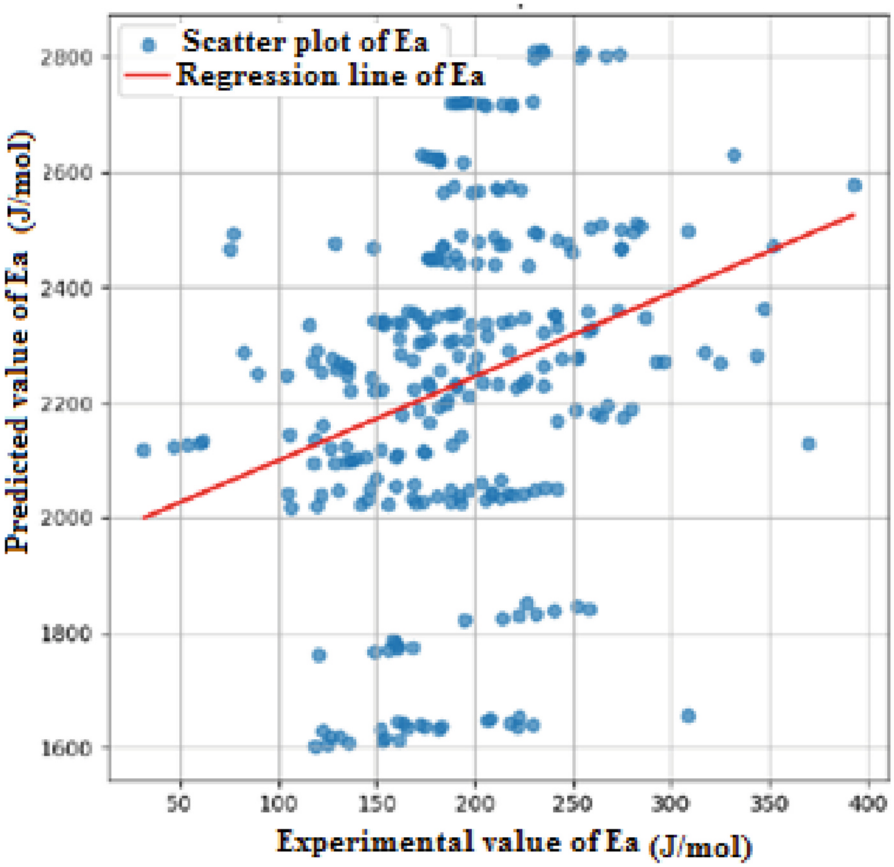

Fig. 4. Prediction of activation energy using RBF.

To overcome the previously observed limitations, a hybrid model combining the RBF network with a GA (RBF-GA) was developed. The results obtained with the RBF-GA model were compared with those of the standard RBF model. This advanced approach allowed for the dynamic optimization of the model's internal parameters, including centers, widths, and weights, leading to a significant enhancement in predictive accuracy. On the test dataset, the RBF-GA model achieved a coefficient of determination value of $R^2 = 0.79$, meaning it could explain 79% of the variability in activation energy values. In addition, root-mean-square error (RMSE) = 21.37 kJ/mol and mean absolute

error (MAE) = 13.45 kJ/mol confirm the predictive accuracy of the model. Cross-validation also shows that the RBF-GA model is robust and has generalization ability, producing an RMSE = 29.91 kJ/mol. Hence, it appears that the hybrid RBF-GA model is appropriate for modeling complex and nonlinear thermogravimetric data with a high degree of accuracy and consistency.

Table 1 presents a detailed comparison between the predicted and experimental activation energy values for different conversion ratios (α).

Table 1. Predicted and experimental activation energy values for different conversion ratios (a).

Conversion Ratio (α)	Predicted Ea (kJ/mol)	Experimental Ea (kJ/mol)
0.20	146.89	160.43
0.25	153.38	170.59
0.30	159.59	175.86
0.35	165.04	184.10
0.40	169.22	190.17
0.45	171.70	194.61
0.50	172.27	193.43
0.55	171.01	199.49
0.60	168.31	197.03
0.65	164.73	200.77
0.70	160.85	203.67
0.75	157.10	207.45
0.80	153.69	205.48

The hybrid RBF-GA model effectively captures the overall trend of Ea variation as a function of the conversion rate (α), demonstrating its ability to simulate complex kinetic behavior. However, a consistent underestimation of Ea values is observed across the entire conversion range. The most significant deviation occurs at $\alpha = 0.8$, where the model predicts an Ea of 153.69 kJ/mol, whereas the experimental value reaches 205.48 kJ/mol. This deviation may be due to the model's limitations in simulating the thermal decomposition of highly stable molecular structures, especially polycyclic aromatic hydrocarbons (PAHs) commonly found in PS. These compounds typically decompose at higher temperatures and conversion rates, which may introduce nonlinearities and kinetic complexities that challenge the model's generalization.

The results show that the RBF-GA model provides better accuracy than the standard RBF model, particularly for higher conversion ratios. This improvement can be explained by the ability of GA to optimize the parameters more effectively.

4 Conclusion

This study compared three modeling approaches for the prediction of Ea during the pyrolysis of petroleum sludge. The model based on ANN showed weak performance, with a coefficient of determination value of only 0.26. The RBF approach provided some improvement ($R^2 = 0.5$), but still insufficient.

The highest accuracy was achieved with the hybrid model RBF-GA, reaching $R^2 = 0.79$ on the test set. This model also reduced errors, with a RMSE of 21.37 kJ/mol and a MAE of 13.45 kJ/mol. Although it slightly underestimates high Ea values, it correctly reproduces the overall trend of the experimental curve, notably the reactivity peak around a conversion rate of 0.5.

These results confirm the relevance of hybrid approaches for modeling complex kinetic phenomena and open up promising perspectives for the development of predictive metamodels applied to the thermal valorization of petroleum residues.

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Theoretical Investigations of CO_2-N_2 Separation on γ-Graphyne Membranes: A Classical Molecular Dynamics Study

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Abstract. γ-graphynes recently emerged as promising candidates for molecular sieving applications due to their intrinsic and tunable nanoporosity. The possibility to modulate the dimension of the pore is, therefore, a key aspect for the design of new-generation nano-materials for carbon-neutrality techniques. In the present contribution, a preliminary analysis on graphtetrayne has been performed in order to characterize the main morphological properties and underline the most important adsorption processes. In details, classical molecular dynamics simulations have been performed, in order to investigate the interaction of a single graphtetrayne layer with CO_2 and N_2 molecules. Preliminary results indicate a stronger interaction of carbon dioxide compared to molecular nitrogen leading to a higher selectivity toward CO_2 over N_2, driven by a combination of energy contributions and morphological aspects. Overall, the present study represents a preliminary investigation aimed at characterizing the adsorption and selectivity properties of graphtetrayne as candidates for the design of membranes for CO_2 - N_2 separation under post-combustion conditions. These findings provide a basis for a more comprehensive study, which will be extended to multilayer configurations in order to better assess their potential for carbon capture applications.

Keywords: Carbon-based nanomaterials · CO_2 Adsorption · Classical Molecular Dynamics · Force Field

1 Introduction

The development of new techniques aimed at removing and reducing the concentration of greenhouse gases became a primary issue in the context of a transition toward sustainable technologies. The increasing level of carbon dioxide (CO_2) in the atmosphere, mainly coming from antropic effects, such as fossil fuels combustion, has been directly linked to climate change and its related environmental impacts. As a consequence, one of the main focuses of modern

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technologies is the development of efficient strategies for CO_2 capture and separation. In this context, various approaches have been proposed as promising techniques for the selective removal of CO_2 from gas mixtures, in particular those containing molecular nitrogen (N_2) which is the main component of the atmosphere. Within this framework, the achievement of high selectivity and adsorption capacity, as well as low energy requirements, is essential for practical development. The use of porous materials [1–5], including zeolites, metal–organic frameworks (MOFs), and covalent organic frameworks (COFs), have been extensively studied for gas adsorption and separation. The main advantages of these structures are related to tunable pore sizes, high surface areas, and different possibilities of chemical functionalization, leading to a high impact on adsorption properties. Together with a series of advantages, several challenges remain open, including high cost of synthesis, limited structural stability under operative conditions and potential degradation over time. These limitations, together with energy requirements, challenge the continuous search for alternative materials. Recently, two-dimensional (2D) carbon-based nanomaterials have emerged as promising candidates for the development of new-generation membranes for gas adsorption and separation [6,7]. Their unique properties, including atomic-scale thickness, high surface-to-volume ratios, and tunable chemical characteristics, enable strong and tunable interactions with gas molecules. The prototypical 2D carbon material is represented by Graphene and it has been widely investigated due to its exceptional mechanical, thermal and chemical properties [8]. However, pristine graphene exhibits limited gas permeability and weak physisorption interactions with many gas species, which reduces its range of applicability. Different strategies have been developed to overcome this issue, including functionalization, introduction of vacancies and defects [9,10]. Another alternative is represented by the use of similar materials, Graphynes, which represent a versatile family of 2D carbon allotropes composed of both sp and sp^2 hybridized carbon atoms, whose structure is characterized by benzene rings interconnected via acetylenic links, which provides intrinsic porosity and tunable structural features. The number of consecutive acetylenic units can be modulated and determines the size and shape of the pores, as well as the mechanical flexibility and electronic properties of the material. A series of computational investigations have been already performed to identify the adsorption properties of different structures, including graph-tryine [11,12] and graph-dyine [13–15], revealing intriguing effects, depending on the nature of the interacting molecules. Among the various graphyne allotropes, graphtetrayne (G4)-defined by four consecutive acetylenic linkages connecting adjacent carbon rings-remains relatively unexplored. The recent syntesys of cristalline graphtetrayne [16], triggered the interest in this peculiar structure. In particular, the expanded pore network and the morphological properties suggest unique adsorption behavior, particularly for small molecules such as CO_2 and N_2. While recent studies have investigated the structural, electronic, and stacking properties of multilayer graphyne systems, the fundamental mechanisms governing adsorption at the single-layer level remain poorly understood. Within this framework, a computational investiga-

tion appears to be extremely important. Atomistic simulations, indeed, provide a powerful framework to investigate these interactions at a molecular level. In details, Classical molecular dynamics (MD), based on a correct description of the intermolecular force fields, allows for systematic exploration of configurational space, enabling the identification of energetically favorable adsorption sites, preferred orientations of adsorbates, and selectivity trends between different gas species. In this work, we performed a preliminary analysis of the interaction of CO_2 and N_2 molecules with a single layer of graphtetrayne, using classical molecular dynamic simulations to analyze the adsorption properties. By establishing these fundamental insights, this study sets the stage for future investigations into more complex systems, including multilayer graphyne assemblies, functionalized derivatives, and hybrid materials. Ultimately, our work contributes to the ongoing effort to design efficient, scalable, and sustainable materials for CO_2 capture and separation technologies, offering potential pathways toward environmentally friendly and economically viable solutions.

2 Theoretical Methods

2.1 *Ab Initio* calculations

An initial analysis on the monomeric structure was performed at the DFT level, in order to characterize the morphological properties of the pore and compare the size of the available site in different types of graphynes (namely graphdiyne, graphtriyne anf graphtetrayne). As already reported in several cases before [17–22], *ab initio* calculations based on DFT theory represent a good compromise between chemical accuracy and computational cost, especially in the case of big systems, which needs a high computational power. For this purpose, geometry optimization and frequency analysis were performed at the B3LYP [23,24] level of theory, in conjunction with the 6-31G [25,26] basis set. The *Gaussian09* [27] was used for electronic structure calculatons, while the visulaization of the frequencies was performed using Avogadro.

2.2 Molecular Dynamics

In order to understand the adsorption properties of a graphtetrayne layer, molecular dynamics simulations were performed to analyze the interaction between the structure and a mixture of CO_2 and N_2 molecules. The DL_POLY [28] simulation package was used, considering the NVT ensemble, where the number of particles (N), volume (V) and temperature (T) are kept constant and using a Hoover-Nose thermostat [29] with a relaxation constant of 0.5 ps. After an initial equilibration period of 1 ns, all the simulations were performed for a total time of 5 ns, considering a temperature of 300 K, while the pressure was calculated using the Peng - Robinson equation of state, and resulting in 5.2 atm. It must be noticed that the reference pressure reported in this work was not used only as an input parameter in the MD runs, but rather to determine the initial density of the gas mixture. In particular, the Peng–Robinson equation of state was

employed to estimate the equilibrium density of the equimolar CO_2/N_2 mixture at the chosen temperature and pressure conditions. This density was then used to define the simulation box size, which remains fixed throughout the NVT simulations. During the simulations, the graphtetrayne membrane structure was kept frozen, and the gas molecules were treated as rigid bodies. The force field was built on the basis of previous works [11,30], where the electrostatic contribution was developed considering a three charge model for N_2 and five charge model for CO_2. The non-electrostatic component of the interaction was described using the Improved Lennard–Jones (ILJ) potential, as detailed in the next section.

Non-electrostatic Long Range Interactions: the ILJ Model. As already reported, the force field built for the MD analysis is composed by two contributions: the electrostatic potential (V_{elec}) and the non-electrostatic contribution (V_{nelec}). In details, V_{nelec}, was evaluated considering the *Improved Lennard-Jones (ILJ)* model [31–35], in which each pair of interacting atoms (or particles) is treated considering the following formulation:

$$V_{nelec} = V_{ILJ} = \varepsilon \left[\frac{m}{n(r) - m} \left(\frac{r_m}{r} \right)^{n(r)} - \frac{n(r)}{n(r) - m} \left(\frac{r_m}{r} \right)^{m} \right] \tag{1}$$

where ε and r_m are, for each interacting pair, the well depth and its position. The ε and r_m values are estimated on the basis of the molecular polarizabilty, partitioned in different components and assigned to each interaction center.

The *n(r)* term is described as:

$$n(r) = \beta + 4 \left(\frac{r}{r_m} \right)^2 \tag{2}$$

where the β parameter represents the hardness of the two interacting species. In particular, the values of the parameters inserted in equation (1) are linked to fundamental quantities that control the strength and the range of the intermolecular potential, including the dipole moment (μ) and the quadrupole moment (Q) and the atomic/molecular polarizability (α). For a comprehensive explanation and a detailed analysis of how these parameters are calculated, see [30,36].

A complete list of the parameters used to build the force field can be found in [11], while the values for the main interacting centers are reported in Table 1

Table 1. List of the main ILJ parameters describing the interaction of CO_2 and N_2 with a layer of graphtetrayne (indicated as G4). The value of β is considered in the range between 6 and 8.

Interaction	ε (meV)	r_m (Å)
N_{N_2}-C_{G4}	3.97	3.83
C_{CO_2}-C_{G4}	3.55	3.56
O_{CO_2}-C_{G4}	5.01	3.67

3 Results and Discussion

3.1 Electronic Structure Calculations

A first geometry optimization was performed in order to characterize the morphological properties of the G4 structure, considering a monomer, composed of three benzene rings linked by four acetylenic units. The resulting geometry is characterized by a triangular-shaped pore with a geometric diameter of around 8 Å. In order to compare the geometrical features of the pore, a comparison were performed considering the optimized structure of G2 and G3. In Fig. 1 are reported the geometries of the three monomers obtained through DTF calculations.

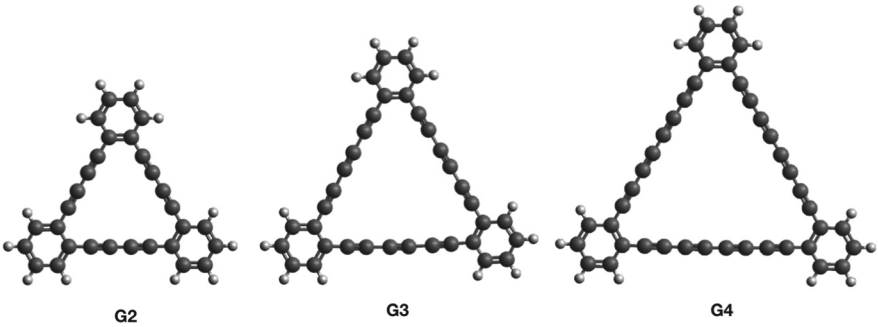

Fig. 1. Schematic representation of the monomeric structure of G2, G3 and G4, obtained through DFT calculations.

As can be seen, the morphology of the structure remains the same, whith a clear modification of the dimension of the pore. The accessible pore diameters of the considered graphyne structures (G2, G3, and G4) were estimated based on the interatomic arrangement and the van der Waals radius of carbon (1.7 Å). As expected, the value of the accessible pore shows an increase of the number of acetilenic units, with G2 showing a relatively small accessible diameter of 2.8 Å, G3 increases to 3.7 Å(as reported also in [11]), and G4 reaches values around 5.0 Å. The differences in the value of the pore diameter can be used to rationalize the possible effects of the structures as material for selective adsorption. The small pore of G2, in fact, can reduce the accessibility to CO_2 and other small molecules, such as N_2, suggesting intrinsic selectivity. G3 provides larger pores that allow both CO_2 and N_2 to penetrate the pore, while G4 may present pores that are too large to sustain strong size-based selectivity, as suggested also in some previous works [37]. These observations highlight the delicate balance between pore size and selective adsorption in graphyne-based materials.

3.2 Classical Molecular Dynamics Analysis

In order to characterize the main adsorption properties and gain insights on the potential selective role of G4 layer, classical MD calculations were performed

considering an equimolar gas mixture of CO_2 and N_2. An appropriate equilibration period of 2 ns was considered in order to allow a fluctuation of the temperature below a factor of 5% and leading the simulations useful to predict and characterize adsorption properties. In Fig. 2 are reported the plots of the radial distribution function in order to characterize the interaction of CO_2 and N_2 with the C atoms of the graphyne layer.

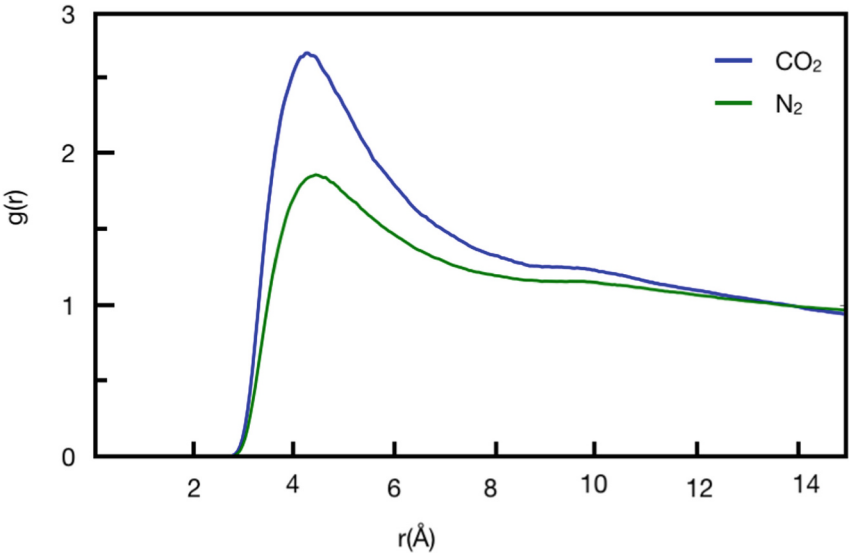

Fig. 2. Radial distribution funtion, g(r), of CO_2 and N_2 molecules interaction with one the C atoms of the G4 layer.

As can be seen, both CO_2 and N_2 show a peak at a distance of around 4.2 Åfrom the surface of the layer. However, a key difference emerges in the intensity of the peak: CO_2 shows a significantly higher and sharper peak compared to N_2. This indicates a higher probability of finding CO_2 molecules at that preferred distance, with respect to N_2. In contrast, the lower peak observed for N_2 reflects weaker correlations and a less pronounced interfacial ordering. This behavior can be rationalized considering the lower intensity of van der Waals forces established between N_2 and the graphyne layer with respect to the case of CO_2 (as already noted also for the case of graph-triyne [11]). At larger distances, both plots smoothly decay toward unity, although CO_2 maintains slightly higher values over an extended range, suggesting a more persistent influence of the surface.

Further insight is provided by the Z-density profiles along the surface-normal direction (z-axis), reported in Figs. 3 and 4.

As can be seen in Fig. 3, the CO_2 density profile is characterized by two peaks located on both sides of the membrane (indicated by the dashed vertical line), revealing the formation of well-defined adsorption layers. The high intensity

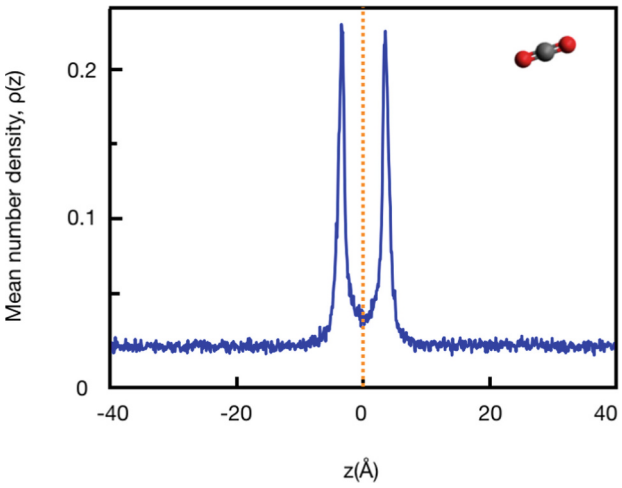

Fig. 3. Z-density profile of CO_2 molecules interacting with the G4 layer, indicated with the orange line.

and narrow width of these peaks reflects the high interaction potential of CO_2 with the graphtetrayne layer. Similarly, the N_2 density profile shows the same behavior but is characterized by less intense peaks, indicating (as expected), that N_2 molecules are less confined near the surface and more uniformly distributed throughout the simulation box. Additionally, the positions of the peaks for both species are comparable, in agreement with the g(r) analysis.

In order to have more consistent initial data and quantify the adsorption process, the number of molecules in the interfacial region was obtained by integrating the z-density profiles over the adsorption domain. In details, the adsorption selectivity was quantified by integrating the number density profiles in the interfacial region corresponding to the pore vicinity and the selectivity was then defined as the ratio between the adsorbed amounts of CO_2 and N_2. This process leads to a value of selectivity of around 1.6, inidcating modest but clear preferential adsorption of CO_2 over N_2. The moderate value of the selectivity suggests that the separation mechanism is governed by weak differences in adsorption strength rather than strong chemical specificity.

Finally, Fig. 5 reports a representative snapshot of the simulation box, obtained from the final step of the calculations, providing a qualitative visualization of the molecular arrangement of the system.

As can be seen, the graphtetrayne layer is located at the center of the simulation box, with both gas species distributed around it. In particular, it's easy to notice that CO_2 molecules are more frequently observed in close proximity to the surface with respect to N_2 molecules, which predominantly occupy the bulk-like regions further away. This visual evidence is consistent with the quantitative observations derived from both the radial distribution functions and the density profiles and can help to highlight the preferential interaction of CO_2

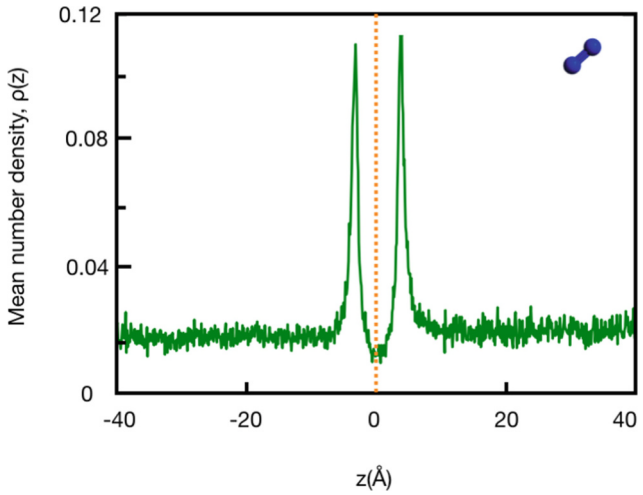

Fig. 4. Z-density profile of N_2 molecules interacting with the G4 layer, indicated with the orange line. (Color figure online)

with the G4 layer. Overall, the combined analysis highlights a clear difference in the effective adsorption strength of the two species. Although both CO_2 and N_2 share the same preferred adsorption distance from the surface, CO_2 exhibits a higher probability of occupying these energetically favorable positions, reflecting stronger intermolecular interactions with the graphyne framework. This behavior can be attributed to the larger quadrupole moment and higher polarizability of CO_2, which enhance its interaction with the carbon-based surface.

Despite this preferential adsorption, which reflects the results of a similar analysis already performed considering G3 systems [11], the overall selectivity can be influenced by the shape of the pore. The relatively large pore size of the G4 graphyne can indeed represent a limitation of the degree of confinement and does not impose a strong steric or energetic discrimination between the two species. As a result, both CO_2 and N_2 can access the vicinity of the surface without significant restriction, and the difference in adsorption strength alone can not be sufficient to achieve highly efficient separation. While pore size and confinement effects play a role in the adsorption behavior, they are not the sole determinant of the observed selectivity. The results indicate indeed that the separation is governed by a combination of geometric confinement and molecule–surface interactions within the G4 layer, where the stronger adsorption of CO_2 can be attributed to its larger quadrupole moment and stronger electrostatic interactions with the graphyne-based pore environment, especially in proximity to the acetylene-rich regions. For this reason, while the G4 monolayer exhibits a measurable preference for CO_2 adsorption, its performance as a selective membrane must be analyszed in details. Future developments will therefore focus on more complex architectures, such as bilayer systems, where the interlayer

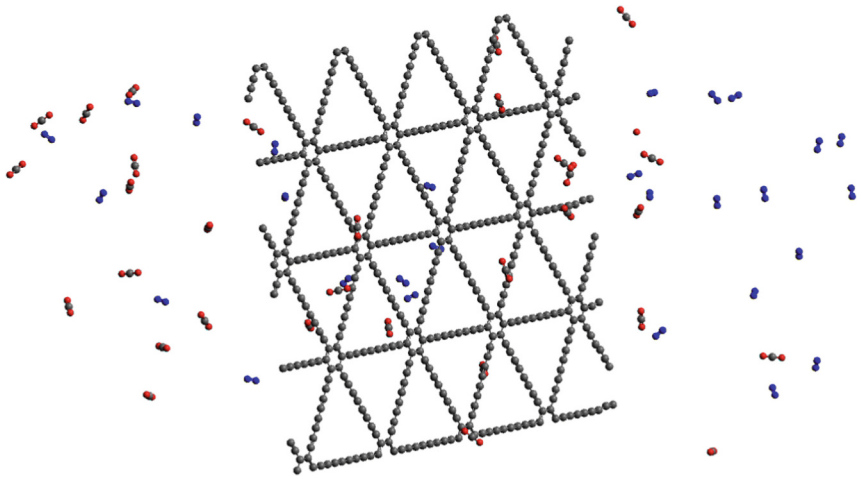

Fig. 5. Snapshot of the final configuration of the system coming from MD calculations.

space can act as a confined adsorption region. In such configurations, enhanced confinement and cooperative interactions between the two layers are expected to increase both the residence time and the selectivity of CO_2, potentially overcoming the limitations coming from the single-layer system and providing a more effective pathway toward gas separation applications.

4 Conclusions

In the present contribution, we performed a preliminary analysis of the adsorption properties of a new generation of carbon-based nanomaterial, composed by graphtetrayne layers, taking into account a gas mixture formed by 50% CO_2 and 50% N_2 molecules, in order to gain useful insights on the potential use of this architectures to remove atmospheric CO_2 molecules in post-combustion environments. Classical MD simulations were performed considering a NVT ensamble to derive structural and physico-chemical information on the system. The analysis of the radial distribution functions (evaluated considering the interaction of C atoms of the G4 structure and CO_2 and N_2 molecules, respectively), corroborated by the plot of the Z-density profiles for both species, clearly show a preferential interaction of CO_2 with the surface of the material, with respect to N_2. This behavior is consistent with the analysis of the strenght of long-range interactions between the selected molecules and the G4 layer. An important parameter to be taken into account for the study of adsorption processes is represented also by the dimension of the pore in the layered structure. In conclusion, although the G4 monolayer exhibits a measurable affinity for CO_2 adsorption, the pore dimensions can affect its properties. The results set the stage for the analysis of more complex architectures, such as bilayer systems, offering a promising strategy to significantly enhance both selectivity and efficiency in gas separation processes.

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

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From BioEmu Monomer Ensembles to AMBER-Ready Holo Models: Subunit-Aware Quality Control of a Cofactor-Rich Aldehyde Oxidoreductase

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Abstract. Generative artificial intelligence (AI) models are emerging as tools for sampling protein conformational ensembles and providing starting structures for downstream molecular simulation. In cofactor-rich metalloenzymes, however, a plausible peptide chain is not enough, as the structure must also support successful reconstruction of cofactors, metal centers, protonation states, and solvent. Here, we present a subunit-aware workflow that converts BioEmu monomer ensembles into solvated, minimized holo models for the three subunits of the tungsten-containing aldehyde oxidoreductase from *Aromatoleum aromaticum* (AorA, AorB, and AorC). The workflow combines Cα-based alignment to the experimental reference with subunit-specific holo reconstruction, solvent preparation, staged minimization, outlier detection, principal component analysis (PCA), and HDBSCAN clustering.

The workflow started with requesting 100 BioEmu conformations per subunit, of which 96 AorA, 91 AorB, and 100 AorC structures remained after BioEmu's built-in filtering of steric clashes and chain discontinuities. At the end of the workflow, final no-flag retention was 79%, 73%, and 89% relative to the requested ensembles (82.3%, 80.2%, and 89.0% of the BioEmu-delivered sets). After minimization, the retained structures remained distinct from the cryo-EM reference, with median final Cα root-mean-square deviation (RMSD) values of 6.60, 1.23, and 2.72 Å for AorA, AorB, and AorC, respectively. At the same time, chemistry-centered metrics remained close to the reference-holo controls. PCA/HDBSCAN analysis showed the clearest density-defined ensemble structure for AorA, intermediate behavior for AorC, and the most diffuse retained ensemble for AorB. Together, these results support a practical workflow in which AI-derived conformations are screened after reconstruction and minimization to identify chemically plausible starting structures for subsequent simulation.

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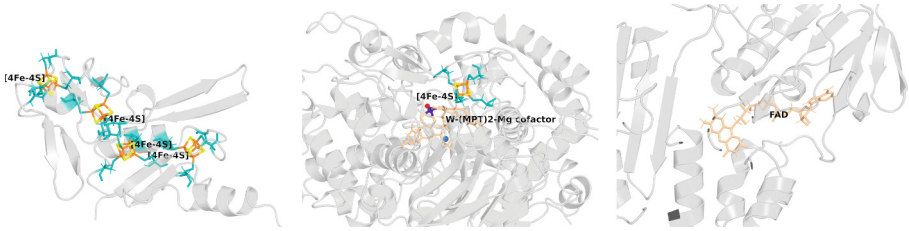
1 Introduction

In recent years, the focal point of structural modeling has shifted into a new direction. For many proteins, obtaining a single folded structure is no longer the primary challenge; instead, it is equally crucial to define a physically realistic ensemble and translate that ensemble into chemical models suitable for simulation [5,12,21]. BioEmu is emblematic of this transition, as it was developed to emulate protein equilibrium ensembles and to generate many statistically independent monomer conformations at a much lower cost compared to large-scale molecular dynamics (MD) simulations [13]. Such models are especially attractive as upstream generators of initial conditions because they can place later atomistic simulations in multiple regions of conformational space instead of forcing every trajectory to start from one experimental conformation [13,17].

However, that promise becomes harder to realize in cofactor-rich metalloenzymes, where a plausible protein backbone is only the starting point. In such systems, chemically important interactions between cofactors and the surrounding protein environment must be preserved during reconstruction. Protonation assignment, local cofactor geometry, explicit metal coordination, structurally retained water molecules, and topology-building choices such as bond definitions, residue templates, atom typing, and protonation-state mapping all influence whether the reconstructed system can be minimized without severe nonphysical local strain and whether it remains chemically interpretable as a starting point for MD [14,15]. These challenges are especially important in systems that combine multiple prosthetic groups and metal-centered chemistry, because even relatively small local distortions can alter coordination geometry, electron-transfer pathways, and access to the catalytic region [20,24].

As a demanding example of such a system, we selected the aldehyde oxidoreductase from *Aromatoleum aromaticum* (AOR_{Aa}). Its experimentally determined structure comprises a chemically heterogeneous assembly in which AorA forms an Fe–S-rich electron-transfer subunit, AorB contains the tungsten bis-metallopterin-magnesium catalytic cofactor together with a proximal [4Fe–4S] cluster, and AorC contains a bound flavin adenine dinucleotide (FAD) cofactor and a nicotinamide adenine dinucleotide (NAD^+) binding site, as shown on Fig. 1 [3,24]. The enzyme therefore combines metal centers and organic cofactors linked to the protein scaffold through both coordination-dependent and non-covalent interactions within one three-dimensional architecture. It is therefore well suited for examining the gap between a plausible AI-generated starting chain and a chemically explicit holo model that remains suitable for downstream simulation.

This study develops a practical methodological workflow for screening AI-derived monomer conformations as chemically acceptable starting points for simulation in a cofactor-rich oxidoreductase system. Using the three AOR subunits AorA, AorB, and AorC as a benchmark, we evaluate how subunit-specific



(a) AorA (b) AorB (c) AorC

Fig. 1. Structural overview of the cofactor architecture in the three AOR subunits used as the benchmark system in this study. (a) AorA, showing the Fe–S relay and the coordinating cysteine environment. (b) AorB, showing the tungsten-bis-MPT active site together with the associated Mg ion and the proximal [4Fe–4S] cluster. (c) AorC, showing the bound FAD cofactor in the flavin-containing subunit. Together, these panels illustrate the chemically heterogeneous architecture that makes AOR_{Aa} a demanding test case for reconstruction, solvent preparation, and staged minimization.

holo reconstruction and staged energy minimization affect the survival of AI-initialized conformations under conservative quality-control criteria. The analysis integrates subunit-specific reconstruction, reference-holo control models, Quality Control (QC) filtering, and density-based ensemble analysis to identify structures that remain chemically plausible after preparation. In this way, the study defines a practical screening framework for AI-derived starting structures in chemically complex oxidoreductase systems.

2 Materials and Methods

2.1 System Definition and Reference Structures

All models were based on the cryo-EM structure of AOR_{Aa} deposited as PDB 8C0Z [24]. Because BioEmu currently samples monomeric protein chains rather than whole multimeric assemblies, and returns structures in a backbone-frame representation that requires downstream side-chain reconstruction [13], the three AOR subunits were modeled separately. This was also the most sensible chemical choice, because each subunit required a different procedure for rebuilding its holo state before AMBER preparation.

BioEmu sampling was performed independently for the FASTA sequence of each subunit. For each subunit, 100 conformations were requested, yielding 96 exported structures for AorA, 91 for AorB, and 100 for AorC after BioEmu's built-in physicality filtering [13]. Detailed sampling settings are given in Appendix A.1. These structures were then converted into per-frame PDB files and rigidly aligned to the corresponding chains from the 8C0Z reference model.

2.2 Alignment and Subunit-Aware Reconstruction

Structural alignment was carried out in Python using MDAnalysis, following a Cα-based fit for both individual structures and the corresponding ensemble

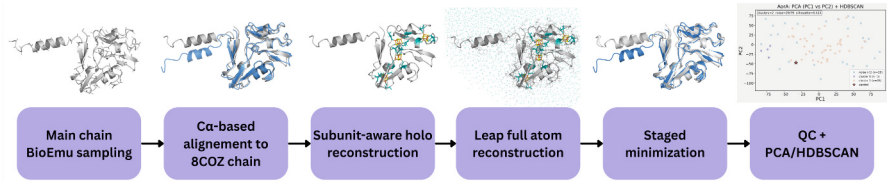


Fig. 2. Overview of the subunit-aware BioEmu-to-AMBER workflow used in this study. Presented above is the AorA subunit (white - BioEmu conformation; blue - Reference), while all three AOR subunits share the same high-level preparation logic, they differ in holo-restoration chemistry and in the need for local pre-relaxation before full minimization. (Color figure online)

sets [10,18]. In the final QC stage, the common alignment maps comprised 142 positions for AorA, 612 positions for AorB, and 424 positions for AorC. Positions absent from the mobile chain relative to the reference numbering were excluded from the common coordinate space.

Once aligned, each subunit underwent a separate holo-restoration procedure (Table 1). This stage not only restored the subunit-specific cofactors and metal centers, but also converted the BioEmu backbone-frame representation into a full-atom protein model during LEaP-based preparation, including side-chain reconstruction for the protein scaffold. AorA required rebuilding of the Fe–S electron transfer chain, including restoration of the [4Fe–4S] clusters and explicit definition of the coordinating cysteines so that the intended Fe coordination pattern was preserved during topology generation. AorB was the most demanding subunit from the chemical point of view. Besides the proximal [4Fe–4S] cluster, its preparation also required reconstruction of the W-bis-MPT-Mg center and structurally retained water molecules near the catalytic site. AorC was treated as a flavoprotein reconstruction problem, with the bound FAD cofactor transferred from the reference structure into the aligned subunit and then prepared with AMBER-compatible parameters.

Detailed protonation, force-field, solvation, and cofactor-parameterization settings are given in Appendix A.2.

2.3 Staged Minimization and Reference-Holo Controls

Energy minimization was carried out in explicit solvent using a staged, subunit-aware AMBER protocol. AorA and AorB were minimized in seven stages (`min0`–`min6`), beginning with a local Fe–S-region pre-relaxation step, whereas AorC followed the same overall logic but without `min0`. Detailed engine settings, restraint definitions, stage parameters, and software versions are given in Appendix A.3.

Reference-holo controls were prepared separately for each subunit using the corresponding experimental coordinates rather than BioEmu-derived backbones. These controls matter for analysis because they separate the accuracy of the pipeline from the variability of the input states. If the same reconstruction and minimization logic preserves the experimental structure but the AI-derived states

Table 1. Subunit scope and preparation logic used in the present AOR benchmark. "BioEmu-delivered" denotes the number exported after the model's built-in physicality filtering. "Retained" denotes the final no-flag set after downstream preparation, minimization, and QC, corresponding to 82.3%, 80.2%, and 89.0% of the BioEmu-delivered sets.

Subunit	Restored chemistry	Minimization schedule	Requested	BioEmu-delivered	Retained
AorA	Four Fe–S clusters and ligating cysteine network	min0–min6	100	96	79
AorB	W-bis-MPT, Mg, proximal Fe–S cluster, catalytic waters	min0–min6	100	91	73
AorC	Bound FAD cofactor and NAD-binding site	min1–min6	100	100	89

remain displaced, the displacement is attributable to alternative starting conformations rather than to a broken preparation protocol.

2.4 Quality-Control Metrics

The QC stage evaluated both global structural behavior and subunit-specific local chemistry. For each minimized system after alignment to the reference chain, we extracted final Cα RMSD, change in RMSD during minimization (ΔRMSD), radius of gyration (R_g) at the start and end of minimization, and final AMBER potential energy normalized by atom count. Here, R_g served as a coarse measure of overall compactness or mass distribution, and ΔR_g denotes the end-minus-start change during minimization. Outliers in energy-per-atom and final Cα RMSD were identified using a median absolute deviation (MAD)-based modified z-score threshold of 3.5 [11].

Additional chemistry-specific filters were applied in a subunit-dependent manner. For AorA and AorB, the reconstructed [4Fe–4S] regions were evaluated using the minimum and maximum Fe–S distances observed after minimization, and a frame was rejected if any Fe–S distance lay outside 2.05–2.45 Å. For AorB, the tungsten site was further assessed using the minimum bond-like W–S distance, with an admissible range of 2.20–2.60 Å. These bounds were derived from separate calibration analyses of metal–sulfur bonding, based on bond-energy calculations and the corresponding bond-length histograms. For AorC, FAD pose RMSD relative to the reference was tracked as a descriptive measure of cofactor placement but was not used as a hard rejection criterion.

The QC thresholds were chosen based on reference-holo baselines, empirical inspection of the minimized distributions, and conservative tolerance windows intended to exclude obvious geometric failures without forcing close agreement

with the control medians. For example, the reference-holo controls gave final minimum Fe–S distances of 2.18 Å for AorA and 2.18 Å for AorB, while retained structures clustered closely around similar values. Likewise, the AorB control gave a minimum-near W–S distance of 2.45 Å, and retained AorB structures remained centered near that value. The adopted Fe–S and W–S windows were therefore broad enough to permit physically reasonable relaxation while excluding clear over-compression or loss of near-contact coordination.

A structure was classified as a *keeper* if it had no active QC flags. The final retained set is therefore intentionally conservative and consists of systems that remained both energetically unremarkable and locally chemically plausible under the chosen criteria.

2.5 PCA and HDBSCAN Analysis

To assess the geometry of the retained ensembles, the common-reference Cα coordinates of all keeper structures in each subunit were projected into principal-component space. The first three PCs were used as input to Hierarchical Density-Based Spatial Clustering of Applications with Noise (HDBSCAN) with a minimum cluster size defined as $\max(4, \lceil 0.03n \rceil)$, where n is the number of keeper structures in the subunit. HDBSCAN was chosen because it does not force all points into clusters and can therefore represent a mixture of dense basins and diffuse background occupancy [16]. Cluster quality was evaluated using the silhouette score on non-noise points and the density-based clustering validity index (DBCV), for which larger positive values indicate stronger density-defined separation [19]. Because HDBSCAN labels noise points explicitly, the silhouette score should be interpreted here as a measure of separation within the clustered subset rather than as a global quality measure when noise fractions differ strongly between subunits. Reference-holo controls were projected into the same PC space to allow direct comparison between experimentally anchored and AI-derived states. Additional implementation details are provided in Appendix A.4.

3 Results

3.1 QC Retention and Rejection Profiles Across Subunits

For each subunit, 100 conformations were requested from BioEmu. After BioEmu's built-in filtering of physically implausible samples, 96 AorA, 91 AorB, and 100 AorC structures entered the downstream preparation workflow (Fig. 3). The final no-flag retention rates therefore corresponded to 79%, 73%, and 89% relative to the originally requested ensembles, or 82.3% (79/96), 80.2% (73/91), and 89.0% (89/100) relative to the BioEmu-delivered minimized sets. Although the initial reduction at the BioEmu stage was limited, 4% for AorA and 9% for AorB, with no losses for AorC, it is important to distinguish this internal physicality filter from the subsequent QC procedure. The former excludes clearly problematic outputs (such as chain-break or clash-prone outputs) before export, whereas the latter evaluates whether a delivered backbone remains chemically

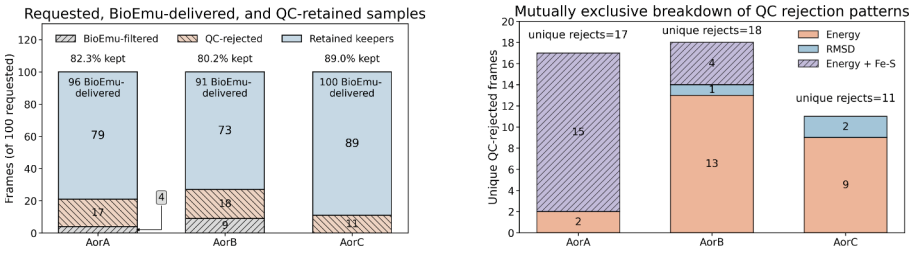


Fig. 3. QC outcomes across the three AOR subunits. Left: bars are normalized to 100 requested BioEmu samples per subunit and show BioEmu-side filtering, downstream QC rejections after preparation/minimization, and final retained keepers. Right: mutually exclusive breakdown of unique QC rejections, with each rejected frame counted once only.

and energetically acceptable after subunit-specific holo reconstruction, solvation, and minimization [13].

Within the downstream QC stage, energy-based outlier detection was the dominant rejection mode in all three subunits. AorA and AorB each showed 17 energy flags, whereas AorC showed 9. However, because some rejected structures carried more than one flag, per-category counts are not equivalent to numbers of rejected structures. In AorA, 15 of the 17 rejected structures combined energy and Fe–S-related abnormalities, whereas 2 were rejected on the basis of energy alone. In AorB, 13 of the 18 rejected structures were energy-only outliers, 1 was rejected on RMSD alone, and 4 showed a combined energy-plus-Fe–S pattern. In AorC, the rejected set consisted of 9 energy-only and 2 RMSD-only cases. Thus, the mutually exclusive rejection profiles differed across subunits, with AorA dominated by combined energy/Fe–S failures, AorB mainly by energy-only outliers, and AorC by energy-only plus a small number of RMSD-only cases.

The subunits also differed in the main features associated with rejection. In AorA, rejected structures showed clear abnormalities in the local Fe–S region, as the median final minimum Fe–S distance in the rejected subset was 1.52 Å, compared with 2.17 Å for the retained structures. In AorB, rejected structures remained very similar to the retained set in both Fe–S and W–S metrics. AorC showed a third pattern, where the rejected structures had a lower median FAD pose RMSD than the retained set. Thus, the three subunits differed not only in retention, but also in the combination of local and global features associated with rejection.

3.2 Structural and Energetic Effects of Minimization

After minimization, the retained structures remained distinct from the experimental reference at the backbone level (Table 2, Fig. 4). The median final Cα RMSD values for the retained sets were 6.60 Å for AorA, 1.23 Å for AorB, and 2.72 Å for AorC. By contrast, the corresponding reference-holo controls remained

essentially identical to the reference in all three cases, with final RMSD values of approximately 5×10^{-4} Å.

The energy distributions support the same general distinction between retained and rejected models. Within each subunit, the retained structures occupied relatively narrow ranges of favorable per-atom energies, whereas the rejected sets included the high-energy tail associated with unresolved strain or otherwise unfavorable geometry (Fig. 4). This separation between retained and rejected energy ranges was clearest in AorA and AorC.

Table 2. Summary of the retained (*keeper*) ensembles and the subunit-specific reference-holo controls. Reported keeper values are medians with interquartile ranges in brackets. Chemistry-aware values are stated only for the metrics relevant to a given subunit.

(a) Retained ensembles

Subunit	n	$\mathrm{RMSD}_{\mathrm{end}}$ (Å)	ΔRMSD (Å)	ΔR_g (Å)	E/N (kcal/mol/atom)	Chemistry-aware metric
AorA	79	6.60 [4.94, 9.00]	0.12 [0.05, 0.16]	0.18 [0.12, 0.24]	−4.15 [−4.16, −4.13]	Fe–S_{min}: 2.17 [2.17, 2.18]
AorB	73	1.23 [1.17, 1.29]	0.19 [0.17, 0.22]	0.39 [0.36, 0.41]	−3.84 [−3.84, −3.83]	Fe–S_{min}: 2.19 [2.18, 2.19] W–S_{min}: 2.45 [2.43, 2.45]
AorC	89	2.72 [2.48, 2.94]	0.15 [0.12, 0.17]	0.11 [0.06, 0.17]	−3.99 [−4.00, −3.95]	FAD pose RMSD: 1.85 [1.58, 2.02]

(b) Reference-holo controls

Subunit	n	$\mathrm{RMSD}_{\mathrm{end}}$ (Å)	ΔRMSD (Å)	ΔR_g (Å)	E/N (kcal/mol/atom)	Chemistry-aware metric
AorA control	1	0.0005	−0.79	−0.33	−4.15	Fe–S_{min}: 2.18
AorB control	1	0.0005	−0.91	−0.62	−3.91	Fe–S_{min}: 2.18 W–S_{min}: 2.45
AorC control	1	0.0005	−0.82	−0.45	−4.05	FAD pose RMSD: 0.0005

The same general picture is supported by the signs of ΔRMSD and ΔR_g. For retained structures, the median ΔRMSD was positive in all three subunits: +0.12 Å for AorA, +0.19 Å for AorB, and +0.15 Å for AorC. The median change in radius of gyration was likewise positive, at +0.18 Å, +0.39 Å, and +0.11 Å, respectively. These positive median shifts indicate that minimization did not simply return the retained models toward the experimental backbone. The largest median ΔR_g was observed for AorB (+0.39 Å), indicating the clearest shift in overall compactness between the pre-minimization and post-minimization structures.

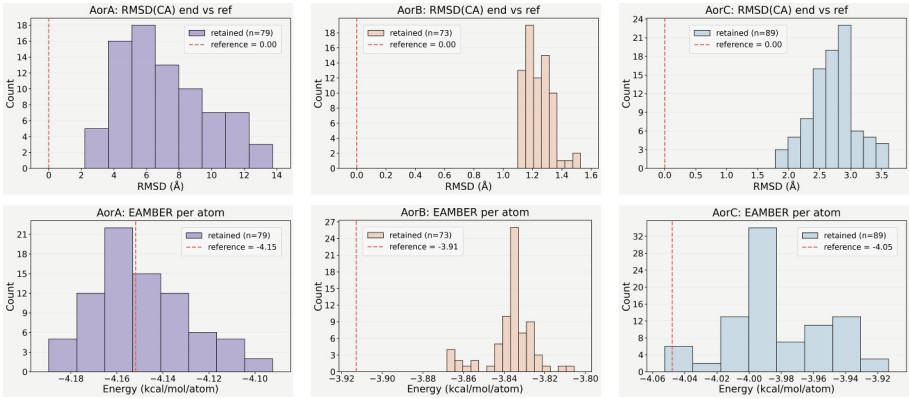


Fig. 4. Top row: distributions of final Cα RMSD to the reference. Bottom row: distributions of final AMBER potential energy per atom. Vertical lines correspond to the subunit-specific reference-holo controls.

3.3 Local Cofactor and Metal-Center Geometry Relative to the Reference-Holo Baseline

The chemistry-centered metrics help to interpret whether the retained structures remained locally plausible after minimization (Fig. 5). In AorA, the median final minimum Fe–S distance in the retained set was 2.17 Å, very close to the control value of 2.18 Å. In AorB, the corresponding median Fe–S minimum distance was 2.19 Å, while the median W–S minimum-near distance was 2.45 Å, again close to the control values of 2.18 and 2.45 Å, respectively. These results indicate that, for the retained structures, the local metal-centered geometry remained close to the reference-holo baseline after minimization, even when the protein backbone did not necessarily return to the experimental conformation.

AorC showed a different but equally informative behavior. The retained structures had a median FAD pose RMSD of 1.85 Å, with an interquartile range of 1.58 to 2.02 Å (Fig. 5). In protein-ligand benchmarking, heavy-atom pose RMSD values around 2 Å are commonly used as an indicator of near-native or chemically useful poses [1,23]. Although FAD is not a docked drug-like ligand and the present workflow involves protein relaxation rather than docking refinement, this scale remains useful as a point of reference. Thus, the retained AorC structures remained centered around a narrow range of FAD pose RMSD values.

3.4 Subunit-Specific Differences in Density-Based Ensemble Structure

The retained ensembles differed clearly in their geometric organization in PC space (Table 3, Fig. 6). AorA showed the strongest density-defined clustering, with two HDBSCAN clusters, 36.7% noise, a non-noise silhouette score of 0.424, and a full DBCV of 0.257. AorC also yielded two clusters, but with a substantially

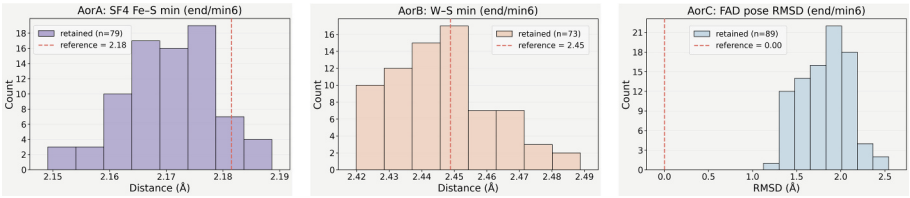


Fig. 5. Subunit-specific chemistry-aware metrics for the retained ensembles. Left: AorA minimum Fe–S distance in the reconstructed [4Fe–4S] relay. Middle: AorB minimum-near W–S distance in the tungsten site. Right: AorC FAD pose RMSD after alignment. In all panels, the vertical line marks the reference-holo control.

higher noise fraction (53.9%) and a lower full DBCV of 0.071. AorB showed the weakest global clustering structure, with 52.1% noise and a full DBCV of 0.043. Together, these metrics indicate a progression from the most compact retained ensemble in AorA to the most diffuse one in AorB, consistent with weaker density-defined separation as quantified by DBCV [19].

The variance explained by the first three principal components followed the same ordering. In AorA, the first three PCs accounted for 88.2% of the variance in the retained set. In AorC, the corresponding value was 60.4%, whereas in AorB the first three PCs explained 18.8% of the variance. This pattern is consistent with progressively more distributed structural heterogeneity from AorA to AorB.

Table 3. PCA/HDBSCAN summary for retained structures. Larger positive DBCV values indicate stronger density-defined cluster structure. The silhouette score was computed only on non-noise points. Cluster sizes and cluster-wise DBCV values are reported for the two clusters detected in each subunit.

Subunit	Kept	Clusters	Noise (%)	Silhouette (non-noise)	DBCV $_{\text{full}}$	Cluster 1 (n, DBCV)	Cluster 2 (n, DBCV)	PC1 / PC2 / PC3 variance (%)
AorA	79	2	36.7	0.424	0.257	5, 0.634	45, 0.380	43.1 / 31.9 / 13.2
AorB	73	2	52.1	0.332	0.043	6, 0.250	29, 0.056	8.2 / 6.0 / 4.6
AorC	89	2	53.9	0.452	0.071	13, 0.168	28, 0.146	28.6 / 21.2 / 10.6

Cluster-medoid representatives of the retained ensembles are shown in Fig. 7, providing structural exemplars of the density-defined regions identified by PCA/HDBSCAN and allowing visual comparison of retained conformational spread across the three subunits.

4 Discussion

4.1 MD-Readiness Beyond Structural Similarity

MD-readiness was defined here in operational rather than purely structural terms. Although RMSD to the experimental reference was tracked throughout

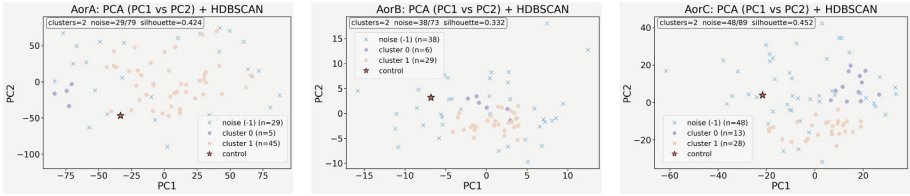
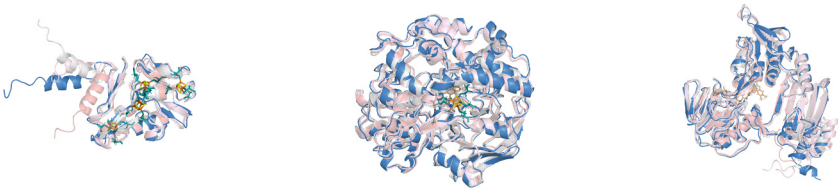


Fig. 6. PCA (PC1 vs. PC2) and HDBSCAN assignments for retained structures. Crosses indicate points labeled as noise, colored circles indicate cluster members, and the star denotes the projected reference-holo control. AorA shows the clearest density-structured separation, AorC is intermediate, and AorB shows the most diffuse retained ensemble with a large noise component.



(a) AorA (b) AorB (c) AorC

Fig. 7. Cluster-medoid representatives for AorA, AorB, and AorC, overlaid with the corresponding minimized reference structures. Colors are consistent across subunits: blue, reference; light pink, noise medoid; salmon, cluster 0 medoid; white, cluster 1 medoid. Cofactors and metal centers are shown from the reference structures. (Color figure online)

the analysis, a low RMSD was not required for a structure to be considered suitable for further simulation. Instead, a structure was classified as MD-ready if it could be reconstructed as a chemically complete holo model, minimized in explicit solvent without evident energetic or geometric abnormalities, and retained by the subunit-specific QC criteria. Under this definition, minimization functions primarily as a physical screening step rather than as a procedure expected to recover the experimental backbone.

This distinction is important for interpretation of the retained ensembles. As shown in the Results, minimization did not simply collapse the accepted models toward the cryo-EM reference. The consistently positive median ΔRMSD and ΔR_g values indicate instead that minimization relieved unfavorable contacts introduced during reconstruction and solvent preparation while preserving much of the conformational character of the starting models. This effect was especially evident in AorB, which showed the largest median ΔR_g, suggesting the clearest systematic shift in overall compactness between the pre-minimization and post-minimization states. At the same time, the reference-holo controls remained essentially coincident with the experimental structure after the same preparation and minimization procedure. This indicates that the protocol itself does not

impose substantial structural drift when applied to a reference-consistent starting state. The deviations observed in the retained BioEmu-derived structures should therefore not be interpreted as preparation artifacts alone.

Importantly, the final minimized coordinates reflect not only the conformational variation introduced by BioEmu, but also downstream side-chain reconstruction, protonation assignment, cofactor and ion transfer, solvation, and local relaxation during minimization. The retained sets therefore represent conformations whose backbone-level diversity survives chemically explicit reconstruction and minimization rather than being erased by the preparation workflow. In this sense, MD-readiness in the present study refers not to close structural agreement with the experimental reference, but to the ability of an alternative starting conformation to remain chemically plausible after full holo restoration and solvent relaxation.

As an additional practical check, selected representative retained structures were propagated for 51 ns in explicit-solvent MD and remained stable, without evident cofactor disruption, structural collapse, or loss of metal-center geometry. These runs support the practical MD compatibility of selected representatives, while broader replicate simulations would be needed for ensemble-wide dynamical validation.

4.2 Subunit-Specific Differences in Physicochemical Behavior After QC

The three subunits define a clear hierarchy in terms of preparation difficulty and post-QC ensemble behavior, where AorC was the most straightforward system to prepare. It showed the highest retention rate, the simplest rejection profile, and a cofactor-restoration problem that remained relatively local. After FAD placement and minimization, the retained ensemble preserved a broad range of conformations while remaining chemically reasonable. Although FAD pose RMSD was not used as a hard rejection criterion, the retained AorC structures remained centered around a narrow range of values, indicating that the cofactor occupied a reproducible binding mode related to the reference geometry even when the backbone did not return to the cryo-EM state. In practical terms, this makes AorC the most accessible starting point for subsequent representative-structure selection and trajectory-level stability checks.

AorA on the other hand, required stricter local control. Although many retained AorA structures remained substantially displaced from the reference at the backbone level, the acceptable Fe–S geometry was confined to a narrow range close to the control baseline. This behavior is consistent with the strongly constrained bonding pattern between the coordinating cysteines and the Fe atoms. In contrast, rejected AorA structures were characterized by unrealistically short minimum Fe–S distances and, in many cases, unfavorable energies. This indicates that the main sensitivity of AorA lies in the local metal-cluster region rather than in global fold variation. Therefore, the dedicated `min0` stage appears methodologically justified, as it allows local relaxation of the Fe–S environment before the broader minimization schedule is applied.

AorB was the most demanding subunit overall, as it combines the proximal Fe–S cluster with the W-bis-MPT center, associated magnesium, and structurally retained waters within a comparatively large catalytic framework. In this case, rejection was not explained primarily by the local metal-center metrics, since the retained and rejected structures remained similar in both Fe–S and W–S measures. Instead, AorB was characterized mainly by a diffuse post-QC ensemble, weak global clustering, and rejection driven largely by energy outliers together with a small number of RMSD outliers. The clustering analysis refines this picture further, as although the full DBCV value was low and just over half of the retained structures were labeled as noise, two local clusters were still detected, indicating that broad structural diffuseness coexists with limited pockets of more coherent organization. AorB should therefore be interpreted not as a failed system, but as the broadest and least compact of the retained ensembles, requiring more careful representative selection than AorA or AorC.

Taken together, these contrasts show that local cofactor- or metal-centered geometry and whole-structure energetic plausibility are related, but not interchangeable, indicators of model quality. A structure can remain locally acceptable yet still belong to a diffuse or energetically problematic ensemble, and conversely, global deviation from the experimental reference does not by itself imply failure of local chemical reconstruction.

4.3 Role of the Reference-Holo Controls

The reference-holo controls provide an essential baseline for interpreting the retained BioEmu-derived ensembles. Because they remain stable under the same preparation and minimization protocol, the deviations observed in the retained BioEmu-derived structures cannot be attributed solely to artifacts of LEaP assembly or minimization. A more plausible interpretation is that these structures represent alternative conformations that remain chemically viable after holo restoration and solvent relaxation.

Furthermore, the controls are also important for interpreting local chemistry. In AorA and AorB, the accepted structures retained Fe–S and W-site metrics that remained close to the corresponding control values despite larger backbone-level deviations. In AorC, the same general pattern was observed for the FAD cofactor, whose pose remained confined to a relatively narrow range even when the protein backbone did not recover the reference state exactly.

More broadly, the controls help distinguish between protocol reliability and input-state variability. They show that the workflow is capable of preserving a reference-consistent structure, while also providing a chemically anchored baseline against which AI-derived alternative states can be judged. This makes them more than a technical sanity check: they are part of the interpretive framework needed to decide whether a prepared model is merely different from the reference or chemically problematic.

4.4 Implications for Simulation Workflow Design

The present results suggest a practical workflow for preparing AI-derived starting structures for simulation in cofactor-rich enzymes. Generative models are useful for introducing backbone-level conformational diversity, but this alone is not sufficient to produce simulation-ready systems. Cofactors, metal centers, associated ions, and structurally important waters must first be restored, followed by explicit-solvent relaxation and QC-based screening. In this sense, the workflow is transferable mainly as a preparation and QC template: the same logic can be adapted to other cofactor- or metal-dependent enzymes, provided that system-specific cofactor parameters, metal-center definitions, reference geometries, and chemistry-aware QC thresholds are available. A suitable workflow therefore consists of three stages: generation of diverse starting conformations, reconstruction of chemically complete holo models, and explicit-solvent relaxation followed by QC-based screening.

The results also argue against applying a uniform filtering strategy across all subunits. Different subunits showed different dominant sensitivities, and these were not captured equally well by any single metric. A single global RMSD threshold would be too restrictive for AorA, where large backbone differences can coexist with acceptable local chemistry, whereas a purely cofactor-centered filter would not capture the broader post-QC behavior observed for AorB. The most appropriate approach is therefore a multi-criterion QC framework that combines general whole-system indicators, such as energy and backbone geometry, with subunit-specific measures focused on the relevant cofactors or metal centers.

The ensemble analysis also has practical implications for representative selection. In AorA, where the retained ensemble is more strongly structured in principal-component space, a smaller number of representative structures may capture much of the retained conformational variation. In AorB, broader coverage is likely to be necessary because the post-QC ensemble remains more diffuse and less compressible. AorC lies between these two cases. This means that even after QC, the effort required to design a representative starting set may remain subunit-dependent.

4.5 Limitations

Several limitations of the present study should be noted. First, the analysis was carried out at the level of individually prepared AorA, AorB, and AorC subunits rather than for the complete quaternary AOR structure described experimentally [24]. Second, the study focused primarily on structure preparation, minimization, and post-minimization QC, rather than on production-scale MD simulations or mechanistic analysis of catalysis. Although selected representative retained structures were propagated for 51 ns and remained stable without evident disruption of the reconstructed cofactor or metal-center environments, these simulations were used as practical stability checks rather than as a statistically complete validation of the full retained ensembles. Third, the clustering analysis was used as a descriptive tool for assessing the geometric organization

of the retained ensembles and was not intended to provide a rigorous estimate of equilibrium populations or transition kinetics.

An additional limitation is that the QC framework was designed primarily as a conservative screening procedure. As a result, the accepted structures can be interpreted more directly than the rejected ones: the former satisfy the energetic and geometry-based criteria adopted here, whereas the latter represent a heterogeneous set of models that failed one or more filters but were not analyzed further in mechanistic detail. Within these boundaries, the results still show that AI-derived monomer conformations can be converted into chemically plausible holo starting structures for a cofactor-rich oxidoreductase system with nontrivial requirements for Fe–S reconstruction, tungsten-site preparation, and FAD placement.

5 Conclusion

This study presented a subunit-specific BioEmu-to-AMBER workflow for the preparation of AorA, AorB, and AorC from the cofactor-rich aldehyde oxidoreductase of *A. aromaticum*. The results show that successful preparation is better assessed in terms of post-reconstruction physical and chemical plausibility than by simple recovery of the experimental reference backbone. Across all three subunits, the retained structures remained diverse after minimization while preserving local cofactor- or metal-centered geometry that stayed close to the corresponding reference-holo controls.

The three subunits also differed clearly in their preparation behavior. AorC was the most straightforward system, AorA remained globally diverse but could be prepared successfully when the Fe–S region was handled explicitly, and AorB showed the broadest and least compact retained ensemble after QC. Taken together, these results indicate that AI-derived conformational diversity can be used productively in cofactor-rich enzyme modeling, provided that it is combined with explicit holo reconstruction and subunit-specific QC.

Future work should extend this analysis to broader MD validation and to the larger AOR assembly. The representative MD checks performed support the practical stability of selected retained models, but a full dynamical comparison across retained ensembles remains a separate downstream objective. More generally, the same workflow may be applicable to other cofactor- or metal-dependent enzymes for which successful simulation setup requires careful reconstruction of the local chemical environment, including cofactors, metal centers, associated ions, and structurally retained waters.

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A Technical Supplementary Methods

A.1 BioEmu Sampling Details

BioEmu sampling was run independently for the FASTA sequence of each AOR subunit using model `bioemu-v1.2` with a fixed base seed of 1770289950782386813. For each subunit, 100 conformations were requested. No steering options were applied, and the `filter_samples` argument was not overridden, so BioEmu's default physicality filtering remained active [13]. The resulting exported sets comprised 96 structures for AorA, 91 for AorB, and 100 for AorC. The overall workflow and subunit scope are summarized in Fig. 2 and Table 1.

A.2 AMBER Preparation Details

Protonation states were assigned with H++ at pH 8.0, after which histidine protonation states were mapped to the corresponding AMBER residue names where needed [2,9]. LEaP assembly used `ff03.r1` for the protein, `gaff2` for nonstandard organic cofactors, and TIP3P water [6]. AorA was solvated with a 12.0 Å buffer, whereas AorB and AorC used a 10.0 Å buffer. Sodium counterions were added as needed for charge neutralization [6–8]. Custom templates, point charges, and bonded parameters for Fe–S clusters were based on the parameterization reported by Carvalho and Swart [4]. W-bis-MPT/Mg templates, partial charges, and bonded parameters were used as supplied from in-house files generated by M. Szaleniec and co-workers using density functional theory (DFT) calculations, following a protocol related to that described in Vilela-Alves et al. [22]. These files were used as supplied for the present benchmark and were not re-parameterized within this study.

A.3 Detailed Minimization Protocol

Energy minimization was performed in explicit solvent with `pmemd.cuda` under periodic boundary conditions at constant volume (`ntb = 1`) using a 10.0 Å nonbonded cutoff. For AorA and AorB, an additional Fe-S-specific pre-relaxation step was applied before the common minimization protocol. In this step (`min0`), the Fe-S cluster, coordinating cysteine residues, and residues within ±2 sequence positions of those cysteines were left unrestrained, whereas the remaining non-ion solute atoms were restrained with a force constant of 100 kcal mol^{-1} $\mathrm{Å}^{-2}$. Solvent molecules and counterions were not restrained. The purpose of this step was to relax the rebuilt FeS coordination region while limiting larger-scale displacement of the surrounding solute. The `min0` step should therefore be interpreted as a local pre-relaxation step rather than as the first point of a monotonic restraint-release schedule. Its output was then subjected to the common restrained-solute

minimization sequence, in which the restraint weight was reduced from 500 to 250, 100, and 10 kcal mol^{-1} $Å^{-2}$ during `min1`–`min4`, followed by two unrestrained minimization stages, `min5` and `min6`. AorC was minimized with the same protocol but without `min0`, since it does not contain an FeS center.

Stages `min0`–`min5` used mixed steepest-descent/conjugate-gradient minimization (`ntmin=1`), whereas `min6` used steepest descent only (`ntmin=2`). The corresponding numbers of minimization cycles were 20,000, 50,000, 50,000, 20,000, 50,000, 100,000, and 300,000 for `min0`–`min6`, respectively. For the mixed stages, `ncyc` values were 10,000 (`min0`), 2,500 (`min1`), 2,500 (`min2`), 5,000 (`min3`), 10,000 (`min4`), and 5,000 (`min5`). All minimizations were performed with Amber/24.3 and AmberTools/24.8, and downstream analysis used NumPy 2.2.6, pandas 2.3.3, matplotlib 3.10.8, scikit-learn 1.7.2, MDAnalysis 2.9.0, and `hdbscan` 0.8.41.

A.4 Additional PCA/HDBSCAN Implementation Details

For HDBSCAN, the `min_samples` parameter was left at `None`, which makes it default to the same value as `min_cluster_size`. This setting was used to avoid introducing an additional tuning parameter beyond the cluster-size rule applied uniformly across subunits.

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Multiscale Computational Study of Perovskite Materials Using Classical Molecular Dynamics and Ab Initio Approaches

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Abstract. In recent years, perovskite materials have emerged as promising candidates for applications in photovoltaics and photocatalysis due to their remarkable optoelectronic properties, low-cost synthesis, and structural tunability. However, their long-term stability and interactions with external molecules, such as CO_2, remain significant challenges for practical applications. In this work, we combine classical molecular dynamics (MD) simulations and ab initio calculations to investigate the structural, electronic, and dynamical properties of perovskite materials. Density Functional Theory (DFT) calculations are employed to optimize the atomic geometries and determine charge distributions, while MD simulations provide insights into the system behavior under different thermodynamic conditions. Particular attention is given to the preliminary analysis of non-covalent interactions between perovskite structures and CO_2 molecules, modeled using the canonical LennardJones potential. The results highlight the balance between long-range attractive and short-range repulsive forces governing these interactions and contribute to a more accurate description of intermolecular potentials. This study provides a basis for the development of improved force fields and enhances the predictive capability of computational models for perovskite-based systems in energy and environmental applications. These findings may support future efforts to optimize perovskite materials for sustainable energy conversion and CO_2 reduction technologies.

Keywords: Perovskite · Molecular Dynamics · Ab Initio Calculations · Density Functional Theory · Non-Covalent Interactions · Photovoltaics · CO_2 Reduction · Force Field Development

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1 Introduction

Perovskite, originally considered the mineral name of calcium titanate ($CaTiO_3$) [1], was discovered for the first time by Russian mineralogist Lev Perovskij. Perovskites are used in photovoltaics because of their increasing power conversion efficiency (PCE), low-cost materials constituents, simple solution fabrication process [2], high absorption coefficient in a wide wavelength range and relatively high carrier mobility of free electrons and holes [1]. Initiated in 2009 with an efficiency of 3.8% [2], Perovskite solar cells (PSCs) have now achieved a lab-scale power conversion efficiency of 26.7% [3], competing with the performance of commercial silicon solar cells. Perovskites have a general chemical formula of ABX_3, where A is usually an organic cation such as methylammonium (MA) or formamidinium (FA), B is a metallic cation like tin or lead and X is an halide, such as I, Br or Cl [4]. The A-site cation is coordinated to 12 X anions, forming a cuboctahedron, while the 6-fold-coordinated B-site cation has an octahedral geometry [1], as shown in Fig. 1.

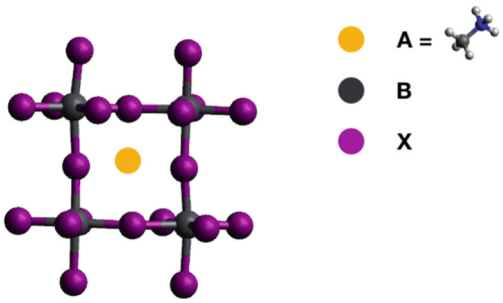

Fig. 1. A 3D molecular structure shows a cubic arrangement of atoms connected by bonds. Three types of atoms are indicated by colored circles: orange for type A, dark gray for type B, and purple for type X. The structure highlights how these atoms are positioned relative to each other, with type B atoms at the cube corners and type X atoms along the edges.

Perovskite solar cells (PSCs) are typically characterized by a layered device architecture consisting of a transparent conductive oxide (TCO)-coated glass substrate, an n-type semiconductor acting as the electron transport layer (ETL), a perovskite absorber layer, a p-type semiconductor serving as the hole transport layer (HTL), and a back contact made of metal, TCO, or carbon [2]. Despite their remarkable optoelectronic properties and high efficiency, the large-scale commercialization of perovskite-based devices is still hindered by their limited stability. The main factors contributing to degradation are moisture, ultraviolet (UV) radiation, and elevated temperatures [5].

The irreversible degradation of the perovskite absorber critically affects the operational lifetime of photovoltaic devices. In particular, exposure to UV light

has been shown to reduce the charge collection efficiency even in encapsulated cells, as demonstrated by transient absorption spectroscopy (TAS) studies [5]. Thermal instability represents another major issue: elevated temperatures can induce significant structural and chemical changes in perovskite materials. For instance, Phillippe et al. [6] investigated the thermal degradation of $MAPbI_3$ and $MAPbI_3$ - xClx films using hard X-ray photoelectron spectroscopy (XPS), which allows for compositional analysis independent of crystallinity. Their experiments, conducted under ultra-high vacuum to isolate temperature effects, revealed that increasing temperature leads to a progressive decrease in the I/Pb and N/Pb ratios, indicating decomposition into PbI_2. Specifically, heating at 100 ^{circ}C for 20 min caused a noticeable reduction in both ratios, while treatment at 200 ^{circ}C resulted in complete conversion to PbI_2.

To address these stability challenges, several strategies have been proposed, including compositional engineering, morphology control, grain size optimization, advanced deposition techniques, and interfacial engineering [7]. Among these, the incorporation of additives represents a simple yet effective approach, as small quantities of suitable compounds can significantly improve both material properties and device stability [7].

Beyond photovoltaics, perovskite materials have recently attracted considerable attention for applications such as water splitting and CO_2 reduction [8]. In the context of the increasing atmospheric CO_2 levels driven by anthropogenic activities [9–12], photoelectrochemical CO_2 reduction emerges as a promising strategy for carbon mitigation and the development of carbon-neutral technologies. Although numerous studies have explored the catalytic potential of perovskites for CO_2 conversion [13–18], the underlying reaction mechanisms remain not fully understood. A crucial initial step in this process is the long-range interaction between the CO_2 molecule and the perovskite surface. This interaction determines the formation of weakly bound precursor states, which in turn guide the system along specific reaction pathways. Therefore, a detailed understanding of intermolecular forces governing these early-stage interactions is essential for elucidating the overall reaction mechanism.

One of the first step of the process, which is common of all chemical processes, is represented by the long-range interaction of the CO_2 molecule with the surface of the perovskite. Such interaction will then lead to different configurations of the weakly bound precursor state of the system, which drives the species involved along specific chanels of the reactivity. Therefore, a detailed analysis of the long-range interaction and of the intermolecular forces driving the initial process can be pivotal for a better understanding of all the reactive process. In order to properly characterize the initial interaction between the two interacting species, a valid approach consists in the use of Molecular Dynamics (MD) simulations considering the appropriate range of thermodynamic conditions. As a first step, it is pivotal to implement the most accurate description of the interactions of the involved molecules through the development of a Force Field (FF), which represents a challenging task [19–21] since the choice of a correct intermolecular force field, modelling the intermolecular forces, crucially

influences the realism and feasibility of the simulation studies [21]. Different functions can be used to describe the non electrostatic component of the intermolecular interaction, including the classical Lennard-Jones potential [22], but also the more accurate *Improved Lennard-Jones* (ILJ) formulation [23], which allow for a better representation of long range attraction and short range repulsion. In the present contribution we performed preliminary MD calculation for the system composed of a perovskite layer, composed of 408 atoms in total, with 40 Pb atoms, 112 I atoms and 32 methylammonium ions ($CH_3NH_3^+$),both isolated and interacting with a CO_2 molecule using a LJ force field. The work constitutes a starting point toward the development of more accurate force field based on the physical properties of the interacting molecules.

2 Theoretical Methods

2.1 Ab Initio Calculations

Ab initio calculations have been performed at the DFT level of theory for the perovskite system. In depth, the structure of the perovskite has been optimized using the PBE functional and ultrasoft pseudopoptentials. The wavefunction and charge density cutoffs have been set to 40 Ry and 360 Ry, respectively. Long-range electron interactions have been taken into account applying the Grimme-D3 correction for the dispersion forces, which have an important role in determining the adsorption energy in large neutral molecules. The k-point sampling mesh is the Γ-mesh and a vacuum of 30 Å was added to create the slab. The same computational strategy has been adopted for the optimization of the CO_2 molecule and the system composed of a carbon dioxide molecule interacting with the perovskite slab. All calculations have been performed with the Quantum Espresso package [24–26].

As already reported in previous works [27], the main properties of the CO_2 molecule, necessary for the correct implementation of the force field, has been obtained through a DFT analysis, which represents a good compromise between chemical accuracy and computational cost [28–33].

2.2 Molecular Dynamics

Classical molecular dynamics simulations have been performed using the DL_POLY [34] simulation package, considering the NVT ensamble, where the number of particles (N), volume (V) and temperature (T) are kept constant. For this purpose, a Hoover-Nose thermostat [35] has been used, with a relaxation constant of 1 ps. Parallelepiped boundary conditions have been used considering a simulation box of 83×89 x 85 $Å^3$. All the simulations have been performed considering a temperature of 10 K and a pressure of 1 atm. An initial equilibration period of 1.5 ns has been performed, considering a total simulation time of 5 ns

Non-covalent Interactions: Potential Energy Surface. In order to obtain a reliable Force Field to be used in the simulation, the global intermolecular interaction energy (V_{Tot}) has been considered as a combination of an electrostatic contribution (V_{Elec}) and a non-electrostatic contribution (V_{Nelec}):

$$V_{Tot} = V_{Elec} + V_{Nelec} \tag{1}$$

where the electrostatic contribution has been calculated taking into account the atomic charge distribution of the CO_2 molecule, already reported in the ref. [27]. Differently than the previous treatment, the $MAPbI_3$ system has been treated considering the various functional groups constituting the Perovskite slab. Consequently, in the construction of the force field, lead was treated as Pb^{2+}, iodine as I^-, and methylammonium was represented as a single effective atom X carrying a charge +1.

The non-electrostatic component of the intermolecular interaction has been evaluated considering the *Improved Lennard-Jones* (ILJ) formulation described in ref. [23]. The ILJ potential model for a pair of neutral particles can be formulated as follows:

$$V_{nelec} = V_{ILJ} = \varepsilon \left[\frac{m}{n(r) - m} \left(\frac{r_m}{r} \right)^{n(r)} - \frac{n(r)}{n(r) - m} \left(\frac{r_m}{r} \right)^{m} \right] \tag{2}$$

where ε and r_m represents the well depth and its location, respectively, while m assumes the value of 6 for neutral-neutral systems. Finally, the term $n(r)$ is defined as:

$$n(r) = \beta + 4 \left(\frac{r}{r_m} \right)^2 \tag{3}$$

The parameters used for the ILJ formulation of the interaction are reported in Table 1

Table 1. List of the Improved Lennard-Jones parameters evaluated for the Perovskite + CO_2 system (where X indicates the $CH_3NH_3^+$ moiety).

Interacting Pair	ε (meV)	r_m (Å)
C - Pb	7.07	3.65
O - Pb	9.67	3.78
C - I	6.69	4.31
O - Pb	10.73	4.36
C - X	6.26	3.94
O - X	9.28	4.03

The value of β is usually considered in the interval between 6 and 8.

3 Results and Discussion

3.1 Ab Initio Results

An initial *ab initio* analysis was carried out (see Sect. 2 for details) considering a relaxation (optimization) procedure, where the first three layers from the bottom of the perovskite structure (along the z-axis) are kept rigid, while the last two layers, which are closer to the CO_2 molecule, are able to relax. The same strategy has been used for both the isolated perovskite and the perovskite interacting with the CO_2 molecule. The resulting structure, obtained through *ab initio* calculations, is reported in Fig. 2.

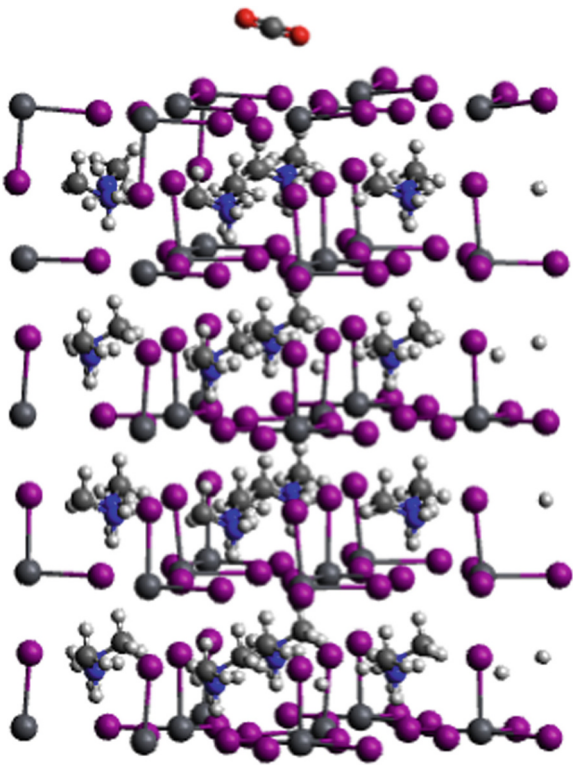

Fig. 2. 3D representation of the structure of the CO_2 molecule interacting with a perovskite system with $E_{ads} = -6.61$ kcal/mol.

The energy of the system can be easily calculated, allowing to quantify the strength of the interaction between the CO_2 molecule in the gas phase and the surface of the perovskite. In details, the adsorption energy can be evaluated as follows:

$$E_{ads} = E_{tot} - E_{per} - E_{\mathrm{CO_2}} \tag{4}$$

where E_{tot} is the energy deriving from the optimized structure of the perovskite with the CO_2 molecule, while E_{per} and E_{CO_2} represent the energies of the perovskite and CO_2 optimized separately, obtained at the DFT level of theory. Following the formulation reported in Eq. 4, a value of $E_{ads} = -6.61$ kcal/mol was obtained. This value is the result of a series of calculations where the initial geometry was modified: specifically, the CO_2 was put once above the Pb and once above the I of the slab and rotated to respect of the C atom with a step of 20^{circ}. So two series of results have been obtained and the most stable interaction has been reported. The same interaction can be evaluated without considering the Grimme-D3 dispersion correction. In this case, $E_{ads} = -6.20$ kcal/mol, with a difference of -0.41 kcal/mol. Although the difference is not very big, it is significant for a little molecule such as CO_2, suggesting that the interaction is driven by both chemical adsorption and van der Waals forces. An additional analysis can be performed considering the geometry resulting from *ab initio* calculations, and in particular taking into account the distance between the CO_2 molecule and the Perovskite layer. In Table 2 are reported the main distances obtained through accurate *ab initio* calculations.

Table 2. Atom-atom distances (in Å) between the CO_2 molecule and the first layer of the perovskite structure, with $E_{ads} = -6.61$ kcal/mol, obtained through DFT calculations (see Sect. 2.1 for details).

Interacting Pair	dist. (Å)
C - Pb	3.944
O - Pb	3.108
C - I	3.608
O - I	3.788

3.2 Classical Molecular Dynamics Results

As already reported in a previous investigation [27], the Perovskite system has been considered as composed of 408 atoms in total, organized in four layers considering a total of 40 Pb atoms, 112 I atoms and 32 methylammonium ions ($CH_3NH_3^+$). In order to run proper MD simulations, an essential step is represented by the accurate selection of an appropriate force field. As reported in previous section, a series of ILJ parameters for the main atom-atom interactions have been derived considering the $CH_3NH_3^+$ ion as an "effective" center (indicated as "X"), carrying the global charge and polarizability of the whole cation. Electrostatic contributions has been taken into account considering a three-center model for CO_2 [27], where the charges for each atom have been calculated at the DFT level of theory, while for the Perovskite the charges of the various functional groups have been considered. No induction therms have been included in the calculations.

An initial assessment of the simulation parameters has been performed considering the evolution of the values of temperature and configurational (potential) energy along the simulation time. In Figs. 3 and 4 are reported the trends of the configurational energy and temperature as a function of the simulation time.

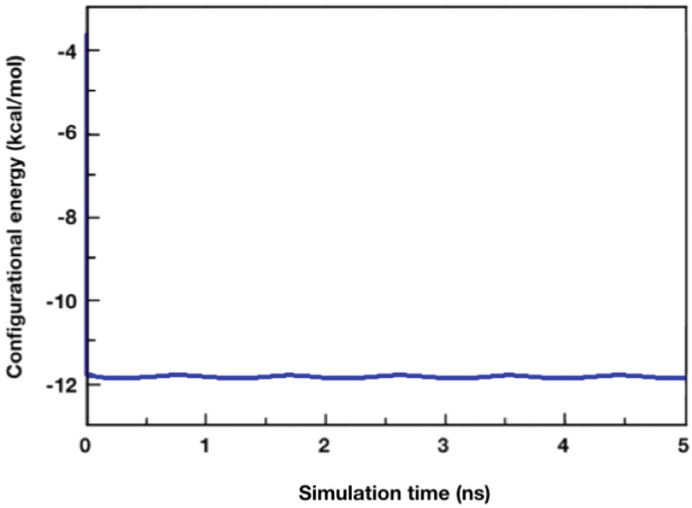

Fig. 3. Trend of the total energy (in kcal/mol) as a function of the simulation time (ns) for the Perovskite system, obtained through MD calculations.

The small fluctuations observed in energy and temperature throughout the MD simulations, relative to their absolute values, indicate that the chosen simulation parameters are reliable and well-suited for the system. Following the same protocol employed for the *ab initio* investigation of the system (see previous sectio for details), the interaction energy was evaluated considering the difference between the configurational energy of the perovskite+CO_2 system and the configurational energy of the two interacting species, calculated separately in the MD framework. The value obtained from classical MD calculation is equal to −11 kcal/mol, showing a significant deviation from the results of *ab initio* calculations. Additionally, the final configuration of the MD analysis can be compared with the geometry of the optimized system at the DFT level of theory. In Fig. 5 is reported a schematic representation of the final structure of the Perovskite-CO_2 system obtained from MD calculations

A significant parameter is represented by the distance between the CO_2 molecule and the Perovskite layer, whose values are reported in Table 3 and compared with the main distances obtained through accurate *ab initio* calculations.

The OI distance is the most representative descriptor of the adsorption geometry, as it approximates the distance between the terminal O of CO_2 and the surface of the perovskite material. A very good agreement is found between DFT

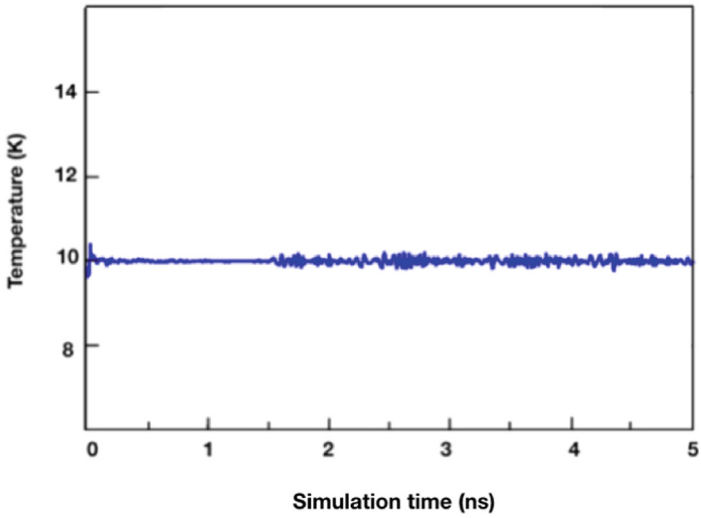

Fig. 4. Trend of the temperature (in K) as a function of the simulation time (ns) for the Perovskite system.

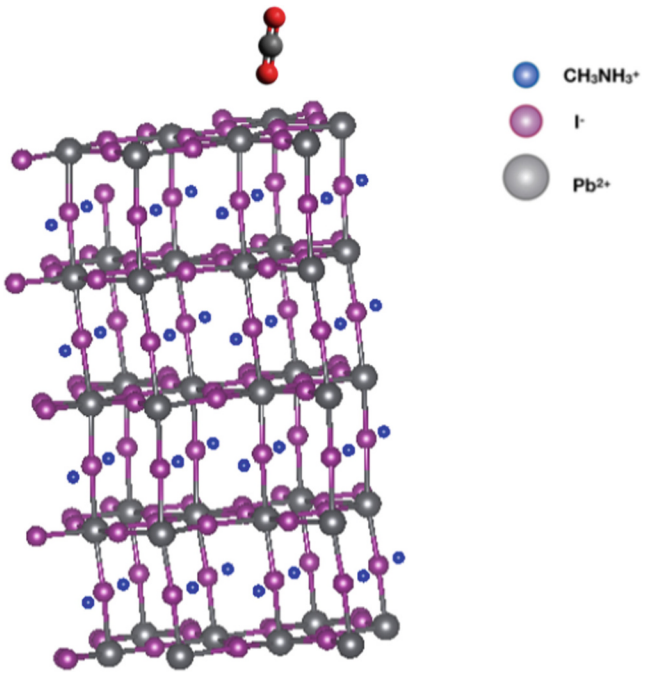

Fig. 5. Schematic representation of the final structure of the Perovskite-CO_2 system obtained from MD calculations.

Table 3. Atom-atom distances (in Å) between the CO_2 molecule and the first layer of the perovskite structure, through DFT and MD calculations.

Interacting Pair	dist. (Å) *DFT*	dist. (Å) *MD*
C- Pb	3.94	5.54
O - Pb	3.11	4.67
C - I	3.61	4.95
O - I	3.79	3.93

(3.79 Å) and MD (3.93 Å), confirming that the classical model correctly reproduces the adsorption geometry. Despite the quantitative difference between the two values of energy, both approaches predict the same order of magnitude for the CO_2-perovskite interaction. Additionally, the ILJ-based classical model was specifically parameterized for this system, rather than adopting generic literature parameters, with the aim of representing polarizability effects as accurately as possible. This approach yields an adsorption geometry in close agreement with the DFT results. The remaining discrepancy in the interaction energy can be mainly attributed to the intrinsically simplified nature of the classical description, in which the methylammonium (MA) cation is treated as a single interaction center. This approximation simplifies the interaction by neglecting internal bonding contributions and reinforces the description of the perovskite as an ionic crystal, which, while computationally efficient, can lead to minor deviations with respect to the fully electronic DFT treatment. Finally, the interfacial spatial correlations between CO_2 and the perovskite surface were characterized using radial distribution functions computed from molecular dynamics trajectories. The distributions were evaluated between CO_2 carbon and oxygen atoms and surface iodide atoms by accumulating pair distances over all simulation frames. The results obtained are shown in Fig. 6

The radial distribution function (RDF) between the oxygen atom of CO_2 and iodine atoms of $MAPbI_3$ shows a primary peak around 3.76 Å, indicating the most probable distance between CO_2 molecules and the halide sites on the surface layer. Lower-intensity secondary peaks, appearing at larger distances, likely originate from interactions with the oxigen atom of the CO_2 molecule and other iodine atoms in subsurface layers, reflects contributions from the perovskite lattice below the outermost layer.

4 Conclusions

In this work, a multiscale computational approach has been employed that combines Density Functional Theory (DFT) and classical Molecular Dynamics (MD) simulations to investigate the structural and interaction properties of perovskite materials in the presence of CO_2 molecules. The study provides a preliminary but insightful analysis of the non-covalent interactions governing the adsorption process at the perovskite surface.

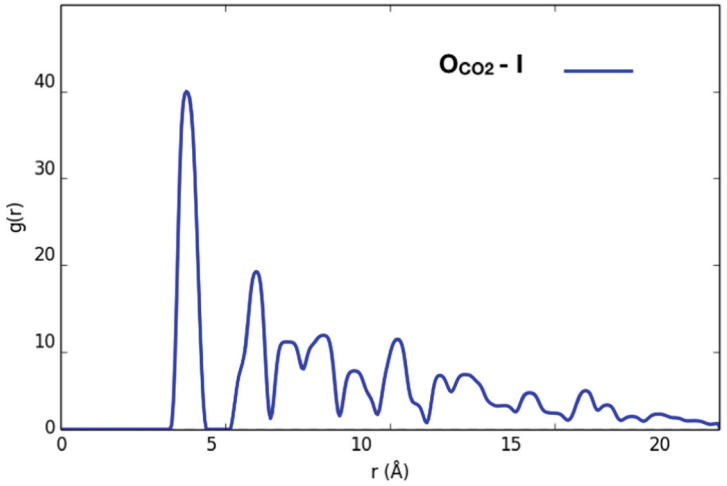

Fig. 6. Radial distribution function between CO_2 and the perovskite surface.

The DFT results reveal that CO_2 interacts weakly with the perovskite surface, with an adsorption energy of −6.61 kcal/mol, confirming the physisorption nature of the process. The optimized geometries highlight the key role of intermolecular distances, particularly involving oxygen and iodine atoms, in defining the adsorption configuration. Classical MD simulations, based on an Improved Lennard-Jones (ILJ) semi-empirical force field, specifically parameterized for this system, successfully reproduce the structural features of the adsorption process, showing good agreement with DFT results in terms of geometrical parameters. Although a discrepancy in interaction energies is observed (−11 kcal /mol from MD), this difference can be attributed to the simplified representation of the system in the classical model, particularly the treatment of the methylammonium cation as a single interaction center.

Overall, the combination of ab initio and classical approaches demonstrates the reliability of the developed force field in capturing the essential physics of the CO_2perovskite interaction. These findings represent a solid starting point for the development of more accurate and transferable force fields, ultimately contributing to improved predictive models. Such advancements are crucial for optimizing perovskite materials in applications related to sustainable energy conversion and CO_2 reduction technologies.

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Symmetry and Deformations in Shape Space: An Invariant Coordinate Description of Clusters and Biomolecules

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Abstract. Within the hyperspherical formulation of N-body systems, the configuration space can be decomposed into external rotations, kinematic rotations, and kinematic invariants. The latter define the intrinsic geometry of the system and constitute a set of shape coordinates, invariant under both spatial and kinematic rotations. In the work of Littlejohn and co-workers, these invariants are closely related to the principal moments of inertia and provide a natural set of variables for describing the internal structure of clusters and molecules. Building on this framework, hyperspherical shape coordinates can be employed as descriptors of molecular deformation, enabling the classification of equilibrium structures and the analysis of minimum-energy configurations independently of orientation and frame choices.

Keywords: Invariant Shape Coordinates · Molecular clusters · Biomolecular structure · Structural deformation · Minimum-energy configurations Potential energy surfaces

1 Introduction

The hyperspherical approach to molecular dynamics has been widely exploited in the field quantum reactive scattering calculations during the last decades, with significant progress in the theory and implementation of methods based on hyperspherical functions [1–3]. Full dimension calculations for three-body systems are now feasible, while much work has been done on hyperspherical harmonics basis sets for four-body systems (see e.g. [4–9]). The quantum Hamiltonian is actually invariant with respect to the possible product arrangements and therefore the hyperspherical method is useful in the study of multi-channel processes.

Besides their use as quantum scattering basis sets, hyperspherical functions are suitable to be applied to the representation of intermolecular and intramolecular interactions in collision studies [10,11,11–20,20–38]. These representations

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are a practical advantage in the dynamical and kinetic study of reactive processes [39–44].

As a matter of facts, the feasibility, in practice, of full quantum dynamics calculations in hyperspherical coordinates has been limited to three- or at most four-atom systems. This restriction can be in part bypassed, extending the hyperspherical methods to classical dynamics, by which medium size and large molecules and atomic and molecular clusters can be simulated, taking advantage of the lower computational cost of classical trajectories (see e.g. [45]). As a consequence of expressing the classical Hamilton function in terms of hyperspherical coordinates, the degrees of freedom get separated into homogeneous sets of variables corresponding to well defined kinetic energy contributions, accounting for shape deformation, ordinary rotations and kinematic rotations [6,46–48]. The hyperangular momenta appearing in the Hamilton function, as well as the other relevant dynamical quantities, are defined within a classical framework. This, in principle, makes it possible to derive the classical hyperspherical equations of motion. However, time propagation in Cartesian coordinates is certainly more convenient, provided that an appropriate matrix transformation is available to evaluate, at each time step, the energy contributions entering the hyperspherical Hamilton function.

As a final remark, the hyperspherical framework partitions the degrees of freedom into two classes of rotational coordinates-ordinary spatial rotations and kinematic rotations. The remaining three degrees of freedom are thus invariant under both transformations and depend solely on the global shape of the particle aggregate. This invariance-based description of structure and dynamics has been validated in several applications [46,49–51].

We consider here the possible application of the hyperspherical invariants deformation as a tool for the analysis for the classification of the structures associated to local and global minima of clusters of molecules and atoms. The following sections introduce the hyperspherical coordinate framework for general N-particle systems and outline its application to the structural characterization of clusters. Selected applications are presented in the final part of the paper.

2 Methodology

The representation of N-particle systems in hyperspherical coordinates is obtained by introducing a set of $N-1$ Jacobi vectors $\mathbf{Q}_\alpha$, with $\alpha = 1, \cdots, N-1$, defined as linear combinations of the particle position vectors $\mathbf{r}_\alpha$ in the center of mass reference frame [46]. A "canonical" sequence of Jacobi vectors can constructed by first considering the vector connecting particles 1 and 2, then the vector connecting the center of mass of this pair to particle 3, and so on, up to the $(N-1)$-th vector, which connects the center of mass of the first $N-1$ particles to the Nth particle. Each vector is scaled by suitable mass-dependent coefficients, ensuring proper normalization (see Sect. 2.1 for details). The subsequent step is to dedine the hyperradius ρ as the norm of a vector in a $3N-3$-dimensional space, which spans the internal configuration space of the system.

The Cartesian components of the hyperradial vector, given by the ordered set of the Jacobi vector components, can be parametrized in terms of the hyperradius and $3N-4$ "hyperangles", thereby defining the hyperspherical coordinate system. Many choices are possible for the parametrization of the angles. One of the alternatives is the representation knwn as symmetric hyperspherical, which is obtained applying a transformation based on the *singular value decomposition*, applied to the position (Cartesian coordinates) matrix. The procedure for the derivation of the hyperspherical coordinates is presented in the next sections, and some of their remarkable properties are described.

2.1 Hyperspherical Coordinates for Atomic and Molecular Aggregates

An appropriate mathematical tool for the representation of N-center systems is the *singular value decomposition* [52], a matrix decomposition theorem that can be applied to any given set of N atoms, after assigning to them a properly defined position matrix.

Let us suppose we have a collection of $N \geq 2$ particles with masses $m_1, \cdots, m_N$ and positions identified by a set of radii vectores in the center of mass reference frame, $\mathbf{r_1}, \cdots, \mathbf{r_N}$. Mass *scaled* radii vectores $\mathbf{q}_\alpha = (m_\alpha/M)^{1/2}\mathbf{r}_\alpha$ $(1 \leq \alpha \leq N)$, can be obtained, where $M = \sum_\alpha^N m_\alpha$ is the total mass of the system.

A $3 \times N$ position matrix denoted by Z containing column-wise the components of the mass scaled vectors, can be generated, as follows:

$$Z = \begin{pmatrix} q_{1,1} & q_{1,2} & \cdots & q_{1,N} \\ q_{2,1} & q_{2,2} & \cdots & q_{2,N} \\ q_{3,1} & q_{3,2} & \cdots & q_{3,N} \end{pmatrix}. \tag{1}$$

Left-multiplication of the position matrix by an orthogonal matrix R^t, (transpose of a matrix $R \in O(3)$), rotates the coordinate frame. A rotation of the coordinate frame can also be performed in the so called *kinematic space* [5,47], by action of an orthogonal matrix (right-multiplication) $K \in O(N)$ on the position matrix Z, $Z' = ZK$.

It is possible to identify a subset of K matrices having the following form (see last column):

$$K = \begin{pmatrix} k_{1,1} & k_{1,2} & \cdots & (m_1/M)^{1/2} \\ k_{2,1} & k_{2,2} & \cdots & (m_2/M)^{1/2} \\ \cdots & \cdots & \cdots & \cdots \\ k_{N,1} & k_{N,2} & \cdots & (m_N/M)^{1/2} \end{pmatrix} \tag{2}$$

and its application to the Z matrix generates a subset of all possible Cartesian frames. Note that the elements of the last column of such rotated Z matrices are always zero, due to the relation $\sum_\alpha^N m_\alpha^{1/2}\mathbf{q}_\alpha = 0$, valid for the mass scaled vectors. In such special cases, one only has to deal with a $3 \times (N-1)$ "reduced"

Z matrix. The physical meaning of such a condition is that one separates the motion of the center of mass. This smaller matrix Z is called *reduced position matrix*.

The sets of (N-1) Jacobi and related vectors form reduced matrices. The Jacobi vectors are defined as a linear combinations of the N Cartesian particle position vectors, with coefficients being a function of the particle masses [53,54]. The different Jacobi vector sets are connected by kinematic rotations. These sets correspond to the different coupling schemes and reactive channels of the system.

The *singular value decomposition* theorem applied to the $3\times n$ position matrix Z (where $n = N$ or $n = N - 1$) leads to the following product of three matrices:

$$Z = R\Xi K^t \tag{3}$$

where $R \in O(3)$ and $K \in O(n)$ are 3×3 and $3 \times n$ orthogonal matrices, respectively. The elements of the $3 \times n$ matrix Ξ are zeroes, with the possible exception of the diagonal entries, $\Xi_{11} = \xi_1, \Xi_{22} = \xi_2, \Xi_{33} = \xi_3$, which are subjected to the inequality $\xi_1 \geq \xi_2 \geq \xi_3 \geq 0$.

In the previous equation, we denoted as ξ_i, $(i = 1, 2, 3)$ the *singular values* of the Z matrix. These values are unique, while the factors R and K in Eq. 3 are not. We have to note that the smallest singular value ξ_3 is zero when $N \leq 3$ and Z is the full $3 \times N$ position matrix. An important relation can be easily obtained [46,47]:

$$\xi_1^2 + \xi_2^2 + \xi_3^2 = \rho^2. \tag{4}$$

The ξ's are invariant under both ordinary rotations in the physical space and kinematic rotations [5,6,47,55], a remarkable property, with possible applications to molecular dynamics [46,56–59] and properties of the minimum energy structures of N-particle aggregates.

For $n = N - 1 = 3$, we are accounting for four particle (or equivalently four centers) systems. This case is special, since the two matrices R and K (of same dimension, 3×3) are no longer *special orthogonal* ($R \in SO(3)$ and $K \in SO(n)$), but just orthogonal matrices ($O(3)$). This implies that for a negative determinant of Z, the sign depends on the sign of the ξ's product, meaning $\xi_3 \leq 0$. This fact is directly connected to the mirror image and chirality sign of the four-center system [49,60,61].

The major consequence of the above result is that the $3N - 3$ degrees of freedom of the system can be partitioned into three distinct sets of coordinates: three angles, parametrizing the rotation matrix R and accounting for spatial rotations, $3N - 9$ angles, parametrizing the rotation matrix K, accounting for rotations in the kinematic space, and 3 ξ's, which are related to the hyperradius.

2.2 Hyperradius and Invariant Deformation Indexes

The singular values (ξ_1, ξ_2, ξ_3) are considered to be "kinematic invariants" [62], since they are independent of spatial and kinematic rotations, see Sect. 2.1.

In addition, they are related to the system moments of inertia, as follows:

$$\begin{aligned}\frac{I_1}{M} &= \xi_2^2 + \xi_3^2 \\ \frac{I_2}{M} &= \xi_1^2 + \xi_3^2 \\ \frac{I_3}{M} &= \xi_1^2 + \xi_2^2\end{aligned} \tag{5}$$

where I_1, I_2 and I_3 are the moments of inertia in the principal axis reference frame. From Eq. 4 one obtains:

$$I_1 + I_2 + I_3 = 2M\rho^2. \tag{6}$$

Consequently, the ξ's can be used to define which kind of rotor the system is, in terms asymmetric, symmetric and spherical. One has a spherical top configurations for $\xi_1 = \xi_2 = \xi_3$, a prolate top for $\xi_3 = \xi_2 < \xi_1$ and an oblate top for $\xi_1 = \xi_2 > \xi_3$.

In order to complete the angular parametrization the invariant ξ's can be expressed by a canonical set of spherical coordinates, ρ, θ and ϕ as follows:

$$\begin{aligned}\xi_1 &= \rho \sin\theta \cos\phi \\ \xi_2 &= \rho \sin\theta \sin\phi \\ \xi_2 &= \rho \cos\theta\end{aligned} \tag{7}$$

This connection of the singular values with the distribution of the inertia associated to the N- particle system, has suggested to define a measure of the deviation from the spherical top shape, by two *deformation indexes* [46]:

$$\xi_+ = \frac{\xi_2^2 - \xi_3^2}{\rho^2}, \;\; \xi_+ \geq 0 \tag{8}$$

which is zero for prolate top configurations, and

$$\xi_- = \frac{\xi_2^2 - \xi_1^2}{\rho^2}, \;\; \xi_- \leq 0 \tag{9}$$

which is zero for oblate top configurations. Both the indexes equal to zero, indicate the cluster is a spherical top.

2.3 Deformation Indexes of Atomic and Molecular Clusters

The global and local minimum energy structures of Lennard-Jones (LJ) clusters of increasing size are now analyzed to show the application the ξ's, the hyperradius and the deformation indexes for in the search of trends, symmetries and regularities in the data set.

To determine the value of the indexes, namely of the invariant ξ's of each cluster configuration, one can simply observe that from Eq. 3 the following relation can be obtained:

$$ZZ^t = R\Xi\Xi^t R^t \tag{10}$$

where the product $\Xi\Xi^t$ is 3×3 square diagonal matrix, whose entries are the squares of the ξ's. The diagonal entries are just the eigenvalues of the matrix product ZZ^t involving the position matrix. Therefore, starting from a given configuration, one can construct the Z matrix, using the Cartesian components of the atomic position vectors (see Section 2.1), calculate the ZZ^t matrix and diagonalize it, numerically or analitically, by using the well known Cardano's formula for the characteristic equation [46].

Here we consider a series of cluster minima structures, freely available from the Cambridge Cluster Database [63]. In particular, we consider Lennard-Jones (LJ) clusters, with N, number of atoms, ranging from 310 to 561 (see Ref. [64]). In Fig. 1, the deformation indexes are reported, as a function of the cluster size (N), for the minimum energy configurations. The trend shows marked oscillations, interrupted by the occurrence of spherical top configurations.

3 Trends and Classification of ξ's and Deformation Indexes

In this section, we analyze the relationship between deformation indexes and cluster size, and consider possible classifications, using two well known machine learning classification methods. The trend of the deformation indexes as a function of the cluster size N, number of atoms, is shown in Fig. 1. The trend is suggestive of the fact that, despite the central (isotropic) character of the pairwise Lenard-Jones potential (the potential depends uniquely on the interparticle distance), the global minimum structures often depart from the spherical symmetry (symmetric top), indicating that particle particle packaging hinders the spherical symmetry.

3.1 Clustering Analysis by K-Means and Mean Shift Methods

A preliminary characterization of the ξ's generated from the atom cluster structures in the considered dataset can be obtained by looking for possible classifications. Accordingly, the xi's map was analyzed using two unsupervised clustering methods, namely K-means and mean shift, frequently used to obtain classifications of molecular properties. The methods are briefly described below (see also, e.g. [65,66]). Mean-shift clustering is an iterative nonparametric algorithm used to identify clusters in a data set by locating the peaks (modes) of the underlying data density. Unlike methods such as k-means, it does not require one to specify the number of clusters in advance (a possible advantage and a possible limitation), and it is in this sense complemental to approaches that require the number of clusters. The corresponding algorithm starts by estimating the density of the data using a kernel (usually a Gaussian function). This kernel defines a window (or bandwidth) around each data point. For a given data point, the algorithm computes the weighted mean of all points within its kernel window. The difference between this mean and the original point is called the mean shift vector. Each data point is then moved (shifted) in the direction of the mean

shift vector. This process is repeated iteratively: at each iteration, the point's new location becomes the center of a new window. The algorithm continues to shift until convergence, when any subsequent movement becomes negligible, indicating that the point has reached a local maximum (a mode) of the density. Once all points have converged to their respective modes, points that converge to the same mode are grouped together and considered to be part of the same cluster. The mean shift clustering method is a useful tool for discovering clusters by iteratively shifting data points toward the highest density regions and, in this sense, is what we need to locate the ξ subspace for LJ clusters. Its ability to detect clusters without specifying in advance their number and to handle arbitrarily shaped clusters makes it suitable for us. In our case, the idea is to identify the coordinate clusters of shapes in the population of ξ's generated from the set of structures. The results are illustrated in Fig. 1

To complement and validate the Mean Shift results, the population of ξs was analyzed using the K-means method. Clustering of K-means is a widely used partitioning algorithm that groups data into predefined (k) clusters by minimizing the variance in the cluster. The method is iterative and assigns data points, in this case a triple of ξ s, but in the literature there are applications to protein feature vectors or NMR chemical shifts assigning points to a centroid, the nearest one, based on the simple Euclidean distance, then updating centroids as the mean of assigned points until convergence. K-means excel in tasks such as structural classification, conformational clustering due to their scalability and simplicity, achieving accuracies up to 80% in classifying, for example, structures of proteins from chemical shift data. However, it requires specifying the number of clusters k, but here we have a clue from Mean-Shift results. Weak points are obvious sensitivity to outliers and, reportedly, the risk of convergence to local optima, so requiring careful initialization and a kind of preprocessing od data, for an optimal performance. The combined use with Mean-Shift is meant to minimize such effects. However, to have a clue about the choice of the number of clusters, it was also estimated using the elbow criterion, based on the analysis of the within-cluster sum of squared distances (SSD) as a function of the cluster number [67].

4 Results

The analysis of Lennard–Jones cluster structures in the size range $N = 310$–561 reveals some trends in the invariant hyperspherical quantities. The deformation indexes ξ_+ and ξ_-, reported as a function of cluster size (Fig. 1), exhibit pronounced oscillatory behavior, indicating systematic departures from spherical symmetry despite the isotropic nature of the pairwise potential. Only specific cluster sizes correspond to configurations of spherical-top symmetry, confirming that geometric packing effects dominate over the isotropy of the potential energy.

The distribution of the invariant coordinates (ξ_1, ξ_2, ξ_3) in the shape space shows regions, although not clearly well-defined, corresponding to distinct rotational simmetry (oblate, prolate, ...). The application of unsupervised clustering

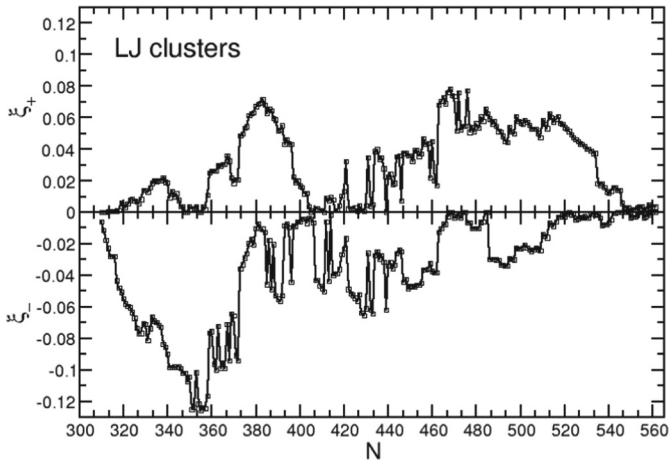

Fig. 1. Cluster deformation indexes as a function of the cluster size (number of atoms) N.

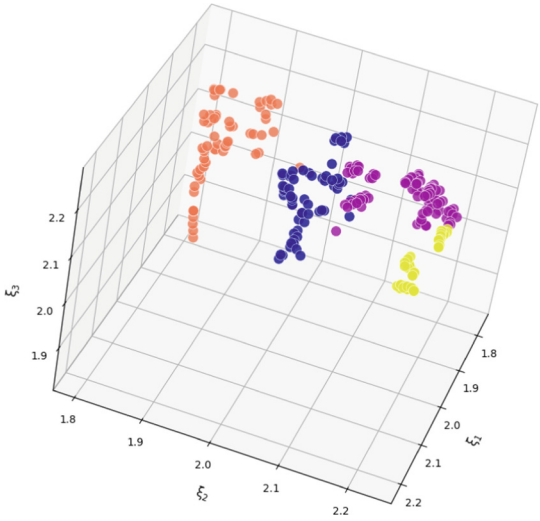

Fig. 2. K-means classification of the ξ's values, based on four different classes (different colors).

techniques provides a quantitative classification of these regions. In particular, K-means clustering identifies four distinct groups in the invariant coordinate space (Fig. 2), suggesting the presence of multiple families of structural packaging. Mean shift clustering, which does not require a predefined number of clusters, detects instead three main maxima of point density (Fig. 3), suggesting the possible existence of underlying structural classes. An estimation of the

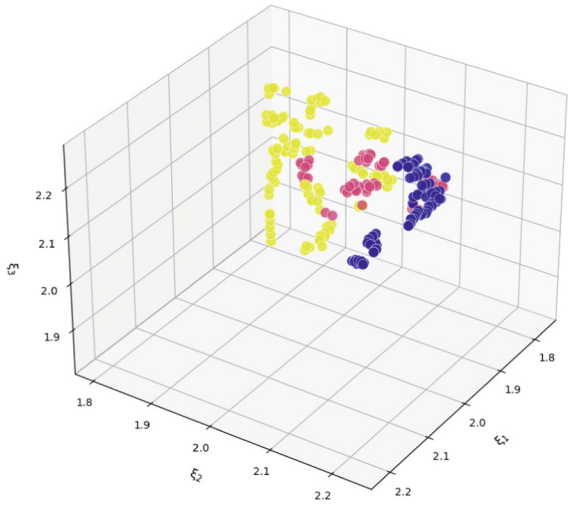

Fig. 3. Mean Shift classification of the values of the ξ's, three classes are identified (different colors).

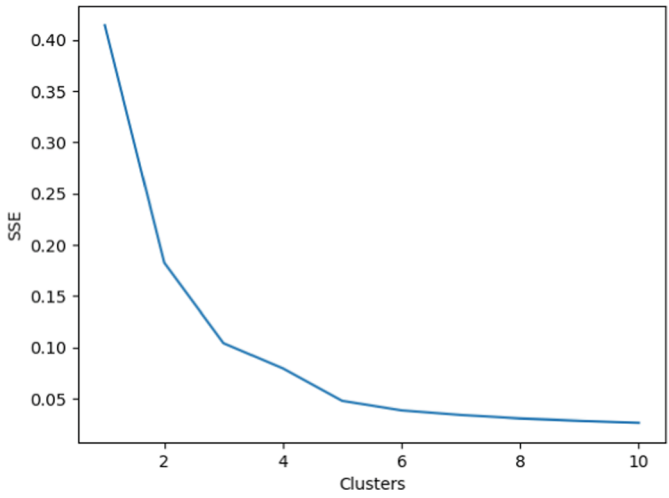

Fig. 4. SSD as a function of the number of clusters.

optimal number of classes was obtained by th so called elbow-method, see Fig. 4, based on the calculation of the SSD.

A similar analysis is performed in the deformation-index space (ξ^+, ξ^-) and shows, similarly, a clear separation of configurations into regions ideally associated with prolate-like, oblate-like, and near-spherical shapes (Figs. 5 and 6). The clustering results, as expected, are consistent with those obtained in the full

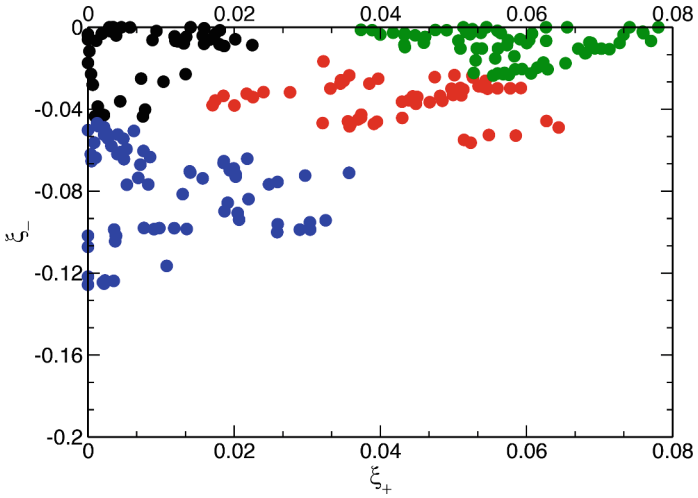

Fig. 5. K means classification of the $\xi_{+/-}$ deformation indexes, for the given structure dataset, $N = 310 - 561$.

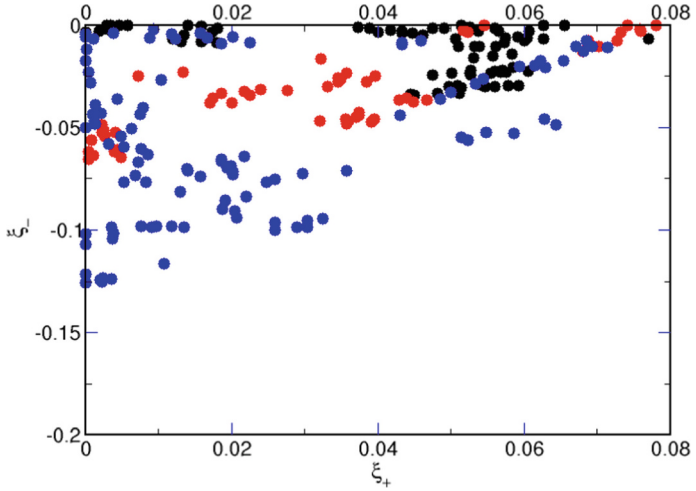

Fig. 6. Mean shift classification of the $\xi_{+/-}$ deformation indexes, for the given structure dataset, $N = 310 - 561$. Three classes are identified.

invariant coordinate space, indicating that the deformation indexes retain the essential information required for structural classification.

The combined use of invariant hyperspherical coordinates and clustering analysis provides a physically meaningful representation of the structural diversity of atomic clusters, enabling the identification of symmetry trends and deformation regimes across a wide range of system sizes.

5 Conclusions and Future Perspectives

In this work, we have analyzed the structure of atomic clusters using invariant descriptors derived from the hyperspherical formulation for general N-body systems. The singular values of the coordinate matrix, interpreted as kinematic invariants, provide a natural and rotation-invariant representation of the cluster shapes, directly connected to the principal moments of inertia and to the classification of rotational tops.

The introduction of deformation indexes based on these invariants allows for a compact quantification of deviations from spherical symmetry and enables the identification of systematic trends in minimum-energy configurations. The results obtained for Lennard–Jones clusters demonstrate that, even in systems governed by isotropic interactions, non-trivial symmetry breaking and deformation patterns emerge as a function of cluster size.

Unsupervised machine learning methods, such as K-means and mean shift clustering, further enhance the classificatory power of the approach. These techniques reveal the existence of distinct families of structures in the invariant shape-space and provide a framework for the classification of molecular configurations.

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From Structural to TRAnsformative-change of City Environment: Challenges & Solutions & Perspectives (TRACE 2026)

Decision Support for Urban Regeneration Through a Territorial Criticality Index

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Abstract. Contemporary urban regeneration processes are increasingly affected by the shortage of economic resources but also by the increasing complexity of territorial contexts; these factors lead to the need of decision-making support tools capable of guiding the definition of intervention priorities in a transparent and comparable way. Within this framework, this paper proposes the development of a composite multi-criteria indicator aimed at identifying urban critical issues in the preliminary planning stages. Moreover the indicator integrates economic, social, and environmental dimensions through a structured process of variable selection, data normalization, and result aggregation, based on the principles of Multi-Criteria Decision Analysis (MCDA).

The methodology is conceived as a flexible and replicable tool, applicable to different urban contexts by adapting the set of indicators without modifying its basic conceptual framework. The approach is tested along the Asse Prenestino of the city of Rome, an urban corridor characterized by marked morphological, functional, and socioeconomic diversity. The results show an uneven distribution of critical issues along the axis and allow for the clear identification of the most vulnerable macro-areas, validating the indicator's effectiveness as a preliminary screening tool. The proposed index does not provide an operational design guidance but suggests a concrete analytical basis for guiding public choices and sustaining informed, comparable, and transparent decision-making processes in complex urban contexts.

Keywords: Criticality Index · Multi-criteria Analysis · Vulnerable Areas

1 Introduction

The growing scarcity of economic, social and environmental resources represents one of the main challenges that characterise urban policies nowadays and, in particular, regeneration processes in large European cities. The intensification of demographic pressures, the reduction in the financial capacity of local authorities and the increase in territorial

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inequalities imply the adoption of decision-making tools capable of effectively and transparently guiding the distribution of public investments. The United Nations 2030 Agenda [1] and the most recent documents of the Organisation for Economic Co-operation and Development (OECD) [2] underline how urban regeneration can no longer be interpreted as a set of specific interventions; it must be directed by a systemic analysis of the territories capable of recognizing those areas greatly exposed to economic, social and environmental vulnerabilities. This uneasy scenario shows that the scarcity of resources translates into the need to strictly define intervention priorities. Public administrations should select the zones where investments can generate the most significant effects, maximizing social returns and avoiding waste of resources. This need is particularly strong in cities characterized by resilient territorial heterogeneity: here spatial inequalities manifest themselves as disparities in income levels, access to services, provision of urban greenery, or quality of the built environment [3]. In the absence of satisfactory analytical tools, the definition of priorities depends on fragmented or weak comparable estimations, with the risk of overlooking particularly vulnerable areas. To address this complexity, literature highlights the growing importance of decision support tools, capable of systematically and transparently guiding public choices based on experimental evidence [4]. Among these, urban indicators represent one of the main tools used to define and assess dissimilar territorial conditions. Economic, social and environmental indicators allow for a multidimensional representation of urban quality, making it possible a comparison among mixed portions of cities through measurable and replicable variables [5, 6]. When complex phenomena become readable information it is particularly useful to start the preliminary phases of urban planning and regeneration procedures. However, when the number of indicators grows and the variables belong to very different domains, there arises the need for tools capable of integrating them and providing a synthetic measure of territorial criticalities. In this context, multi-criteria evaluation approaches (MCDA – Multi-Criteria Decision Analysis) are now broadly recognized as operative methodologies for aggregating mixed information and comparing it according to transparent and reproducible processes [7, 8]. The use of MCDA allows for the combination of economic, social and environmental sides in a single index, so facilitating the identification of priority areas in complex urban contexts characterized by poor resources. In this respect, numerous studies show how these methods are particularly appropriate for the initial screening phases [9]. The Roman context, and in particular the Asse Prenestino, offers a substantial case study for testing the effectiveness of a multi-criteria approach to defining regeneration priorities. The axis, which connects the central hub of Rome Termini with the eastern areas up to the peri-urban sector towards Gabii, passes through a sequence of neighborhoods characterized by deep differences in terms of socioeconomic conditions, infrastructural facilities and environmental quality. Together with consolidated residential areas, there are also places marked by social fragility, reduced quality of public space, limited greenery, high percentages of impermeable soil and property values lower than the city average [10]. This mixture makes the axis particularly suitable for testing the ability of the multi-criteria indicator to integrate different information and provide a synthetic reading of the territorial criticalities, showing strengths and weaknesses. According to this concept, the case study does not represent the main object of the research, but a test bed to evaluate the applicability,

strength and potential of the proposed method. The construction of the multi-criteria indicator is therefore configured as a general methodological contribution, aimed at supporting the definition of intervention priorities in settings characterized by resource scarcity, through a clear and replicable procedure. Compared to existing MCDA applications in urban studies, the proposed approach emphasizes simplicity, transparency and replicability, making it particularly suitable for data-constrained contexts. In this sense, the model is conceived as a preliminary screening tool rather than a fully operational decision-support system.

2 Aim

The aim of this paper is to propose techniques to construct a multicriteria indicator to support decision-making processes, aimed at identifying urban emergencies within a wide urban territory where regeneration interventions may be necessary. The indicator mixes economic, social, and environmental dimensions, providing a concise measure of territorial criticality, useful for the definition of priorities. The tool does not aim to determine how to get involved, but rather to identify where priority should be focused, providing an objective, transparent, and comparable base for the first planning phases. The proposed methodology is designed to be applicable to any urban scenario, adapting the set of indicators to local specificities.

The following part of the paper is organized as described below. Section 3 describes the methodology. Section 4 is dedicated to the presentation of case study and the application of methodology. Finally, in Sect. 5 the conclusions are discussed. Therefore, the practical implications of the research and further insights are illustrated.

3 The Methodology

The methodological approach adopted for the construction of the multicriteria indicator is based on a series of steps and this procedure is divided into: identification of the dimensions of the indicators, definition of the variables to be included, data normalization, assignment of weights and final aggregation.

3.1 Types of Indicators

The construction of the indicator starts from the identification of three large conceptual dimensions, broadly recognized in the literature as fundamental in evaluating the quality and vulnerability of urban scenarios:

- Economic indicators, which describe the level of material well-being, the attractiveness of the area and the dynamics connected to the real estate market. They usually reflect the solidity of the productive fabric, the availability of resources and the economic flexibility of the territory [11, 12].
- Social indicators, which represent aspects linked to the demographic composition, the socio-economic condition of residents, social inclusion, the presence of marginalization or housing pressure. This dimension of indicators allows us to understand the frailty of a community and its ability to support urban renovations [13, 14].

- Environmental indicators, which refer to the ecological quality of the built environment, the availability of green spaces, the permeability of the soil and, more generally, the aspects that influence the sustainability of urban settlements [15, 16].

These three dimensions allow for a multidimensional interpretation of the area, offering an integrated knowledge of its vulnerabilities. The specific indicators selected within each dimension are shown in detail in Sect. 4, related to the case study.

3.2 Indicator Selection Process

The selection of indicators that make up the three economic, social and environmental dimensions was made according to consolidated methodological criteria, which include the following features:

- interpretative relevance, i.e. the indicator's ability to represent a key phenomenon for interpreting critical problems;
- robustness and reliability of data, with preference for indicators available for all areas and derived from institutional sources such as the National Institute of Statistics (ISTAT), the Statistical Portal of the Municipality of Rome, the Higher Institute for Environmental Protection and Research (ISPRA), the Revenue Agency's Geopoi platform, and geomarketing software such as UrbiStat;
- discriminating capacity, i.e. the indicator's ability to show real differences between the portions of territory analysed;
- replicability, so that the indicator can also be applied to urban contexts other than the case study.

The selection process was guided both by literature review and by data availability constraints, ensuring consistency and applicability across the analysed areas.

3.3 Normalization of Indicators

Since the data referring to the indicators have different scales, units of measurement and orders of magnitude, a normalization was carried out in order to report all the variables on a single scale between 0 and 1 [17].

A min–max normalization was adopted, defined by the following formula:

$$x_{\text{norm}} = \frac{x - x_{\text{min}}}{x_{\text{max}} - x_{\text{min}}}$$

The normalization was applied across all macro-areas simultaneously in order to preserve relative differences among territorial units.

This transformation allows for the comparison of mixed values without introducing interpretative distortions.

Two methods were applied according to the nature of the indicator:

- direct normalization, when higher values of the indicator relate to more critical conditions (e.g. unemployment, density, housing pressure);

- inverse normalization, when higher values specify better conditions and therefore must be inverted so that a high value equates to greater criticality (e.g. income, urban greenery, permeable soil).

The use of the combination of the two methods allows for all the indicators to be oriented in the same interpretative direction: higher values of the final index always correspond to more critical conditions.

3.4 Aggregation and Assignment of Weights

Once normalized, the indicator data was aggregated to obtain a synthetic criticality index. Aggregation occurs by combining:

1. the normalized values of the data referring to the individual indicators,
2. the weights associated with each dimension of indicators (economic, social, environmental).

The integration follows the logic of the following multi-criteria models:

$$\text{Criticality index} = \frac{\sum(x_{\text{norm}} \cdot w)}{\sum w}$$

where:

- x_{norm} = normalized value of the indicator,
- w = weight attributed to the category to which the indicator belongs.

The aggregation follows a linear additive model, widely adopted in MCDA applications for its simplicity and interpretability.

The assignment of weights responds to the necessity to balance the relative importance of the three dimensions, avoiding that only one controls the result [18].

The specific values of the weights used in the case study will be shown in the following section, while here it is emphasized that:

- weighting gives coherence to the index;
- the sum of the products normalized value × weight allows us to identify the overall criticality level of each macro-area;
- the index allows for immediate comparison.

The methodology used is part of the broader framework of Multi-Criteria Decision Analysis, which provides a set of flexible techniques for facing decision-making problems characterized by multiple dimensions and even non-homogeneous criteria.

The proposed indicator thus fits within the wider structure of Multi-Criteria Decision Analysis (MCDA), adapting its rules to the peculiar needs of the case study [19].

4 Case Study

The Asse Prenestino is one of the main urban corridors of the city of Rome, extending from the central hub of Termini Railway Station to the eastern area in the direction of Gabii. It is a historical and strategic linear axis, corresponding largely to the ancient Via

Praenestina, one of the most important consular roads of the Roman era, which linked the city with the ancient Praeneste (today's Palestrina). For centuries it was a strategic route for economic exchanges, military movements and the settlement development of the eastern area of Rome [20]. Even today this historical legacy is visible in the urban structure: the Prenestina is still one of the most important crossing axes, capable of connecting the historic centre with the fringe areas and with the peri-urban territories beyond the Grande Raccordo Anulare (GRA).

From a morphological and functional perpective, the axis shows a deep inner heterogeneity. In the central portion, high-density, culturally stratified historical urban fabrics prevail; proceeding towards the east, areas of urban transformation appear: production voids, abandoned warehouses, large linear infrastructures and residential sectors that developed in different ages. Moving towards the GRA (ring road), the continuity of the built environment becomes weaker and leaves space for mixed or fragmented areas; finally, beyond the ring road, the landscape takes on peri-urban connotations, with large agricultural fields and remarkable archaeological sites, such as the Gabii district. This complexity in its structure, functions, and rhythm of transformation makes the Asse Prenestino a particularly significant case for testing using analytical tools aimed at identifying the most critical areas and intervention urgencies.

Figure 1 shows the extension of the Asse Prenestino.

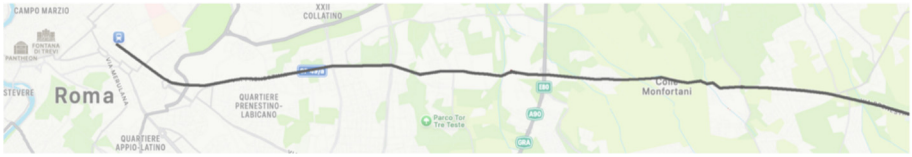

Fig. 1. Representation of the Prenestino Axis.

4.1 Subdivision of the Asse Prenestino

To analyze the territory in a uniform and comparable way, the axis was first divided into three main macro-areas, identified on the basis of territorial continuity, functional characteristics, presence of urban centers, and variations in the morphology of the built fabric. These macro-areas extend from the historic urban core to the Aurelian Walls, from the Aurelian Walls to the Grande Raccordo Anulare, and from the Grande Raccordo Anulare to Gabii, each characterized by a relatively homogeneous territorial identity.

Due to its considerable spatial extension and marked internal heterogeneity, the intermediate macro-area was further subdivided into three sections. This additional articulation allows for a more detailed interpretation of the transitional dynamics between the consolidated urban fabric and the peripheral areas.

As a result, the axis is partitioned into five segments. Although this classification does not rely on official statistical units, it provides a consistent analytical framework for examining the variations in urban structure along the axis.

The sub-macro-areas identified (Fig. 2) are the following:

1. Prenestina 1 – Inner City / Aurelian Walls
2. Prenestina 2.1 – From the Aurelian Walls to Portonaccio
3. Prenestina 2.2 – From Portonaccio to Palmiro Togliatti
4. Prenestina 2.3 – From Palmiro Togliatti to the Grande Raccordo Anulare
5. Prenestina 3 – From the Grande Raccordo Anulare to Gabii

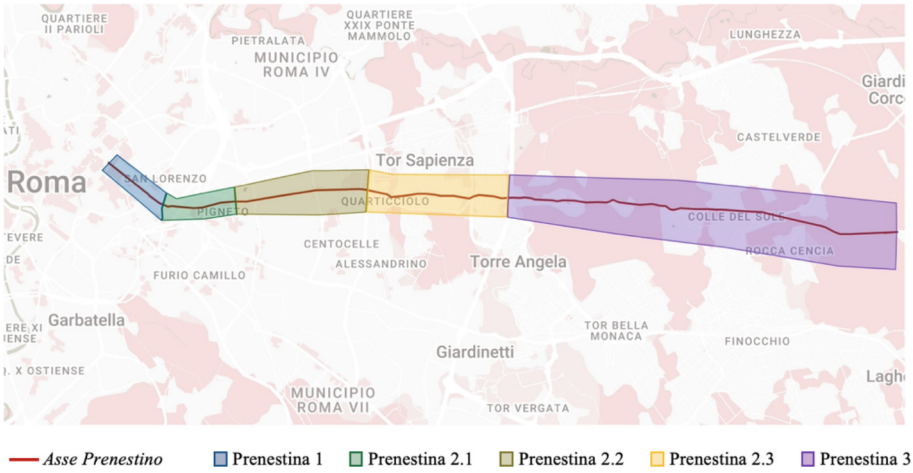

Fig. 2. Representation of the identified sub-macro-areas. Source: authors' elaboration based on Mymaps https://www.google.com/intl/it/maps/about/mymaps

Prenestina 1 – Inner City/Aurelian Walls

The first area identified lies between "Dente Cariato" *(= decayed tooth)*, a derelict structure, and Piazza dei Cinquecento. It is an extremely stratified urban space, featuring overlapping archaeological sites, office buildings, railway infrastructure, and historic buildings. The area is characterized by a solid urban development, intense traffic flows, and complex infrastructure that deeply touches its urban form. Porta Maggiore, the tomb of Minerva Medica, and the abandoned railway areas are key features that reveal both the site's historical value and its critical functional necessities. It is a high-density urban context, culturally significant but affected by congestion, low quality public space, and fragility related to the presence of huge empty areas and abandoned zones.

Prenestina 2.1 – From the Aurelian Walls to Portonaccio

This macro-area is a transitional stretch between the inner city and the easternmost part of the axis. Important legacies of the industrial city can be found here, such as the former SNIA industrial site, today partially redeveloped by the Energy Park and Lake Bullicante. Strong functional heterogeneity characterizes this area: abandoned industrial areas coexist with compressed residential areas, cultural facilities, university functions, small businesses, and large-scale linear infrastructure. This variety of functions and morphologies produce a fragmented urban landscape, with high potential but also critical

problems linked to degraded spaces, development pressures, and a lack of environmental value.

Prenestina 2.2 – From Portonaccio to Palmiro Togliatti
The identified macro-area shows elements of greater residential regularity and the positive existence of green spaces. This is where important historical and cultural landmarks of the area, such as Villa Gordiani and Forte Prenestino, are located. The urban fabric is predominantly residential, with medium-high density, and extensive commercial activities and local services. The presence of widespread green spaces and a consolidated built fabric gives the area a good urban quality, despite the presence of problems related to population pressure, traffic, and discontinuity between certain parts of the neighborhood. Generally, the area is relatively balanced, with reasonable criticalities if compared to the other macro-areas.

Prenestina 2.3 – From Palmiro Togliatti to the Grande Raccordo Anulare
The macro-area is one of the most complex segments of the axis, characterized by a remarkable presence of manufacturing activities, warehouses, logistics facilities, and large mobility infrastructures. The urban landscape is marked by some discontinuous features: manufacturing areas undergoing transformation, irregular lots, large commercial spaces distributed along the road, residual spaces, and a considerably reduced quantity of green space. The proximity to the GRA (ring road) emphasizes the morphological fragmentation, which provokes a weakening of the urban continuity and an increase in impermeable surfaces. This area points out both environmental and socioeconomical strongly critical conditions, as confirmed by the indicator analyses.

Prenestina 3 – From the Grande Raccordo Anulare to Gabii
The macro-area beyond the GRA (ring road), where the axis opens onto a peri-urban and semi-rural environment, is an alternation of scattered settlements, agricultural zones, land use facilities, and archaeological sites of great value, including the Gabii complex. The area also hosts hubs such as Rocca Cencia, currently being decommissioned, and large agricultural sectors along the Ponte di Nona corridor.Population density is remarkably lower than inland macro-areas, and the landscape features a greater presence of permeable soil and open spaces. Despite presenting challenges related to accessibility and the fragmented nature of the built environment, this area is generally less vulnerable than the other ones.

4.2 Indicators Selected for the Case Study

The indicators were selected to avoid redundancy, favoring different but non-overlapping variables in representing the same phenomena, while ensuring their transversal applicability to different territorial scenarios. Within this framework, Table 1 reports the non-normalized values of the indicators selected for each macro-area. All the data reported in the table were obtained from the Urbistat portal based on 2025, an official platform that provides urban statistical indicators derived from national databases. These values form the empirical basis of the analysis and allow us to observe the differences between the areas in economic terms (per capita income and OMI value (i.e. Real Estate

Market Observatory), social terms (population density, unemployment rate, residential buildings, commercial buildings, occupied dwellings, aging index, illiteracy rate), and environmental terms (permeable soil and green space).

Table 1. Unnormalized values of selected indicators.

Indicator	Prenestina 1	Prenestina 2.1	Prenestina 2.2	Prenestina 2.3	Prenestina 3
Per capita income (€)	24,646	24,598	24,586	24,574	24,566
OMI value (€/m^2)	3,429	3,095	2,738	2,416	1,564
Population density (inhabitants/km2)	14,408.80	14,374.50	15,795.90	2,566.90	1,283.10
Unemployment rate (%)	10.4	3.3	4.4	13.9	12.1
Residential buildings (%)	69.7	75.3	80.6	45.2	84
Commercial buildings (%)	30	19.1	18.7	51.7	13.9
Occupied dwellings (%)	80.5	89.7	95.4	91.1	71.2
Old age Index	163.3	189.2	218.3	156.3	96.67
Illiterate (%)	0.2	0.1	0.1	0.4	0.4
Permeable soil (%)	25	30	35	20	45
Green space (m^2/inhabitant)	5	8	12	10	25

Source: authors' elaboration based on data retrieved from the Urbistat portal https://www.urbistat.com/eng/

The preliminary analysis of the unnormalized data allows for an earliest interpretation of the differences between the five macro-areas of the Prenestino area, pointing out the magnitudes and original distribution of the variables examined. This phase is useful for understanding the nature of the observed phenomena and identifying any extreme values and imbalances. Direct observation of the raw values also allows for a grasp of the mixed framework of the Asse Prenestino: some areas are characterized by high population density, others show higher levels of greenery, and still others highlight socioeconomic frailties that are immediately apparent in the original data. Figure 3 shows the trend of the raw values of the economic, social, and environmental indicators. These representations support the first level of interpretation, allowing us to highlight the differences between

the five areas for each variable and predict some of the critical issues that will emerge in the next phase of the multicriteria analysis.

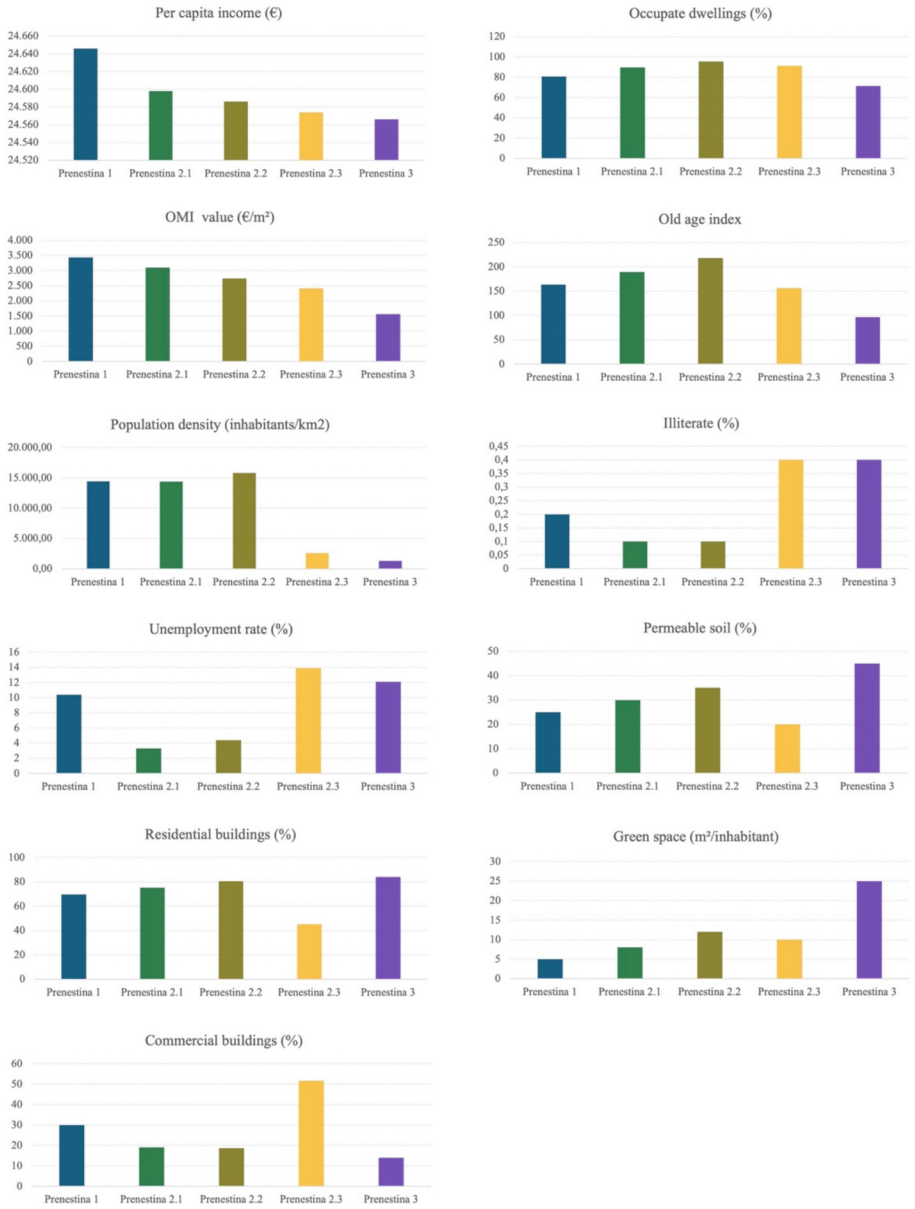

Fig. 3. Graph of the non-normalized indicators for each macro-area identified on the axis. Source: authors' elaboration.

4.3 Normalization of Indicator Values

Due to the different measurement scales and heterogeneous orders of magnitude, the values of the indicators considered are not directly comparable and require a normalization process through which all indicators are reported on a single common scale between 0 and 1 and then transformed into a set of homogeneous indicators. The normalization methods adopted for each indicator are described below, and the normalized data are shown in Table 2.

Table 2. Normalized values of the selected indicators.

Normalization	Prenestina 1	Prenestina 2.1	Prenestina 2.2	Prenestina 2.3	Prenestina 3
Per capita Income	0.000	0.600	0.750	0.900	1.000
OMIvalue	0.000	0.179	0.371	0.543	1.000
Population density	0.904	0.902	1.000	0.088	0.000
Unemployment Rate	0.670	0.000	0.104	1.000	0.830
Residential buildings	0.631	0.776	0.912	0.000	1.000
Commercial buildings	0.426	0.138	0.127	1.000	0.000
Occupied dwellings	0.384	0.764	1.000	0.822	0.000
Old age Index	0.548	0.761	1.000	0.490	0.000
Illiterate	0.333	0.000	0.000	1.000	1.000
Permeable soil	0.800	0.600	0.400	1.000	0.000
Green space	1.000	0.850	0.650	0.750	0.000

Per capita income (€)
Criterion: Inverse normalization

- 0 = area with higher income → less critical
- 1 = area with lowest income → more critical

Why: A lower income indicates lower spending power, social vulnerability, and less residential attractiveness.

OMI value (€/m^2)
Criterion: Inverse normalization

- 0 = area with higher real estate value → less critical
- 1 = area with lowest real estate value → more critical

Why: Low property values may reflect low demand, deteriorating buildings, or poorer urban quality.

Population density (inhabitants/km^2)
Criterion: Direct normalization

- 0 = area with lower density → less critical
- 1 = area with higher density → more critical

Why: Higher density means more urban planning pressure and less public space per inhabitant.

Unemployment rate (%)
Criterion: Direct normalization

- 0 = area with fewer unemployed → less critical
- 1 = area with more unemployed → more critical

Why: A high unemployment rate indicates socioeconomic fragility and potential social hardship.

Residential buildings (%)
Criterion: Direct normalization

- 0 = less residential area → less critical
- 1 = more residential area → more critical

Why: A very high residential share indicates monofunctionality and high housing pressure.

Commercial buildings (%)
Criterion: Direct normalization

- 0 = area with less commercial buildings → less critical
- 1 = area with greater presence of commercial buildings → more critical

Why: A very high percentage of commercial buildings may indicate a functional imbalance in the urban fabric, with a reduced presence of residential spaces and potential congestion, increased local traffic, and a decrease in livability. A high concentration of commercial activities can also put pressure on mobility services, a lack of public spaces, and increased exposure to noise and air pollution. In this sense, a higher percentage is interpreted as an indication of greater urban pressure and potential criticality.

Occupied dwellings (%)
Criterion: Direct normalization

- 0 = area with fewer occupied homes → less housing pressure
- 1 = area with more occupied homes → more critical

Why: More occupied housing means higher effective population density and greater burden on services.

Old age index
Criterion: Direct normalization

- 0 = area with lowest aging index → less critical
- 1 = area with higher aging index → more critical

Why: A high aging index indicates a significant demographic imbalance due to the high proportion of older people compared to younger people. This leads to greater pressure on social and health services, a lower capacity for socioeconomic innovation, and greater overall vulnerability of the region. At the urban level, a very elderly population may face greater difficulties in accessing services, in daily mobility, and in participating in urban transformation processes, contributing to a critical social situation.

Illiterate (%)

Criterion: Direct normalization

- 0 = area with lowest percentage → less critical
- 1 = area with higher percentage → more critical

Why: A high percentage of illiteracy is an indicator of social exclusion and cultural fragility.

Permeable soil (%)

Criterion: Inverse normalization

- 0 = area with more permeable soil → less critical
- 1 = area with less permeable soil → more critical

Why: Less permeability means greater risk of flooding, heat island effects, and less environmental sustainability.

Green space (m^2/ab)

Criterion: Inverse normalization

- 0 = area with more greenery available → less critical
- 1 = area with less greenery → more critical

Why: A low level of greenery reduces the quality of life, healthiness, and social opportunities.

The radar chart in Fig. 4 provides a direct visualization of the multidimensional profile of the five macro-areas, comparing the relative intensity of individual indicators after normalization. The radial representation highlights, through the width and shape of the different "footprints," the presence of heterogeneous configurations among the analyzed areas: some show marked peaks corresponding to specific critical factors, while others present more balanced or distributed profiles. A comparative reading of the trajectories allows for a quick understanding of which dimensions—economic, social, or environmental—contribute most to general vulnerability and to the identification of the zones where critical issues are most concentrated.

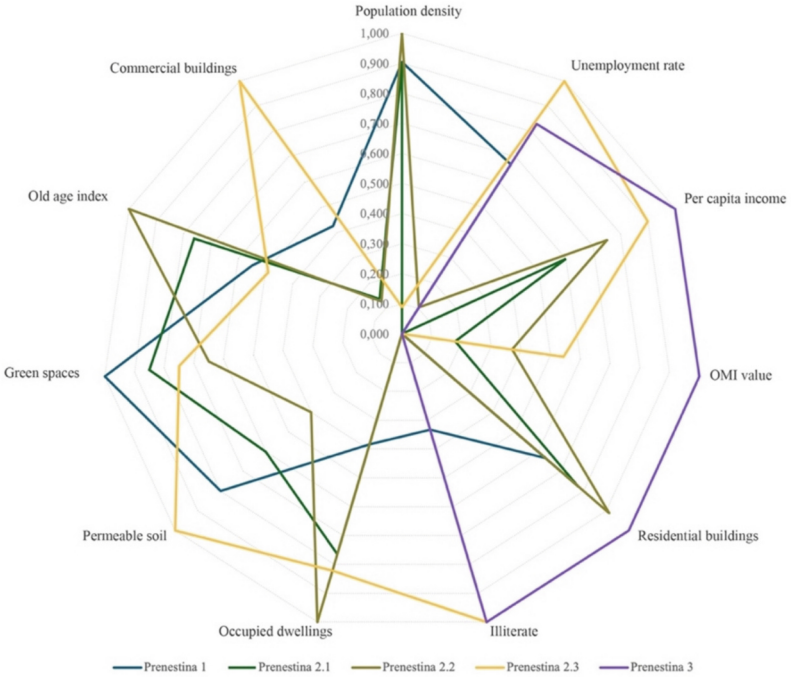

Fig. 4. Graphing of the 5 macro-areas. Source: authors' elaboration.

4.4 Synthetic Criticality Index

To define the synthetic criticality index, it was necessary to assign a weight to each indicator, reflecting the relative importance of the three dimensions considered—economic, social, and environmental—in the overall evaluation process. Consistent with the methodological approach adopted, the choice was made to assign equal overall weight to the three dimensions, thus evenly distributing the relevance of the dimensions comprising the multi-criteria assessment. The assignment of equal weights to the three dimensions reflects the idea that urban criticalities arise from the combined interaction of economic, social, and environmental factors and that no one of these components, in an initial analysis phase, should be considered a priori prevailing over the others. In this way, homogeneous weighting allows for an integrated interpretation of territorial vulnerability, limiting the risk of a single dimension excessively influencing the final result. Therefore each dimension contributes one-third to the final index but, within each dimension, the weight is distributed among the indicators that comprise it. The following structure results:

- Economic dimension → 2 indicators
  - o Overall size weight: 1/3
  - o Weight of each indicator: $1/3 \div 2 = 1/6 \approx 0.1667$
- Social dimension → 7 indicators

- Overall size weight: 1/3
- Weight of each indicator: $1/3 \div 7 = 1/21 \approx 0.047$

- Environmental dimension → 2 indicators
  - Overall size weight: 1/3
  - Weight of each indicator: $1/3 \div 2 = 1/6 \approx 0.1667$

In this way, each of the three dimensions—economic, social, and environmental—contributes 33.3% to the final indicator, preventing a single dimension from becoming dominant and ensuring an interpretative balance between the components of urban vulnerability.

The criticality index is calculated by combining the normalized values of the indicators with their respective weights according to the following formula:

$$\text{Criticality index} = \sum (x_{\text{norm}} \cdot w)$$

where:

- x_{norm} = normalized value of the indicator,
- w = weight assigned to the indicator.

Since the sum of the weights is equal to 1, a subsequent division by the total weights is not necessary. The result obtained (Table 3) represents a synthetic value, between 0 and 1, which expresses the relative level of criticality of each of the analyzed macro-areas, allowing for immediate comparison and the selection of the most vulnerable area.

Table 3. Criticality index values for each macro-area.

Area	Prenestina 1	Prenestina 2.1	Prenestina 2.2	Prenestina 2.3	Prenestina 3
Criticality index	0.483	0.529	0.557	0.739	0.466

4.5 Analysis of the Results

The application of the multicriteria indicator allowed us to obtain, for each macro-area of the Asse Prenestino, a synthetic criticality value derived from the combination of the normalized values and the weights assigned to the three indicator dimensions.The integrated interpretation of the index lets us immediately grasp the internal heterogeneity of the corridor and to outline a hierarchy of territorial vulnerabilities. The analysis of the results clearly shows that Prenestina 2.3 is the area with the highest widespread criticality level. Its value, significantly higher than the value of the other areas, is the result of the negative interaction between economic, social, and environmental dimensions. According to an economic vision, the combination of lower OMI values and a lower average income compared to the rest of the axis suggests the area's low attractiveness and the presence of real estate devaluation dynamics. Beyond that there is a complex social situation, characterized by higher unemployment rates and a less balanced population structure.

From an environmental perspective, the situation appears further intricate by limited soil permeability and a modest supply of urban greenery, factors that contribute to general worse environmental conditions compared to more central or external macro-areas. The Prenestina 2.1 and Prenestina 2.2 areas fall into an intermediate criticality range, presenting values that reflect a heterogeneous territorial condition. In Prenestina 2.1, the indicators show a coexistence of elements of fragility—such as the presence of high-density residential neighborhoods or abandoned industrial places—with more favorable elements, such as proximity to quality green spaces and the presence of emerging cultural functions. Prenestina 2.2, however, shows a slightly better balance: the supply of greenery and the presence of consolidated residential fabrics help mitigate some issues of social and infrastructural nature, even if they do not completely eliminate vulnerabilities related to population density and demographic structure. The corridor's outermost areas, Prenestina 1 and Prenestina 3, present lower levels of criticality. Prenestina 1, despite being located within the inner city, takes advantage of the presence of office buildings, greater accessibility to central infrastructure, and higher property values than other areas. However, heavy urban development and saturation of urban spaces produce a rigid balance between strengths and weaknesses. Prenestina 3, characterized by peri-urban conditions and a lower population density, presents more favorable environmental indicators—such as greater soil permeability and a greater availability of green spaces—which offset the presence of socioeconomic vulnerabilities and distance from major infrastructure and services.

The overall graph in Fig. 5 provides a visual summary of the distribution of critical issues along the Prenestina corridor, facilitating comparative analysis across macro-areas. The clear distinction between the Prenestina 2.3 value and the single one of the other zones highlights the usefulness and efficacy of the multicriteria indicator as a preliminary screening tool.

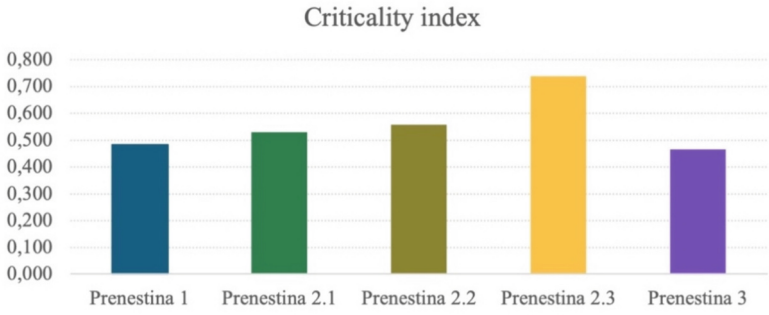

Fig. 5. Graph of the criticality index for each identified macro-area. Source: authors' elaboration.

The confirmation of Prenestina 2.3 as the most problematic area is a fully consistent evidence referring to the observed territorial conditions, and constitutes a basic step towards defining targeted project scenarios, where it is useful to concentrate resources, tools, and urban regeneration policies. This result strengthens the validity of the approach

adopted and gives a significant contribution to the construction of a decision-making process based on comparative analyses and transparent criteria.

5 Conclusions

This analysis demonstrates how the construction of a multicriteria indicator can be a significant tool to support decision-making processes in urban regeneration, especially in contexts characterized by really complex territorial structures and limited resources.

The methodological transparency and replicability of this method represent one of the its strengths: the indicator's structure, based on selected indicators, normalized, and aggregated according to explicit criteria, allows the approach to be adapted to diverse urban scenarios, appropriately modifying the set of indicators without modifying its conceptual structure. Therefore the index operates as a preliminary screening tool, useful for focusing attention on the most vulnerable conditions and sustaining the definition of intervention priorities in the earliest planning phases. At the same time, the approach possesses some core limitations due to its synthetic nature. The index is not planned to describe socio-spatial dynamics in detail or to provide operational design control, but rather to provide an initial understanding for more in-depth analyses. From this point of view, the criticality index does not substitute other assessment tools, but rather suggest a complementary element within a wider decision-making process. A significant side involves the assignment of weights to the various dimensions and indicators [21]. This aspect highlights the sensitivity of the model to weighting assumptions, reinforcing the need for future research aimed at testing alternative weighting schemes and evaluating their impact on the results. This paper aims at the choice of a uniform weighting between the economic, social and environmental dimensions, and responds to the necessity to guarantee interpretative balance and simplicity of application. Yet, this choice opens up possible future developments: the involvement of institutional, technical and local stakeholders in the processes of defining and calibrating the weights could allow for the attribution of a differential significance to the various dimensions based on particular objectives, political priorities or the features of the context analysed, strengthening the participatory and decision-oriented nature of the tool. Further developments refer to the extension of the approach to subcategories, i.e. mobility, accessibility to services, environmental quality or energy efficiency, as well as the integration with more advanced spatial analysis techniques. In this perspective, recent studies highlight how the integration of Artificial Intelligence within decision-support systems can enhance the capacity to interpret and intecetive complex urban dynamics and support faster and more adaptive planning responses [22]. Moreover, the particular attention is referred to identification of shared sustainability indicators and the development of Minimum Indicator Sets can further strengthen the comparability and effectiveness of evaluation frameworks, supporting more coherent and aligned urban policy strategies [23]. Generally, the paper underlines how multi-criteria approaches can offer a flexible basis for addressing complex decision-making problems, and they propose useful tools to guide public choices in a coherent, comparable and informed way.Finally, they can be adaptated and improved over time.

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Context-Based Indicators and Data-Driven Multi-Level Assessments for SDG-Oriented Urban Regeneration

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Abstract. The paper proposes a multi-level comparative evaluation methodology based on a data-driven approach for urban regeneration processes, integrating the targets of SDG 11 with the dimensions of urban quality through a system of indicators articulated on several territorial scales.

The methodology avoids the construction of a single synthetic index, providing for the construction of a correspondence matrix, within which binary relationships between indicators, targets and urban quality classes are defined, allowing the weighting of variables according to their thematic relevance and spatial coherence. The model combines weighting procedures with variance analysis to identify intervention priorities, which are subsequently interpreted through SWOT analysis. The study highlights the potential of a context-based approach oriented towards impact assessment for urban regeneration processes.

Keywords: Evaluation · Urban Transformation · Sustainability · Indicators

1 Introduction

Urban regeneration processes, in line with the principles promoted by UN-Habitat [1, 2], are oriented towards sustainability and require the adoption of assessment tools capable of interpreting territorial transformations in relation to the Sustainable Development Goals by translating the principles of sustainability into measurable objectives and targets [3–5]. In this perspective, urban planning aimed at ensuring lasting benefits requires an integrated approach, which involves the use of tools and methodologies capable of adapting design choices to the specificities of the territorial context. At the European level, the Nomenclature of Territorial Units for Statistics (NUTS) classification [6] ensures statistical harmonization and comparability between regions and metropolitan areas. However, this system does not exhaust the spatial complexity of urban transformations, which often manifest themselves at the local scale of interventions.

The abundance of urban data and the diffusion of indicator systems do not always make it possible to intercept the complexity of urban processes or to support effective assessments of the actions to be taken. On the contrary, if properly interpreted, the

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abundance of data becomes an opportunity for innovative approaches to the planning and management of settlement transformation processes [7].

In recent years, numerous information systems have been developed, such as, for example, the global indicator framework of the 2030 Agenda for Sustainable Development [8, 9], and the database developed by Eurostat [10] which makes it possible to monitor the achievement of the objectives of the European Green Deal [11] by means of twenty-six indicators including, for example, the net index of greenhouse gas emissions, the total economic losses related to climate events and primary energy consumption. These are flanked by numerous thematic databases and territorial observation systems, such as the European Copernicus programme [12], which provides environmental and climate information through satellite remote sensing systems, and services that can be integrated with mapping systems and GIS platforms and territorial geoportals. Classification systems and guidelines for the evaluation of the quality of urban regeneration interventions are also relevant, such as those proposed, for example, in Italy by AUDIS, which identify categories of analysis referring to the environmental, economic, social and morphological-functional dimensions of urban transformation [13]. These approaches are consistent with several international protocols for assessing the urban quality and sustainability of interventions, including the LEED for Cities and Communities, BREEAM Communities and the ITACA Urban Scale protocol, which propose multidimensional frameworks for the evaluation of urban performance and settlement quality [14–16]. Considering the growing availability of data and evaluation tools, there is a need to integrate them into methodological models capable of selecting indicators consistent with both the specificities of the territorial context and with the evaluation objectives of urban transformation processes. GIS-based multi-criteria decision analysis (MCDA) has become increasingly relevant in urban planning studies. These approaches are particularly useful for assessing accessibility, environmental quality, land-use suitability. GIS-MCDA models support the identification of spatial criticalities and potentialities by combining quantitative indicators with territorial representations [17–19]. The study aims to define a multilevel evaluation model aimed at identifying a set of indicators consistent with the evaluation purposes of urban regeneration processes, taking as a reference the targets of the SDGs [20], with particular attention to SDG 11 "Make cities and human settlements inclusive, safe, resilient and sustainable". The proposed method is based on the integration of the NUTS classification systems and the Local Administrative Units (LAUs) adopted by Eurostat, taken as a reference structure for the organization and reading of data. This approach makes it possible to build a coherent analytical framework across different administrative scales, facilitating the harmonization of information and its comparability. In this context, the methodology has been defined in such a way as to ensure coherence, transferability and replicability, and has been applied to a case study in order to verify its operational effectiveness and ability to support evaluation processes oriented towards the definition of urban regeneration strategies. The paper is structured into three main sections. The first section presents the methodological framework, articulated into four phases. The second section applies the methodology to a case study, following its different stages. Finally, the third section discusses the results and presents the main conclusions.

2 Metodology

2.1 Methodological Process

The proposed methodology is based on a comparative and multilevel approach aimed at identifying multidimensional and multiscale indicators that allow to express evaluative judgments aimed at supporting the definition of strategies and actions aimed at improving the conditions present even in contexts on a limited territorial scale. The aim is to interpret the existing conditions and support the identification of priority actions in urban redevelopment processes. The approach assumes an integrated logic that operates simultaneously on two dimensions: a vertical one of a sectoral nature, referring to the different components of sustainability, and another horizontal, of an intersectoral nature, oriented towards grasping the interrelationships between social, economic and environmental aspects. To avoid sectoral readings of urban phenomena, the interpretative framework of the methodology takes as a reference the United Nations Sustainable Development Goals [21]. In particular, the analysis focuses on Goal 11, which promotes the development of sustainable cities and communities and identifies a series of targets directly related to urban transformation processes. The adoption of this reference framework makes it possible to translate global sustainability objectives into operational territorial parameters and to build an evaluation system consistent with the main dimensions of urban quality. After defining the assessment objectives, the methodological process does not provide for a rigid distinction between the analytical phase and the interpretative phase but is configured as an iterative path in which the different phases interact and overlap, as in Fig. 1 [22, 23].

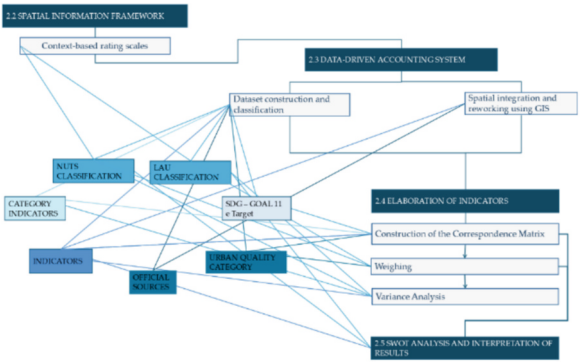

Fig. 1. Methodological process – Source: own elaboration

Context analysis (2.2. Spatial information framework), the construction of the data-driven accounting system (2.3) [24], the elaboration of the indicators (2.4) and the SWOT analysis and the subsequent interpretation of the results (2.5) are in fact interconnected moments of a single evaluation process. This approach makes it possible to structure an analytical framework consistent with the objectives of urban sustainability and to support the definition of strategies and actions aimed at improving the present conditions and

future prospects of the territorial context analyzed, as well as, after their implementation, to measure the results obtained [25–28].

2.2 Spatial Information Framework

The construction of the methodology is placed within a conceptual and informative reference framework that provides for the systematic consultation of institutional and official sources as well as the use of databases recognized at national and European level. From the point of view of sustainability goals, SDG 11 – "Sustainable cities and communities" and its targets (11.1, 11.2, 11.3, 11.4, 11.5, 11.6, 11.7, 11.a, 11.b, 11.c) are identified as an interpretative reference. This framework represents the context within which the data are selected and the system of indicators used in the evaluation process is built. The main sources of information include Eurostat databases, permanent population and housing censuses produced by national statistical institutes and public geoportals of spatial and environmental data, including those made available by ISPRA [29] and the Copernicus program. These sources provide access to demographic, social, economic, infrastructural and environmental information covering a recent and consistent time frame. The use of official sources ensures the comparability of data and allows them to be integrated into a multilevel information system consistent with the territorial classifications adopted at European level. Within this process, it is important to distinguish between data and indicators. Data represent the basic information derived from statistical and territorial sources, while indicators are variables obtained through the processing or aggregation of such data and are used to represent and measure specific urban phenomena. The indicator system enables the construction of a synthetic representation of territorial dynamics and supports the subsequent evaluation phase.

Context-Based Rating Scales

Objectives and magnitude of the intervention determine the evaluation's territorial basis for interpretation. The NUTS (Nomenclature of Territorial Units for Statistics) classification is used at the European level to ensure statistical data comparability and support economic and social cohesion policies. This classification has four territorial levels: NUTS 0 (State), NUTS 1 (regional areas), NUTS 2 (subdivision of the previous level into large territorial areas: north, south, centre), and NUTS 3 (subdivision into circumscribed territorial areas, e.g. metropolitan areas) to interpret socio-economic and territorial dynamics at different scales. These levels are flanked by Local Administrative Units (LAU), usually municipal, which execute numerous local regulations and urban planning instruments. Along with these levels, a sub-LAU scale is created for analytical reasons to characterise special phenomena in certain parts of the municipal territory that often do not match urban transformation intervention regions. This scale, which can be subdivided, is not part of Eurostat's classification but can help analyse urban and social dynamics. Data may refer to territorial boundaries that do not necessarily overlap. This condition necessitates an interpretative strategy that accounts for spatial information's multidimensionality and integrates data across scales.

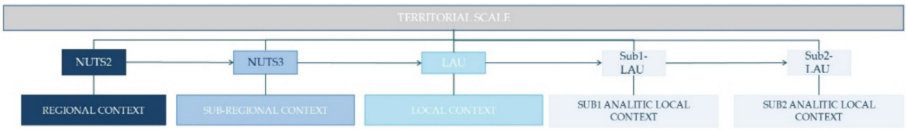

Fig. 2. Territorial scale– Source: own elaboration

2.3 Data-Driven Accounting System

Based on the previously defined reference framework, the available level of information is recognized in order to build a dataset that is consistent with the evaluation purpose. The selection of data/indicators follows three main criteria:

- Territorial coherence in relation to the NUTS/LAU/subLAU hierarchy and the scale of the intervention object;
- Temporal consistency with datasets of recent time frames;
- Relevance to the evaluation objectives by directing the selection towards data relevant to the environmental, social and economic dimensions of urban sustainability, as well as to the targets of SDG 11.
- The survey also makes it possible to verify the type and level of detail of the information available, as well as the presence of data and indicators already georeferenced, an important element for integration into the geographic information system.

Depending on the characteristics of the information available, the indicators derived from the data can be traced back to three main analytical categories, as in Fig. 3.

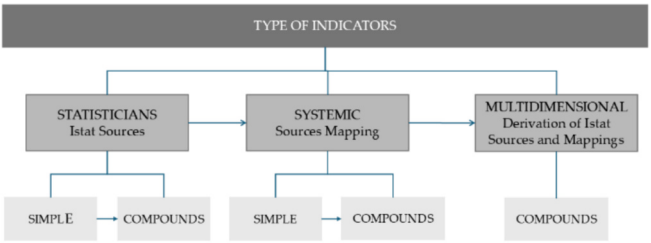

Fig. 3. Type of indicators – Source: own elaboration

In particular, indicators can be divided into different categories according to their nature and the way in which they are constructed. A first category is made up of statistical indicators, which derive from official sources and describe phenomena that can be quantified through direct numerical values. Within this category, it is possible to make a further distinction between simple indicators, when they derive directly from a single data or statistical indicator, and composite indicators, when they derive from the combination or relationship between two or more data or indicators, as in the case of population density. A second category includes systemic, or spatial, indicators derived from official maps and cartographic sources. These can be distinguished into simple indicators, based on direct measurements (e.g., green area per zone), and composite indicators, resulting from the combination of multiple spatial variables (e.g., the ratio between built

and total area). Alongside these, multidimensional indicators integrate statistical and spatial data, enabling a more comprehensive interpretation of urban dynamics. They are particularly relevant in the final analysis phase, as they capture multiple dimensions of the urban context simultaneously. The identification and classification of available information support the construction of a coherent dataset, enhancing the transparency of the evaluation process and providing the basis for assessing the potential impacts of urban transformation processes.

Dataset Construction and Classification

Based on the reconnaissance, the dataset is built and the systematic classification is carried out (Table1). This step allows you to verify the consistency between the level of information available and the objectives of the evaluation to identify the possible need to develop additional indicators.The dataset construction phase translates the criteria identified in the analytical survey into an organized information structure, functional to the subsequent evaluation processing. The purpose of the indicator system is not only descriptive, but also interpretative, as it allows us to build a structured representation of the intervention area and supports planning-oriented assessments.

The construction of the dataset includes a set of common descriptive fields so that each indicator is equipped with a card with the following fields indicated:

- Indicator ID: Progressive number of indicators;
- Indicator: Indicator name;
- Source Survey: source from which the indicator was found;
- Description: Information content of the indicator;
- Determination of the Indicator: formula or method of calculation (method);
- U.M: unit of measurement.

This structure enables the methodological traceability of each indicator.

Each indicator is explicitly associated with the territorial scale of origin, in line with the NUTS/LAU/sub-LAU hierarchy previously defined (Fig. 2). The assignment of the scale is not for descriptive purposes but allows the consistency between the level of the indicator and the level of the intervention to be verified and the subsequent multilevel aggregation to be arranged. At the same time, each indicator is qualified according to the nature of the data, distinguishing between statistical, systemic, and multidimensional indicators as shown in Fig. 3 that they allow you to interpret several dimensions of the urban context simultaneously. The resulting dataset is structured as shown in Table 1.

Table 1. Data Framework - Source: own elaboration

Id	Indicators name	Source	Description	Method	U.M	NUTS 3	LAU	SubLAU	Indicator Statistical (ST)	Indicator Systemic (SY)	Indicator Multidimensional (MU)
n.ID1											
[…]											
n.IDn											

Spatial Integration and Reworking Using GIS
To ensure a context analysis consistent with the evaluation purpose, and therefore the object of transformation, the possibility of producing GIS elaborations aimed at deriving spatial indicators at the local scale through proximity analysis, accessibility analysis and calculation of territorial metrics is envisaged to obtain relevant information at the level of the evaluation under analysis and thus make context-based impact assessments possible. These multidimensional indicators play a fundamental role in describing the functional structure of the intervention area and in identifying the spatial conditions that can support or hinder future urban transformation processes. The information adequacy of the dataset is ascertained by means of a survey in relation to the coverage of the main analytical dimensions of the evaluation system (environmental, social and economic), guaranteed by the availability of indicators referring to coherent territorial levels (LAU and Sub-LAU). On this basis, the correspondence matrix is constructed.

2.4 Elaboration of Indicators

Construction of the Correspondence Matrix
The phases of the methodology indicated so far make it possible to obtain a system of indicators consistent with the scale of the object of intervention. To assume an evaluation function, the criteria identified must be verified in relation to the reference framework articulated in the three dimensions of sustainability and in the targets of SDG 11. To this end, this framework is translated into a multilevel interpretative structure, which allows the different levels of analysis to be organized and related. On this basis, the methodology provides for the construction of a correspondence matrix (Table 2) aimed at explaining the relationships between the criteria considered – the targets of SDG 11 pertinent to urban regeneration processes, the urban quality classes, the territorial level of availability or derivation of the indicator – and the components of the framework.

Table 2. Correspondence matrix - Source: own elaboration

Indicator	SDG 11	Urban Quality Classes				Territorial level		
ID	Target	Urban planning and Architectural	Social	Economical	Environmental and Energy	NUTS	LAU	SubLAu
n.ID1	T.n	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No
n.ID2	T.n	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No
n.IDn	T.n	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No	Yes/No

The correspondence matrix is constructed by assigning a relationship between indicators and targets of the SDGs and between indicators and categories of urban quality and territorial level, based on the conceptual alignment identified in the planning frameworks.

Weighing
Based on the results of the correspondence matrix, the indicators considered most significant for the purposes of the evaluation are selected, as they are more aligned with

the targets of SDG 11 and can be traced back to the main categories of urban quality. Weighting involves assigning weights to the selected indicators considering the following criteria:

1. *Number of SDG 11 targets to which the indicator contributes*: to each iA score equal to the number of SDG 11 targets to which it is aligned is assigned. For example, an indicator that contributes to two targets receives a score of 2; if it contributes to six targets, it receives an equal score of 6.
2. *Number of urban quality classes affected by the indicator*: the score corresponds to the number of urban quality dimensions affected by the indicator. An indicator that responds to two classes receives a score of 2; if it affects four classes, it receives a score of 4.
3. *Territorial level of availability or derivation of the indicator:* the attribution of the score is calibrated in relation to the evaluation purpose and the scale of the intervention analyzed. The score is awarded in relation to the number of scales considered for each indicator: 1 point for one scale, 2 points for two scales, 3 points for three scales and 4 points in the case of a higher number of scalese.

The "raw" weight of the indicator is determined as the sum of the three components:

Weight W_i= (number of SDG targets involved) + (number of quality classes involved) + (scale coefficient). Since the sum of the three components can generate heterogeneous values, the raw weights are then normalized to a scale of 0–1 to ensure comparability in the aggregation phase:

$$w_i = \frac{w_i - w_{min}}{w_{max} - w_{min}}$$

Standardization makes it possible to make the weights of the indicators within the evaluation system comparable.

Variance Analysis

The analysis of deviations is applied only to the indicators selected as significant and aims to assess the relative positioning of the intervention area with respect to the higher territorial levels. For each selected indicator, a comparison is made between average values on the NUTS 2, NUTS 3, LAU, sub-LAU scales. The relative deviation is expressed as a percentage change with respect to the reference level, in order to identify conditions of advantage, delay or criticality. This multilevel comparison makes it possible to avoid isolated readings by highlighting regional and metropolitan dynamics, reinforcing the context-based approach of the methodology. To make the reading comparable, the deviation can be expressed as a relative change from the reference level:

$$\Delta_i = \frac{V_{area} - V_{ref}}{V_{ref}}$$

The deviation is integrated with the weighing to build, for example, a priority criterion that will be included in the subsequent SWOT analysis:

$$P_i = w_i \cdot \mid \Delta_i \mid$$

The indicators can thus be read by integrating, where possible, the normalized weight and the deviation from the territorial level of reference. This priority index makes it possible to combine the relevance of the indicator in the evaluation system with the intensity of the deviation, supporting the identification of the main critical issues and potential of the area according to their significance for the urban regeneration process.

2.5 SWOT Analysis and Interpretation of Results

SWOT analysis is not used as an autonomous qualitative assessment tool, but as the strategic interpretation phase of the quantitative evaluation process. Weighted scores and multi-level deviations are translated into strengths, weaknesses, opportunities, and threats, based on weighted synthesis [30–33]. In the phase of analysis of the deviations, the value of the indicator calculated for the area of intervention is compared with the territorial reference levels. If pedestrian accessibility to commercial services in the project area is higher than the average territorial levels, these indicators can be interpreted as Strengths of the urban system, as they highlight the presence of a good supply of proximity services and an urban structure favorable to pedestrian mobility. On the contrary, if the indicator shows a negative deviation from the territorial context, it can be classified among the Weaknesses of the urban system, indicating a lack of proximity services or poor pedestrian accessibility to commercial polarities or the data is not available at that territorial level. The SWOT does not take on a merely qualitative character but represents the interpretative translation of a structured evaluation process allowing the identification of priorities for intervention, or not, to support the definition of *ex ante* scenarios, *in itinere* and the *ex post* verification of urban transformations. The final output of the multilevel assessment methodology therefore consists of a decision-making framework consistent with the targets of SDG 11, with the urban quality classes and with the territorial specificity of the area subject to intervention.

3 Demonstration Case

3.1 Definition of the Evaluation Objectives

The evaluation methodology described above is applied to a case study for the definition of a possible urban transformation in the metropolitan city of Rome. The structure of the methodological application to the case study explicitly follows the phases and subparagraphs defined in the Methodology section, to ensure consistency, transparency and replicability of the evaluation process.

3.2 Spatial Information Framework

The area subject to application is the district of *Nuova Ponte di Nona*, falling within the Municipality VI of Rome, falling mainly in the Length (8E) urban area and *Acqua Vergine* (8D) for a small portion. It is an urban area, with a predominantly residential fabric, developed since the early 2000s, with the presence of significant commercial polarity (East Rome) and with an urban configuration that highlights morphological

discontinuities. As an interpretative reference, SDG 11 – "Sustainable cities and communities" and targets 11.1, 11.2, 11.3,11.4,11.5,11.6,11.7, 11.a, 11.b,11, c, as reported above in the methodology considered most relevant to metropolitan urban regeneration processes, are applied. The explicitness of the targets in this phase does not have descriptive purposes, but constitutes the basis for: guiding the selection of indicators, verifying the thematic coverage of the dataset, building a correspondence matrix that makes heterogeneous data comparable with respect to shared and measurable objectives.

Context-Based Rating Scales

In line with the multilevel approach, the area is framed within the NUTS/LAU/sub-LAU territorial hierarchy, identifying the levels of comparison of data and indicators useful both for contextual reading and for the analysis of deviations (Fig. 4). In this framework, for the case of intervention, the availability of data referring to two analytical sub-LAUs (Fig. 4) has been identified, which allow to describe, analyze and represent the socio-economic phenomena of the urban scale within which the perimeter of the intervention area is located.

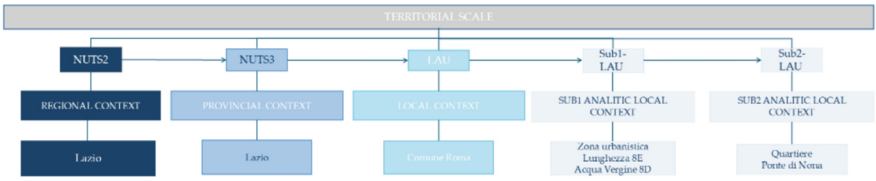

Fig.4. Context-based rating scales: Ponte di Nona - Source: own elaboration

3.3 Data-Driven Accounting System

The data collection was conducted by integrating official statistical sources and georeferenced territorial databases, to build a coherent multilevel information system.

The socio-demographic and housing data were obtained from ISTAT sources grouped in the Statistical Annex (16–12-2024) [34, 35] which contains the permanent census of population and housing, in particular updated data on resident population, age structure, households, housing status, indicators of socio-economic hardship and density.

From these sources, 62 indicators were found available on the LAU scale (Municipality of Rome) and on the two analytical articulations sub1-LAU1 (urban areas 8E and 8D) relating to: total resident population and by age group; incidence of foreigners; population density; number of families; housing crowding index; employment/unemployment indicators. Among the available indicators, those referring to the 8E area were selected, as the data relating to the 8D area, limited to the small portion of the urban fabric in which Ponte di Nona falls, were not sufficiently representative for the purposes of the analysis. From the Geoportal of *Roma Capitale* [36] 28 indicators were extracted on a sub2-LAU-scale relating to: i) public services (schools, libraries, health facilities; ecc); ii) small equipment (fountains, dog areas, parking, columns, ecc).Although some of the indicators are also available at higher territorial scales, the analysis was conducted

with reference to the sub2-LAU scale, corresponding to the Ponte di Nona district, as it coincides with the intervention area. Consequently, for the purposes of the evaluation, the indicators referring to this level were selected and processed as a priority, ensuring consistency between the information base and the scope of application.

Dataset Construction and Classification

In line with the methodology, the dataset is constructed in such a way as to organize the available information as an information base for the evaluation phase (Table 3). Each indicator is associated with a descriptive sheet that explains an identification code, the indicator, the source, the description, the method of determination, the unit of measurement, the distinct territorial scale as in Fig. 2 and the type subdivided as in Fig. 3.

Table 3. Extract of the compiled dataset - Source: Own Elaboration

Id	Indicator	Source	Description	Method	U.M	LAU	Sub1 LAU	Sub2 LAU	ST indicator	SY indicator	MU indicator		
1	Population density -	Istat, Territorial Bases - Year 2021	Ratio between the population residing in the area and the relative surface area in square kilometers of the area	Density = population/area	ab/km^2	Yes				Yes			
2	Total resident population	Istat, Census of population and housing Territorial Bases - Year 2021	Total population excluding homeless	point value from the Cesus/Registry	n	Yes	Yes		Yes				
[n]		[…]	[…]	[…]	[…]	[…]	[…]	[…]	[…]	[…]			[…]

Of the 90 indicators identified, 62 are directly available at the LAU and sub1-LAU scales and contribute to the definition of the socio-demographic framework of the context (SDGs 11.1, 11.3). The remaining 28 indicators of a territorial nature are not immediately available in the required form and require derivative processing, as they are aimed at representing spatial relationships and functional characteristics of the territory. To this end, spatial analysis techniques such as geographically based counting and proximity analysis using GIS tools are used.

Spatial Integration and Reworking Using GIS Tools

In order to obtain quantitative and qualitative information on the area under study, in this case coinciding with the sub2-LAU classification, and to bridge the gap between the administrative scale of the data and the actual scale of the urban intervention, GIS elaborations were carried out that allowed to derive more specific indicators at the local scale through: precise allocation of equipment; buffer construction (300–500 m); calculation of pedestrian isochrones (10–15 min); calculation of percentage indices (built area, land consumed).

The use of GIS software has made it possible to obtain new derived information, such as proximity and accessibility to public services, the distribution of green areas, or

the percentage of housing built in the area. The spatial measurement of indicators was carried out through GIS-based processing at the sub2-LAU scale, corresponding to the intervention area. Buffer distances of 300–500 m and pedestrian isochrones of 10–15 min were adopted to approximate neighborhood-scale accessibility conditions. In particular, 12 multidimensional indicators have been identified, considered sufficient to represent the main dimensions of the urban system as they allow us to build a detailed analytical description of the intervention area, integrating the contextual information provided by the indicators available at the higher territorial levels. In the case study analyzed, the availability, albeit limited, of indicators derived from the scale of the intervention area made it possible to orient the evaluation towards this territorial level, as it is more consistent with the actual scale of the urban transformation process. The sufficiency of the information of the dataset was verified by checking the coverage of the main analytical dimensions of the evaluation system (environmental, social and economic), which were adequately represented by indicators of the Sub2-LAU level. On this basis, the correspondence matrix was constructed.

3.4 Elaboration of Indicators

Construction of the Correspondence Matrix

To avoid sectoral readings and link the global objectives to local urban specificities, the SDG framework is integrated with the urban quality classes recognized in many classification systems and guidelines for the evaluation of the quality of urban regeneration interventions and in the AUDIS framework, divided into: urban and architectural quality, social quality, economical quality, environmental and energy quality. The integration of SDG 11–urban quality, applied within the NUTS/LAU hierarchy, constitutes the interpretative basis for the application analysis. The correspondence matrix developed for 102 (68 statistical, 28 systemic, 12 multidimensional) indicators to which correspondence to the target and to the indicated urban quality is associated. This operation allows to select the indicators most consistent with the evaluation system, which will subsequently be used for the SWOT analysis and for the evaluation phase. Table 4, by way of example, shows some indicators selected by category, to illustrate the method of association between indicators, SDG 11 targets, urban quality classes and territorial levels adopted.

Table 4. Extract Correspondence matrix – Source: own elaboration

Indicator	SDG 11	Urban Quality Classes				Territorial Level		
ID	Target	Urban planning and Architectural	Social	Economical	Environmental and Energy	LAU	Sub1 LAU	Sub2 LAU
[…]								
ST6	11.3			Yes				Yes
[…]								
ST8	11.3		Yes				Yes	
[…]								
ST18	11.3		Yes				Yes	

(*continued*)

Table 4. (*continued*)

Indicator	SDG 11	Urban Quality Classes				Territorial Level		
ID	Target	Urban planning and Architectural	Social	Economical	Environmental and Energy	LAU	Sub1 LAU	Sub2 LAU
[…]								
ST21	11.3		Yes	Yes				
[…]								
ST31	11.1		Yes	Yes			Yes	
[…]								
ST42	11.3 11.7 11.a	Yes	Yes				Yes	
[…]								
ST56	11.1	Yes	Yes	Yes	Yes		Yes	
[…]								
MU64	11.1 11.3 11.a	Yes	Yes	Yes		Yes	Yes	Yes
[…]								
SY78	11.3	Yes	Yes	Yes			Yes	Yes
SY80	11.3 11.a	Yes	Yes				Yes	Yes
[…]								
MU82	11.a 11.3 11.6	Yes	Yes	Yes	Yes			Yes
[…]								
MU88	11.3 11.6 11.7	Yes	Yes	Yes	Yes			Yes
[…]								

Weighting

Based on the indicators selected through the correspondence matrix, the weighing phase is carried out, aimed at quantifying the relative relevance of each indicator within the evaluation system in respect to the Sustainable Development Goals. Table 5 shows the raw weights and the corresponding normalized values, calculated according to the methodology (see paragraph 2.4).

Table 5. Weighing Extract – Source: own elaboration

ID	Indicator	Wi Raw weight	wi Normalized weight
[…]			
ST6	Old-age index	4	0,17
[…]			
ST8	Prevalence among young people aged up to 24	3	0,00
[…]			
ST18	Employment rate (aged 20–64)	3	0,00
[…]			
ST21	Proportion of households at risk of financial hardship	4	0,17
ST22	Proportion of substandard housing	4	0,17
[…]			
ST31	Average property value of residential dwellings	4	0,17
[…]	…		
ST42	Total number of schools	6	0,50
[…]			
MU64	% of residential buildings in the area	8	0,83
[…]			
SY74	Car-sharing parking spaces	7	0,67
SY78	Libraries	6	0,50
[…]			
MU82	Walking distance to local shops: 10 min	8	0,83
[…]			
MU88	Index of tree-lined areas within the local area	8	0,83
[…]			
MU90	Detached and semi-detached houses	7	0,67

The normalized weights were calculated by a linear transformation on a scale of 0–1, using the minimum and maximum values of the raw weights (Wmin = 3; Wmax = 9). This operation made it possible to preserve the relative differences between the indicators, while ensuring comparability in the aggregation phase. It should be noted that indicators with a weight of 0.00 will not be used directly in the construction of the priorities envisaged in the analysis SWOT.

Variance Analysis

Only metrics where the sub1-LAU level and territorial reference level LAU could be

compared were analyzed for deviations. The indicators in Table 6 were selected using the aforesaid approach to analyses deviations for application. This decision preserves the analytical framework's completeness, avoiding the omission of key indicators, while preserving quantitative comparison methodological consistency. The deviation sign is unchanged from the observed values. Thus, greater levels imply favorable conditions for positive indicators and crucial situations for negative indications.

Table 6 shows an excerpt of the results of the variance analysis for a subset of selected indicators, to illustrate the calculation procedure.

Table 6. Variance (example) - Source: own elaboration

ID	Indicator	Δi Variance	wi Normalized weight	Pi
[…]				
ST6	Old age index	-0,36	0,00	0,00
[…]				
ST22	Rate of improper housing	-0,99	0,17	0,17
[…]				
MU64	% Residential buildings on the territory area	-0,88	0,83	0,11
[…]				

The findings indicate a partial compliance with SDG-related indicators, although do not indicate favorable demographic or housing conditions; rather, they highlight a context of socio-demographic fragility, housing inadequacy, and limited service provision, which constrain the overall performance of the urban system.

3.5 SWOT Analysis and Interpretation of Results

SWOT analysis, the interpretative synthesis of quantitative results, yields a framework in which the main strengths are a basic endowment of services, fair pedestrian accessibility, and the availability of school equipment, which create relatively favourable conditions compared to the reference context and provide an infrastructural base for urban quality interventions. These elements have strong structural criticalities. The key drawbacks include restricted public rail access, a largely residential and low-density urban form, and fragmented proximity services. Demo-graphic dynamics can contribute to a socio-territorial picture of fragility. This presents numerous big opportunities. Public housing and basic services can help implement integrated urban regeneration policies and proximity-based settlement patterns. Green spaces, albeit undervalued and under integrated into the urban system, have untapped potential that can be realised via focused redevelopment and enhanced connectivity. However, risk factors remain. Limited local services and housing vulnerability may exacerbate functional marginalisation and private car dependence, lowering quality of life and social inclusion.

From this evidence derives the opportunities and threats that guide the priority actions of intervention as summarized by the SWOT Analysis reported in Table 7.

Table 7. SWOT Analysis - Source: own elaboration

S Indicators	⊕ **Strengths**	**W** Indicators	⊖ **Weaknesses**
ST42 MU82 MU83 MU84 MU88	Presence of basic services in the local fabric; Discreet pedestrian accessibility to proximity services; Presence of school equipment; Provision of green spaces, with potential for urban enhancement and integration; Proximity to the main road network (Grande Raccordo Anulare).	ST6 ST56 MU64 MU82 MU83 MU84 MU90	Limited accessibility to public rail transport; Urban structure with low density and prevalence of residential; Fragmentation of proximity services; Socio-demographic fragility of the context.
O Indicators	⊕ **Opportunities**	**T** Indicators	⊖ **Threats**
ST42 MU60 MU84 MU88	Presence of ERP assets as a regeneration lever; Potential development of the 15-minute city; Potential redevelopment and enhancement of the green system; Integration between services, sustainable mobility and public space.	ST22 SY72 SY76 SY77 SY78 SY80	Risk of functional marginalization; Risk of functional polarization of the urban system around the shopping center; High dependence on the car; Poor enhancement of public spaces and greenery.

The SWOT analysis, built on the integration of weights and deviations, allows us to identify the priorities for intervention in a structured way. These priorities have been translated into a system of strategies (Table 8), defined according to a binary correspondence: SO – Strategies (Strengths–Opportunities), WO – Strategies (Weaknesses–Opportunities), ST – Strategies (Strengths–Threats), WT – Strategies (Weaknesses–Threats).

Table 8. Strategic Implications (SO, WO, ST, WT)- Source: own elaboration

SO – Strategies (Strengths–Opportunities)
Enhancing the green system to build an integrated urban ecological network Strengthening proximity services to support the 15-min city model Integrating schools and services as multifunctional civic hubs
WO – Strategies (Weaknesses–Opportunities)
Regenerating ERP assets to increase functional mix and urban density Enhancing sustainable mobility to compensate for weak rail accessibility Reorganize fragmented services by creating local centralities
ST – Strategies (Strengths–Threats)
Strengthening and diversifying local services to reduce trade polarisation Enhancing and connecting the existing green system to structure an urban ecological network Using schools and services as social anchors
WT – Strategies (Weaknesses–Threats)
Reducing car dependency through alternative mobility Increase functional density by adding new services Activate social inclusion policies

4 Discussion and Conclusions

The application of the proposed evaluation model demonstrates the effectiveness of a data-driven and spatially explicit approach for integrating heterogeneous indicators across multiple territorial scales, enabling a multilevel interpretation of urban systems.. By combining socio-economic, morphological, and accessibility-related variables within a unified analytical framework, the model supports a comprehensive assessment of urban performance that goes beyond purely descriptive analysis. The results indicate that the indicators exerting the highest influence on the evaluation outcomes—namely low settlement density, fragmentation of the urban fabric, and limited accessibility to major transport nodes—have a statistically significant impact on overall system performance. This finding suggests that urban criticalities are not primarily related to the mere availability of services, but rather to the structural capacity of the urban system to ensure their effective accessibility, spatial distribution, and functional integration. In this respect, accessibility emerges as a key latent variable, mediating the relationship between physical infrastructure and actual service usability. Particular attention is given to multi-scalar indicators, especially those related to pedestrian accessibility and spatial proximity. Although these indicators are not always directly comparable across different territorial scales due to issues of normalization and data resolution, they provide analytically robust insights into local spatial dynamics. Their inclusion allows the identification of spatial patterns and latent territorial characteristics that are not captured by conventional statistical indicators alone, thus reinforcing the interpretative depth of the model. The comparison between administrative indicators and spatially derived metrics highlights a critical methodological aspect. While administrative data provides a standardized and comparable framework, they often result in a partial and static representation of urban phenomena. Conversely, the integration of GIS-based spatial elaborations enables the capture of relational and network-based dynamics, offering a more accurate representation of urban complexity and functional interdependencies. The relationship matrix and associated weighting scheme represent each indicator's relative value in the evaluation framework. The weighting procedure, based on statistical dispersion measures and expert-driven calibration, gives environmental quality, accessibility, and urban compactness variable importance depending on the regeneration strategy and territorial context. This flexible framework makes the model more adaptable to different planning circumstances. Study methodological flaws are also revealed. First, deviation and variance studies are limited to a selection of indicators due to data availability and resolution differences among territorial sizes. This issue shows that spatial planning data infrastructures need more harmonization and interoperability. Second, although consistent with normalization and weighting processes, indicators with zero or negligible weights raise important problems about variable selection and model sensitivity. It emphasizes the need for sensitivity and robustness assessments to assess results stability under different weighting methods. The integration of weighting procedures with variance-based analysis enables a transition from a purely descriptive framework to an evaluative and decision-oriented approach. A SWOT analysis should not be seen as a qualitative add-on, but as the practical translation of a quantitatively grounded priority framework. Strategic actions like improving accessibility networks, rebalancing service distribution, promoting selective densification, and valuing environmental assets are directly derived

from the model's analytical outputs and consistent with the main structural weaknesses identified. Future methods may allow stakeholders to choose indicators, design weighting systems, and analyze outcomes. Integration would improve technical evaluation and decision-making, legitimizing and contextualizing planning outcomes. Integrating dynamic and time-dependent metrics to track urban system evolution is another development. Time-series analysis and longitudinal datasets would improve the model's urban transition monitoring and evaluation. Multi-temporal, adaptive decision-support system for strategic planning and policy changes is possible using the framework.

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From Text to Economic Exposure: Measuring Intrinsic Risk in Urban Real Estate

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Abstract. Corporate disclosures usually describe the firm's strategies, expectations, and perceived risks. Beyond purely numerical indicators, these narratives provide a broader and often more nuanced view of the firm. In this sense, working with textual information allows researchers to capture and organize these insights in a more structured and meaningful way. The starting point of this paper is that traditional classifications, such as sector categories or fixed developer typologies, are often too rigid to reflect the diversity of the firms that are operating in the built environment. In practice, mixed-use models, infrastructure-linked assets, and the changing nature of urban functions tend to blur these boundaries. For this reason, the study has adopted an approach that considers firms as interpreters of economic and urban change, drawing on their own published language to capture underlying exposure. The empirical strategy builds a textual corpus for each firm, using sources such as regulatory filings, investor presentations, earnings calls, and business descriptions. Embeddings then convert these texts into semantic representations, enabling them to position firms within a continuous economic space. Rather than assigning each firm to a single category, similarity within this space is used to infer partial exposure to different economic narratives. This makes it possible to identify shared sensitivities to structural drivers, such as financing conditions, tenant composition, logistics demand, retrofit pressures, technological change, and urban redevelopment. Afterward, it incorporates these semantic exposures into a multi-factor risk model, which distinguishes common structural risk from firm-specific residual risk. By incorporating semantic exposures into a multi-factor risk model, the analysis distinguishes common structural risk from firm-specific residual risk. Real estate benefits particularly from this framework. Interest-rate shocks, liquidity stress, and capital allocation changes can alter firm risk in real estate before conventional classifications fully capture these alterations. More broadly, the study links firm-level narratives, asset pricing, and urban transformation, showing how the analysis of corporate text can contribute to a more adaptive understanding of risk.

Keywords: real estate · urban transformation · capital allocation · risk · semantic embeddings · natural language processing

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1 Introduction

Urban real estate firms operate where financial markets, spatial change, infrastructure development, demographic shifts, and regulations meet. Their risk profile is not shaped just by accounting figures, asset values, or formal classifications. Interest rates also influenced it, as well as refinancing issues, tenant demand, logistics, energy availability, climate change, and redevelopment cycles. Many of these factors appear in company communications before they affect market prices. Annual reports, regulatory filings, investor presentations, business descriptions, and earnings-call transcripts give insights into how firms perceive and communicate changes in the built environment.

The focus of this paper is on dispersed economic knowledge. Hayek argues that relevant economic knowledge is spread among many actors; it is often local, contextual, and incomplete [1]. This is particularly true for urban real estate, where firms hold specific information about tenants, financing conditions, asset degradation, infrastructure limits, regulations, and local demand. Corporate narratives partially reflect how firms understand their economic surroundings. Although these documents are not impartial and may use strategic language, they contain organized information that can be systematically examined.

This paper builds on existing literature that uses text as data in economics and finance. Tetlock shows that media language reveals investor sentiment and financial outcomes [6]. Loughran and McDonald point out that financial language needs particular handling, especially in corporate filings [3]. Baker, Bloom, and Davis use newspaper text to create a measure of economic policy uncertainty [5]. Gentzkow, Kelly, and Taddy offer a general framework for using text as data in economics. Additionally, Hassan et al. review recent applications of textual analysis in economic research, firm disclosures, and risk narratives [2, 4].

Another relevant body of work uses corporate text to assess firm similarity and economic classification. Hoberg and Phillips build text-based industry networks from 10-K product descriptions, illustrating that language can measure firm similarities beyond fixed industry codes [10]. Their related research also uses text used to study product-market synergies and competition [11]. Bybee, Kelly, Manela, and Xiu show how large-scale business news can be turned into topic-based measures of economic conditions [12]. These studies indicate that textual data can yield organized economic variables.

The paper also draws from portfolio theory and factor-risk modeling. Markowitz draws attention to the importance of variance and covariance in portfolio selection [8]. Fama and French reveal that common risk factors explain shared variations in asset returns [13]. Fisher's theory of interest provides a basic account of discounting, time, and valuation [7]. Kelly, Pruitt, and Su connect observable firm characteristics to conditional risk exposures [14]. This paper follows the general structure of factor models but suggests that firm stories can create continuous semantic exposure matrices to complement or partially replace fixed industry classifications.

In spite of these contributions, several gaps exist. First, much of the text-as-data research focuses on sentiment, uncertainty, topic frequency, or product-market similarity. There has been less focus on turning firm narratives serving as economic exposure vectors for risk assessment. Second, traditional sector classifications impose rigid boundaries on firms whose business models are usually mixed. A real estate firm may have simultaneous

exposure to logistics, data infrastructure, healthcare demand, redevelopment, energy limits, or urban densification. Third, urban real estate studies often examine asset values, locations, regulations, and spatial changes, but less often link firm-level narratives to structure financial risk estimation. This creates a gap between qualitative analysis and quantitative risk assessment.

This paper discusses that gap by supplying a method for converting corporate accounts into semantic economic exposures. The contribution is in the technique. The goal is not to suggest that written material alone can gauge risk, or that corporate disclosures offer an unbiased view of reality. Instead, the paper proposes a standardized approach for cleaning textual information, converting it into embeddings, comparing it with meaningful economic categories, and normalizing the results into exposure weights. This approach is consistent with emerging research in urban decision-making, which emphasizes the integration of Artificial Intelligence with structured evaluation frameworks to bridge qualitative and quantitative dimensions in complex urban systems [15].

The proposed method unfolds in five steps. First, a firm-level corpus is created from corporate disclosures, including annual reports, regulatory filings, investor presentations, business descriptions, and earnings-call transcripts. Second, the texts are processed to eliminate duplicates, generic phrases, or uninformative content. Third, each firm corpus and each reference economic category are transformed into vector representations using a specified language-embedding model. This development relies on modern natural language processing, including attention-based architectures, contextual language models, and sentence embeddings designed for comparing semantic similarity [16–18]. Fourth, the semantic similarity between each firm and each category is calculated, for instance, using cosine similarity. Fifth, a parameter controlling the spread or focus of the resulting exposure profile converts into continuous exposure weights. A low value allows firms to maintain broad hybrid exposures, while a high value creates sharper classifications that correspond more closely with traditional categories.

This work is presented in three stages. First, Sects. 2 and 3 lay the conceptual groundwork of the proposal by connecting dispersed knowledge, economic coordination, and the role of firms as interpreters of transforming economic conditions. Second, Sects. 4 to 6 present the central methodology of the paper: using text as data, representing corporate narratives semantically, and transforming semantic similarity into economic exposure. Third, Sects. 7 and 8 apply this system to risk assessment and urban capital allocation, showing how semantic exposures can help measure intrinsic risk in the built environment. Section 9 concludes with a summary of the contributions, limitations, and future research directions.

2 Dispersed Knowledge and Economic Coordination

A central problem in economics concerns how societies coordinate production and allocate scarce resources. The knowledge relevant to economic decision-making is not concentrated in a single authority but dispersed across different actors, like individuals, firms, places, and institutions in general [1]. Prices, contracts, and organizational routines help to aggregate part of the knowledge, although a significant share remains embedded in local judgments, tacit capabilities, and expectations about the future.

This issue becomes particularly visible in sectors such as real estate (the sector that encompasses the largest share of global assets in the form of land, buildings, and infrastructure) and urban development. In these contexts, the determinants of value extend beyond current cash flows and include factors such as regulation, land-use constraints, financing conditions, technological change, demographic trends, and neighborhood transformation.

From this perspective, the economy can be seen as a system of distributed interpretation. Firms do not simply react to market signals; they also generate and communicate their own interpretations of changing economic conditions. Through disclosures, strategic plans, earnings presentations, investor materials, and regulatory filings, firms reveal how they understand the opportunities, risks, and competitive pressures. These narratives not only provide information to shareholders for buying or selling company shares but also offer a window into the underlying diversity of the economy. They reflect differences in business models, capital intensity, exposure to interest rates, sensitivity to urban demand, technological adoption, and organizational strategy. In this sense, corporate disclosures become an important medium through which dispersed knowledge becomes partially observable, provided that appropriate tools and methodologies are used for analysis and decision-making.

This insight is particularly important for capital allocation. In standard neoclassical frameworks, resource allocation is often described as the outcome of relatively clean price signals. In practice, however, investors and managers must interpret information that is incomplete and constantly evolving. This implies that a substantial amount of relevant information may not be fully reflected in prices, and can therefore be extracted to improve forecasts of future prices by analyzing the institutional processes used to produce, share, and evaluate firms' conditions. Firms compete not only in goods and asset markets but also in the credibility and clarity of the narratives they present about their future prospects. Market valuations capture more information than the value of their assets; they capture a stream of interpreted expectations about their growth, resilience, or exposure, which implies that the systematic collection of information is in itself a productive activity. Managers gather information to evaluate investment opportunities, identify rivals, benchmark performance, anticipate regulatory changes, and detect shifts in consumer demand. Analyzing the functioning of urban sectors, especially those highly dependent on the real estate market, becomes particularly complex; asset values present cross-dependencies with multiple overlapping spatial processes that include: i) sociological factors such as migration, local labor demand, or the household family model in the area, ii) extrinsic urban factors such as location, infrastructure, or zoning [19], or iii) economic factors such as financing costs. No single metric can fully capture these dynamics, so the language firms used to describe their activities become an additional source of evidence on where economic change is taking place and how capital may be reallocated.

The increasing digitization of corporate communication further expands the ability to capture this complexity. While earlier research often relied on balance sheet variables or broad industrial classifications, more recent empirical work incorporates richer textual signals. These signals do not resolve the problem of dispersed knowledge; rather, they allow agents to observe additional elements and make new decisions that influence

market prices, thereby altering the information conveyed by those prices. They allow researchers to examine the way firms classify themselves, how they frame risks, how they describe strategic adaptation, and how they position their activities within broader economic and urban systems. In this way, published information becomes both a decision tool for firms and an empirical proxy for otherwise unobservable heterogeneity in the economy [2].

3 Firms as Agents of Economic Interpretation and Valuation

If knowledge in the economy is dispersed, firms occupy a distinctive position as agents that collect, synthesize, and communicate fragments of that knowledge. A firm is not only a production unit but also an interpretive institution. The firm receives signals from suppliers, tenants, creditors, regulators, customers, municipalities, and competitors, and translates them into strategic narratives that not only combine quantitative and qualitative elements but also include important descriptions of business, economic, and social developments with high communicative value. This interpretive role matters because market valuation depends to a large extent on how the future is made understandable. Investors observe not only financial outcomes but also the informational structure through which management explains those outcomes.

The sources of this information are diverse. Regulatory documents, such as corporate annual reports (including, for example, 10-K forms regulated by the Securities and Exchange Commission), provide standardized disclosures on business segments, operating risks, financing conditions, litigation, market competition, and macroeconomic exposure. Investor relations materials add further detail through earnings presentations, asset reports, capital allocation updates, sustainability disclosures, and management commentary. Conference call transcripts provide insight into tone, emphasis, and managerial confidence, while corporate presentations often make strategic direction more explicit, particularly in transforming sectors. Taken together, these sources form a disclosure ecosystem through which firms contribute to a broader interpretation of their operations and of the economy [2].

For empirical research, these documents are valuable because they capture more than simple promotional information. They provide descriptions that are at once structured and heterogeneous of how firms perceive and communicate their environment. A logistics REIT, for example, may emphasize e-commerce penetration, tenant concentration, and the resilience of warehouse demand, while a data-center operator may focus on cloud infrastructure, AI workloads, and power constraints. In contrast, a residential platform may highlight household formation, affordability pressures, or migration patterns. Even within the same sector, firms often reveal quite different economic exposures through their narratives, which leads them to communicate those elements that reflect their particular interests and competitive positioning. This is where textual analysis becomes particularly useful, as it allows researchers to move beyond formal classifications and examine how firms describe the sources of their own value creation.

At the same time, these documents must be interpreted with caution. Corporate communication is inherently strategic and selective. Firms may emphasize favorable themes, downplay uncertainty, or adopt language that suggests innovation without there

necessarily being clear operational backing. This implies that textual information should not be treated as a direct reflection of fundamentals, as its value for firm analysis lies in revealing how management positions the company within a broader set of expectations [3]; this positioning is economically relevant because valuation depends not only on realized performance but also on the credibility and coherence of these narratives, insofar as whether a firm is perceived as defensive or cyclical, innovative or mature, or more or less sensitive to broader economic conditions can influence both its cost of capital and its investor base.

In real estate and the built environment, this interpretive dimension becomes particularly relevant. As these firms are grounded in large portfolios of built assets that are fixed in space, yet whose valuation evolves significantly over time due to factors such as demographic changes, income levels, or economic complexity, their relative value in turn depends on how firms interpret location-specific demand, redevelopment opportunities, financing conditions, regulatory constraints, and infrastructure linkages. For example, when a real estate company presents itself as an urban logistics platform, a digital infrastructure provider, or a life-science ecosystem operator, it is implicitly positioning itself within a broader economic narrative. These choices can influence analyst coverage, peer comparisons, and ultimately portfolio allocation. Firm documents, therefore, are not only descriptive but also form part of the valuation process itself.

Viewing firms as agents of economic interpretation also helps connect micro and macro perspectives. Corporate disclosures can show how broader economic forces are filtered through specific business models. Inflation, interest rate changes, demographic shifts, decarbonization, or urban restructuring do not affect all firms equally; their impact depends on firm-specific characteristics (such as the composition of assets, liabilities, tenants, technologies, or geographic exposure). It is at this point that textual data captures the process by revealing how firms interpret these socioeconomic forces and translate them into strategic priorities aimed at creating shareholder value and enhancing valuation. In this sense, firm-level text provides a useful lens for observing economic interpretation as it unfolds.

4 Text as Data in Economic and Financial Research

The transformation of text into data has become one of the most important methodological developments in contemporary economics and finance [4]. The basic idea is straightforward: written language contains information that can be systematically extracted, quantified, and related to firm-level outcomes. Rather than treating reports, transcripts, and disclosures as purely qualitative material, the use of machine learning and artificial intelligence tools transforms them into analyzable objects. This shift has led to a large body of literature on sentiment, uncertainty, disclosure quality, topic detection, managerial tone, and information asymmetry, significantly expanding the amount of information that can be extracted from such documents.

Early approaches relied primarily on word counts, dictionaries, and bag-of-words representations. These methods enabled important advances, particularly in measuring sentiment or uncertainty from financial news and corporate reports. However, they also present significant limitations. For instance, frequency-based techniques often ignore

context, syntax, and semantic substitution. Two firms may describe similar economic activities using different vocabularies, yet a simple keyword-based model may classify them as unrelated. Conversely, the repeated use of the same term may obscure substantial differences in meaning, depending on context. These issues become especially relevant in sectors characterized by technological convergence or hybrid business models [5], significantly limiting their effectiveness for the valuation purposes pursued in this paper.

The text-as-data approach is particularly promising for identifying economic exposure. Traditional classifications such as GICS or NAICS, which assign firms to fixed categories, may be useful for reporting and benchmarking, but they are taxonomic frameworks that impose discrete boundaries on economic realities that are often continuous and overlapping. Textual analysis allows researchers to observe firms more flexibly, as instead of asking only which sector a firm officially belongs to, it examines how the firm describes its revenues, assets, risks, customers, and strategic trajectory, thereby opening the possibility of measuring exposure as a gradient rather than as a binary membership.

In finance, this approach can enrich factor modeling, peer identification, event studies, and valuation analysis. Two firms may exhibit similar accounting ratios and yet have very different narrative exposures; alternatively, firms belonging to different official sectors may reveal common dependencies through their language. Text can therefore serve as a bridge between observable financial performance and the underlying economic structure [6], being particularly useful for capturing forward-looking or qualitative dimensions that remain only weakly reflected in traditionally analyzed accounting data.

The urban and real estate domain provides a particularly suitable context for this methodology. Urban systems are shaped by heterogeneous actors whose economic activities are intertwined with location, infrastructure, regulation, and social change. Developers, REITs, construction firms, utilities, mobility platforms, logistics operators, data-center firms, and property services companies all participate in the built environment, but in ways that go beyond conventional sector boundaries. Textual data allows researchers to trace these interdependencies. For example, a firm may formally operate in real estate and yet describe itself using the language of digital infrastructure, last-mile logistics, senior care, or energy transition; these narratives reveal how urban capital is being reorganized both within firms and across the broader economy.

For this reason, the text-as-data approach is not simply a technical complement to real estate research, but becomes a means of representing urban complexity. Through corporate language, we can capture elements such as neighborhood-level demand, tenant composition, urban reconfiguration, capital investment priorities, and exposure to local policies in a way that combines scalability and comparability. This represents a new capability that is particularly relevant when urban real estate is studied as an evolving system rather than as a static asset class. If cities are understood as spaces where capital, regulation, and infrastructure interact, then firm-level texts provide a distributed record of how these interactions are perceived and managed by market participants [2].

5 Semantic Representations of Economic Narratives

The methodological evolution of text analysis in economics and finance has moved from discrete lexical methods toward semantic representations capable of capturing meaning at a higher level of abstraction. Early approaches, such as bag-of-words, term-frequency, or dictionary methods, represent documents through observed word counts. These techniques remain useful for measuring tone, uncertainty, or the salience of predefined topics, but they are limited when the objective is to identify deeper economic similarity across firms. Two companies may operate in closely related activities while using different vocabularies, different reporting styles, or different narrative emphases. For this reason, more recent approaches rely on embeddings, which represent text as dense vectors in a continuous latent space.

Let D_i denote the textual corpus associated with firm i, constructed from regulatory filings, annual reports, investor presentations, earnings-call transcripts, or other corporate disclosures. The text is mapped into a vector representation through an embedding function.

$$e_i = \phi(D_i), e_i \in R^d,$$

where $\phi(\cdot)$ denotes the embedding model and d is the dimension of the semantic space. The resulting vector e_i is a compact numerical representation of the firm's economic narrative. Firms whose texts describe similar business models, risks, markets, or strategic orientations tend to lie closer to one another in this space.

The central advantage of this representation is that similarity is no longer based on exact word overlap, but on semantic proximity. To make this economically interpretable, firms can be compared to a set of reference categories.

Let

$$C_1, C_2, \ldots, C_k$$

denote K category descriptions, where each category represents a sectoral narrative, or a business model, or an economic theme. Embedding these category texts in the same latent space gives

$$C_k = \phi(C_k), k = 1, ..., K.$$

Once both firms and categories are represented in the same vector space, the semantic similarity can be obtained through cosine similarity:

$$s_{ik} = cos(e_i, c_k) = \frac{e_i^T c_k}{||e_i||||c_k||}$$

This measure captures the angle between the two vectors and therefore identifies similarity in direction rather than magnitude. And if the vectors are normalized, this can be reduced to the simple inner product

$$s_{ik} = e_i^T c_k.$$

The quantity s_{ik} measures the degree to which the narrative of firm i aligns with category k. A higher value indicates greater semantic proximity between the firm's published text and the economic content represented by that category. However, these raw similarity values are not yet directly interpretable as exposures; in this form, they indicate proximity but do not provide normalized weights across categories. To transform semantic similarity into economically meaningful exposures, it is necessary to normalize them using a softmax function:

$$p_{ik} = \frac{exp(\gamma s_{ik})}{\sum_{j=1}^{k} exp(\gamma s_{ij})}, k = 1, \ldots, K,$$

where $\gamma > 0$ controls the sharpness of the assignment. The resulting weights satisfy

$$p_{ik} \in (0, 1), \sum_{k=1}^{K} p_{ik} = 1$$

Therefore, they can be interpreted as continuous exposure weights or as soft memberships across categories. This formulation represents a substantial improvement over discrete classifications, as under a one-hot scheme, each firm is assigned to a single category, such that its exposure vector satisfies:

$$p_{ik} \in \{0, 1\}, \sum_{k=1}^{K} p_{ik} = 1$$

Such an approach is often too rigid for firms whose activities span multiple domains. By contrast, the embedding-based framework allows a firm to have partial exposures across several categories simultaneously, which is particularly important in contexts where sectoral boundaries are fluid, where firms combine multiple business functions, or where economic identity evolves.

The parameter γ plays an important role in this setting; higher values make the Soft-Max more concentrated, bringing it closer to a hard classification, while lower values produce more diffuse exposures, preserving ambiguity and overlap across narratives. In that sense, γ controls the degree to which semantic similarity is translated into concentrated or diversified economic exposure.

The full procedure can be summarized in three steps. First, embed the firm texts and category texts:

$$e_i = \phi(D_i), c_k = \phi(C_k).$$

Second, compute semantic similarity:

$$s_{ik} = \frac{e_i^T c_k}{||e_i||||c_k||}$$

Third, normalize the similarity scores into exposure weights:

$$p_{ik} = \frac{exp(\gamma s_{ik})}{\sum_{j=1}^{k} exp(\gamma s_{ij})}$$

Collecting all p_{ik} produces an exposure matrix

$$P \in R^{NxK},$$

whose rows summarize the semantic positioning of firms across economically meaningful categories.

Modern embedding models and large language models strengthen this framework because they produce contextual representations. The meaning of a word depends on the document in which it appears, and this matters greatly in economic and financial language. Terms such as "development", "platform", or "infrastructure" may describe very different economic activities depending on the type of firm. Contextual embeddings reduce this ambiguity by encoding the meaning of phrases and documents rather than isolated tokens. As a result, semantic similarity becomes a more precise measure of the underlying economic narrative, so that semantic representations act as a bridge between corporate text and economic interpretation. Text is transformed into vectors, vectors into similarity measures, and these into continuous exposure weights, resulting in a flexible representation of firms' economic identity that is better suited than rigid taxonomies to environments characterized by heterogeneity, overlap, and structural change.

6 From Semantic Similarity to Economic Exposure

The key analytical step consists of moving from semantic resemblance to an economically interpretable notion of exposure. Similarity in language is not, by itself, a financial variable, but becomes useful when it is linked to the idea that firms describing similar activities, constraints, and opportunities may tend to share common drivers of value. Under this interpretation, semantic similarity acts as a proxy for proximity in economic function, capturing the idea that firms are exposed not only to broad market movements but also to latent thematic forces reflected in their business narratives.

Within this framework, each firm's textual disclosures can be represented through embeddings and compared either with other firms or with a set of thematic prototypes. The resulting similarity scores can then be normalized into continuous exposure weights; rather than assigning a firm exclusively to categories such as "industrial," "retail," or "data center," the model allows for fractional exposure across several economic themes, which is particularly important for diversified, transitional, or hybrid firms. In this way, a company such as a platform operating at the intersection of storage, logistics, and digital infrastructure is not forced into a single category when its valuation depends on multiple overlapping narratives.

The economic meaning of these exposures lies in common sensitivity. If two firms use different words but converge semantically on issues such as energy demand, tenant retention, redevelopment optionality, life-science leasing, or e-commerce penetration, they may respond similarly to shocks affecting these themes. Semantic exposures approximate latent factor loadings rooted in firm narratives and can be interpreted as a map of the conceptual space within which valuation takes place [2].

This perspective also helps explain why textual analysis can matter for prices. From a fundamental standpoint, valuation can be understood as a problem of discounting uncertain future cash flows, where expectations about those flows depend on beliefs

regarding growth opportunities, competitive durability, financing conditions, and operating risks [7]. In this context, investors implicitly process firm narratives by extracting thematic exposures. An embedding-based approach formalizes this process, adding analytical value by transforming narrative proximity into a quantitative structure that can be related to returns, volatility, and cross-sectional differences in performance.

Once semantic exposures have been estimated, they can be used to extract the main factors influencing firm valuation, which do not necessarily coincide with traditional sectors. In the context of the built environment, these may correspond to dimensions such as interest-rate sensitivity, urban logistics intensity, digital infrastructure demand, demographic dependence, proximity to healthcare, or redevelopment optionality. The advantage of this approach is that these factors emerge from the language firms use to describe themselves, rather than being entirely imposed a priori, making the resulting structure potentially more adaptable to economic change.

At a theoretical level, the shift from similarity to exposure reflects a move from classification to measurement, where classification asks what a firm is, while exposure asks which forces it is close to. For asset pricing and urban analysis, the latter question is often more informative. Firms are not static types, but bundles of contingent relationships, and semantic methods provide a way to estimate these relationships between text and connect them to market valuation [8].

7 Economic Exposure and the Measurement of Intrinsic Risk

Once semantic exposures have been estimated, they can be incorporated into a standard multi-factor risk framework. Let $r_t \in R^N$ denote the vector of asset returns at date t. In a Barra-style specification, returns are decomposed into two components: systematic and idiosyncratic:

$$r_t = Xf_t + \varepsilon_t$$

where $X \in R^{N \times K}$ is the exposure matrix, $f_t \in R^K$ is the vector of factor returns, and ε_t is the vector of specific returns. In this context, semantic exposures extracted from text replace or complement traditional sector dummy variables, allowing firms to load continuously on multiple economic factors rather than being forced into a single category.

Factor returns are estimated cross-sectionally, while total risk is decomposed into two components: a systematic component driven by common factors and a firm-specific component. If Σ_F denotes the factor covariance matrix and β_i the vector of factor loadings for asset i, factor-driven variance is

$$\sigma_{F,i}^2 = \beta_i^\top \Sigma_F \beta_i$$

Specific variance is estimated from residual returns,

$$\sigma_{\beta,i}^2 = Var\left(\varepsilon_{i,t}\right),$$

so total variance becomes

$$\sigma_i^2 = \sigma_{F,i}^2 + \sigma_{\varepsilon,i}^2$$

This decomposition is central to valuation and risk control because it distinguishes between risk explained by shared economic structure and risk that remains intrinsic to the firm [8].

From a financial perspective, semantic exposure matters because structural changes in a firm's narrative may anticipate changes in its true economic risk. If a firm becomes more exposed to debt-sensitive activities, cyclical tenants, speculative development, or capital-intensive expansion, this shift may later be reflected in its realized betas, in the covariance structure of factor returns, and ultimately in its intrinsic risk [9]. Text thus provides a forward-looking signal of changing vulnerability. Rather than treating beta as a fixed parameter, the framework allows it to be understood as partly driven by evolving economic exposure [2], which may ultimately translate into changes in firm valuation.

This is particularly relevant in real estate. The sector is highly exposed to structural risks that are not always immediately reflected in accounting data. An increase in interest rates can compress asset values, leading to higher refinancing costs and translating into weaker transaction activity, thereby reducing the relative attractiveness of income-producing assets. A lack of liquidity can further amplify this process; for instance, if capital markets tighten or asset sales become more difficult, firms with short debt duration, aggressive external growth models, or fragile tenant bases may experience a significant increase in both systematic and idiosyncratic risk. In this sense, structural risk in real estate is not limited to market risk, but also emerges in the form of financing risk, duration risk, rollover risk, and valuation risk concentrated in specific business models.

A semantic risk model can help identify these vulnerabilities by grouping firms according to their underlying economic similarity rather than relying solely on formal sector classifications. Two firms may both be classified as real estate companies and yet exhibit very different sensitivities to interest rate shocks, liquidity stress, lease duration, technological obsolescence, or cyclical demand, while firms in different formal subsectors may share common structural exposures. A continuous exposure framework is therefore better suited to capturing the true propagation of risk within the built environment.

This is also relevant for robustness to tail risk. Volatility alone is an incomplete proxy for risk, as it does not capture the asymmetry and concentration of losses that emerge during stress episodes. In particular, higher-order risks associated with skewness, kurtosis, and non-normal return distributions may become critical in real estate markets exposed to interest rate repricing or liquidity shocks. By contrast, a multi-factor model does not eliminate tail risk, but it provides a more robust framework by isolating systematic channels of exposure before analyzing residual extreme risk separately.

In summary, the measurement of intrinsic risk improves when economic exposure is modeled as continuous, dynamic, and text-informed. In the real estate sector, whose capital structure, valuation volatility of underlying assets, financing conditions, and market liquidity play a decisive role in firm outcome, this approach offers a more realistic way to understand how structural risk enters valuation and how vulnerabilities can accumulate before being fully reflected in prices.

8 Urban Systems and Capital Allocation in the Built Environment

The broader significance of this framework becomes particularly clear when firms are understood as sensors of urban systems and cities are not viewed as mere physical agglomerations, but as dense configurations of capital, labor, infrastructure, regulation, and social demand. Firms operating within the built environment continuously register changes in these configurations; through leasing patterns, development pipelines, financing strategies, tenant feedback, and investment plans, they provide distributed signals about the evolving structure of urban economies.

From this perspective, the study of firms contributes directly to understanding urban development. Corporate narratives reveal where demand is intensifying, where infrastructure constraints are emerging, which types of space are becoming obsolete, and which asset classes are attracting strategic investment. The language used by firms can therefore be interpreted as a sensor network for the city, where an increase in narratives around themes such as cold storage, last-mile distribution, laboratory conversion, power availability, or demand for senior housing may indicate deeper transformations in the allocation of urban capital [2].

This matters because capital does not flow neutrally across space, but instead moves toward sectors, locations, and business models that appear capable of absorbing and reproducing value. When firms change, the capitalization of the sector changes with them; for example, a wave of firms repositioning around digital infrastructure can redirect investment toward data centers, telecom assets, energy interconnection, and related land markets, while a re-narration of logistics as strategic urban infrastructure can attract capital to warehouse corridors, intermodal nodes, and peripheral development areas. Similarly, if residential firms increasingly emphasize affordability, mobility access, or demographic resilience, these themes may shape both investor attention and interactions with urban policy.

The built environment thus emerges as a space where semantic interpretation and material allocation intersect, such that firm narratives influence valuation, valuation in turn affects the cost of capital, and the latter determines which urban projects become viable. This creates a feedback loop linking textual representation to physical transformation. Consequently, studying firms through their published texts is not only a financial exercise but also a way of analyzing how urban systems evolve.

For research in urban economics and real estate, this suggests a fruitful integration of market data, textual analysis, and spatial interpretation. Firms can be analyzed as intermediaries between macroeconomic forces and urban form, with their disclosures revealing how abstract drivers such as interest rates, digitalization, aging, or decarbonization materialize in buildings, land uses, and metropolitan investment patterns. A methodology capable of capturing these signals can help explain why some urban sectors attract persistent capital while others undergo repricing or decline.

This is the context in which textual analysis of firms offers more than an improvement in classification tools; it provides a way to observe the co-evolution of language, capital allocation, and urban transformation by treating firms as interpretive and sensing agents within the built environment. It thus becomes a tool that allows researchers to better understand how economic narratives are translated into a geography of investment.

9 Conclusions

This paper proposes a methodological model for transforming corporate narratives into measurable economic exposures and using those exposures to assess risk in urban real estate firms. The central argument is that firms operating in the built environment are not only holders of physical assets or members of fixed industrial categories; they are also interpreters of economic change. Their disclosures contain information about financing conditions, tenant demand, infrastructure constraints, redevelopment strategies, regulatory pressures, and spatial transformation. When systematically reviewed, these accounts can help identify shared sensitivities that are not fully captured by traditional sector classifications.

The paper's contribution is methodological rather than purely conceptual. It delivers a standardized sequence of steps for moving from text into risk assessment: corpus construction, text cleaning, embedding, semantic comparison, exposure normalization, acuity calibration, financial-noise filtering, factor-return estimation, and decomposition of total risk into systematic and intrinsic components. This workflow responds to the need for a replicable procedure that can be applied by other researchers and practitioners. It also clarifies the operational meaning of the proposed approach: corporate text is not treated as anecdotal evidence, but as an empirical input that can be converted into an exposure matrix and tested within a multi-factor risk model.

The framework contributes to three areas of research. First, it extends text-as-data methods by focusing not only on sentiment, uncertainty, or topic frequency, but on the construction of continuous economic exposures. Second, it contributes to real estate and urban studies by providing a way to connect firm narratives linked with structural transformations in the built environment. Third, it contributes to financial risk modeling by replacing or complementing discrete industry classifications with semantic exposure vectors that enable firms to load partially onto multiple economic narratives simultaneously.

The most important implication is that intrinsic risk can be defined more precisely once common semantic exposures have been controlled for. A firm may appear risky because it belongs to a volatile sector, is exposed to a common structural driver, or contains genuinely idiosyncratic vulnerabilities. The proposed model helps distinguish these cases. For example, two real estate firms may both be formally classified within the same broad sector but may differ sharply in exposure to refinancing conditions, logistics demand, healthcare tenants, energy infrastructure, data-center growth, or redevelopment optionality. Conversely, firms assigned to different official categories may share exposure to the same structural urban transformation. A semantic exposure model can reveal these overlaps, thereby improving risk attribution.

The paper additionally emphasizes that methodological transparency is essential. The embedding model must be specified, the reference categories must be documented, the acuity parameter must be calibrated rather than chosen arbitrarily, and the filtering procedure must be described in sufficient detail to permit replication. In this respect, the proposed framework should be understood as an empirical protocol. Its usefulness depends on whether other researchers can reproduce the exposure matrix, evaluate alternative category definitions, test different embedding models, and compare the resulting risk decomposition against conventional benchmarks.

Subsequent research should develop the empirical side of the framework in four directions. First, the model should be tested on larger international samples of listed real estate firms, REITs, infrastructure firms, developers, and urban service providers. Second, semantic exposures should be compared with traditional sector classifications to assess whether they improve explained variance, specific risk estimation, and portfolio risk attribution. Third, the acuity parameter should be calibrated through formal criteria, including exposure entropy, stability, and out-of-sample performance. Fourth, the model should be extended spatially by linking firm-level narratives to geographies, asset locations, and urban indicators such as density, transport accessibility, demographic change, climate exposure, and infrastructure investment.

In conclusion, the paper argues that corporate text can function as a bridge between qualitative economic interpretation and quantitative financial risk assessment. In urban real estate, where value is formed by long-lived assets, spatial restrictions, capital-market conditions, and structural transformation, this bridge is especially valuable. The proposed framework does not replace accounting data, market prices, or traditional risk models. Rather, it complements them by making firm narratives measurable and enabling them to enter a transparent risk-decomposition framework. This creates a more adaptable approach to measuring economic exposure and intrinsic risk in the built environment.

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Regulatory Divergence and Operational Market Structure in Short-Term Rentals: A Comparative Analysis of Rome and Vienna

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Abstract. The expansion of short-term rentals industry reflects a broader transformation in how urban housing is valued and distributed, one in which digital platforms have played an active and challenged role in redefining residential property as an investment asset. Given these shifts, European cities have responded with different regulatory approaches. Yet, the structural consequences of these decisions are still not clear. This research focuses on modelling the heterogeneity of the markets in Rome and Vienna using logistic regression, to evaluate how different regulatory rules shape the housing market and its structural configuration. The results show that the model demonstrates solid discriminatory power, with an AUC-ROC (Area Under the Curve/Receiver Operating Characteristic) of 0.8030 and an overall accuracy of 70.7%, confirming that the two capitals exhibit structurally distinguishable market configurations even under assumptions of linearity. Among all variables tested, accommodation typology stands out as the sharpest dividing line between the two markets, one that effectively encodes, in categorical form, the institutional gap between Italy's light-touch registration system and Vienna's land-use-based restrictions. Specifically, categories such as pensions, boutique hotels, and serviced apartments act as nearly definitive indicators of Vienna's regulated market. On the other hand, in the Roman market, holiday homes and private residences are the accommodations that best characterise their least restrictive regulation. This shows that regulatory frameworks leave their mark on market configurations. It is also observed that the model has limitations when analysing nonlinear variables such as the professionalization of hosts and spatial concentration, which leads us to highlight the need to incorporate complementary approaches. These findings reinforce the belief that regulatory norms are actions that actively shape the spatial and operational logic of platform-mediated housing markets.

Keywords: Sharing economy · Short-term rentals · Regulatory frameworks · Urban housing markets · Logistic Regression · Urban housing regulation

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1 Introduction

The sharing economy has recently become an influential global model, altering economic activities, optimising resource utilisation, and generating substantial structural change [1, 2]. In this context, platforms that allow individuals to offer short-term stays in privately owned dwellings, typically described as peer-to-peer (P2P) or home-sharing accommodation, have gained a central role within the tourism lodging market [3]. This rapid expansion is reflected in recent European Union statistics: in 2025, the total number of tourist nights in the EU, including hotels and online booking platforms, reached an all-time high of approximately 3.1 billion, consolidating the recovery following the health crisis and positioning Italy among the continent's most dynamic markets [4, 5].

However, this growth has given rise to dynamics associated with so-called "platform capitalism," characterized by significant professionalization and concentration of income. Empirical work consistently shows that short-term rental (STR) markets are strongly concentrated. Reported Gini coefficients close to 0.68 imply that a small set of professional hosts captures most of the income [6]. This pattern becomes even more pronounced in cities with a high density of cultural sites. In Rome, STR growth is linked to land-use change and to a shift in how housing is valued, with proximity to cultural attractions increasingly priced in as an investment attribute [7]. Vienna follows a different pattern: demand for platform-mediated accommodation appears relatively price inelastic, suggesting scope to raise revenues via tariff changes [8].

This context has stimulated a substantial and multidimensional debate. Proponents argue that it accesses to tourism and allows middle-income households to generate income from underused housing assets. Recent literature, however, links STR growth to gentrification and touristification [9], with measurable effects on the socio-economic profile of historic areas. STR expansion is also associated with a contraction in the long-term rental supply, upward pressure on rents, and reduced affordability for residents [10–12].

This is often discussed within the broader financialization of housing [5], in which dwellings are increasingly treated as investment vehicles rather than as homes. Within this framing, short-term holiday rentals are now a material urban issue: platforms have enabled rapid scaling, while the resulting market reconfigures residential patterns, sharpens place-based competition, and creates new demands for local regulation [4, 5, 7].

In response to these challenges, European cities have implemented regulatory measures to balance economic activity with broader public interests, significantly shaping the composition of supply as well as its spatial distribution and degree of professionalisation [4, 13].

However, local responses remain fragmented, and a lack of transparency in data hinders the effective enforcement of regulations. Furthermore, the shift by operators toward medium-term rentals poses new challenges for urban affordability. In this regard, the comparison between Rome and Vienna is particularly relevant, as both cities exhibit contrasting regulatory and morphological structures, allowing us to observe how institutional arrangements are reflected in the empirical structure of tourism markets. In addition, there is a gap in the comparative research evaluating how differing regulatory frameworks influence the predictive power of supervised learning architectures. While

Rome is grappling with overcrowding in its historic centre, which is driving the adoption of strict zoning regulations, Vienna operates under a regulatory framework aimed at protecting its housing stock through strict limits on construction days and urban planning controls [4, 13]. Consequently, this research is warranted by the lack of international comparative studies that analyse the impact of legal frameworks on market inequality and centralization.

Accordingly, the following research question is formulated: ¿To what extent do the various regulatory regimes applied to short-term rentals influence rental market prices and the structure of the residential supply in Rome and Vienna?

The objective of this study is to determine how different regulatory regimes influence the rental market and the structural configuration of housing in the cities of Rome and Vienna. The study is spatially limited to these two capitals because they represent contrasting market dynamics and regulatory structures.

To address the research objective, two hypotheses are proposed:

H1: In Vienna, the physical attributes of housing have a greater ability to differentiate the market because regulation causes intrinsic value to be a more significant factor.

H2: Regulatory regimes produce structurally distinct market configurations.

The study begins with an introduction, followed by a review of the general theoretical framework relevant to the topic under study. Next, the methodology is presented, followed by the research findings, and finally, discussion and conclusions.

2 Theoretical Framework

Short-term rentals trace their roots to the sharing economy, an arrangement built around putting idle assets to productive use through digital intermediaries. This approach relies on individuals' willingness to offer idle goods or services through digital intermediaries, which has expanded the ways in which production, distribution, and consumption take place in urban settings [7]. Scholars broadly concur that the sharing economy substitutes access for ownership as its organising principle, although each author emphasizes different aspects. Using the most cited definition of the model, he describes it as follows: "a new form of economic activity whose main characteristic is peer-to-peer exchange, in which individuals share surplus resources, reducing the need for property and avoiding redundant production." [10]. What makes this approach interesting is efficiency, where the emphasis is on the production of fewer identical goods and less waste of resources. Also, five essential elements that underpin the collaborative economy have been identified: shared resources, distributed networks, trust and reputation mechanisms, the existence of an intermediate platform, and forms of shared governance, with a socio-technical approach [14].

Other authors present the collaborative economy as a catch-all that integrates various practices, organizational models, and economic justifications in various sectors [15–17]. As a result, the environment has been increasingly adapting to the professionalization of supply and the growing concentration of income, which has given rise to platform capitalism. In this context, various studies show that short-term rental (STR) markets have ceased to function as spaces of equitable exchange and have become structures with great inequalities, where a small number of professional hosts mainly benefit [7,

10]. This process shows the consolidation of a market dynamic typical of mature digital platforms, where professional management, investment capacity, and algorithmic visibility generate advantages that are difficult for occasional hosts to copy. Thus, a vision of the complexity of the phenomenon can be appreciated, which serves as a basis for analysing how regulatory frameworks seek to act on the urban, social, and economic impacts derived from the expansion of STRs. In accordance with what has already been stated, a review is presented below that aims to compare the regulations in force in Rome and Vienna, where opposing regulatory approaches to the same problem can be observed. In Europe, the Services Directive (2006) has been tasked with defining regulatory frameworks, along with the E-Commerce Directive (2000), which has been renewed by the Digital Services Act (DSA). In judgments of 2024, the shortage of rental housing is addressed and qualified as a "primary reason in the public interest" by the CJEU in joint cases C-724/18 and C-727/18 (Cali Apartments. In a recent Regulation (EU) 2024/1028, it is sought to harmonize the collection and exchange of data to improve transparency and allow evidence-based governance [18, 19].

We have been able to observe that the Italian regulatory framework has a mix of national regulations and municipal competencies aimed at strengthening traceability, tourism safety, and tax compliance. Recently implemented reforms have made the National Identification Code (CIN) and other registration systems mandatory, allowing for more widespread use of residential properties for tourism purposes. It presents greater flexibility for the use of residential properties for tourism. Giving the authorities the ability to supervise, with the requirement of the identification of each accommodation, and in this way, facilitate fiscal and administrative supervision [20]. By contrast, Vienna operates under a more restrictive regime based on the Wiener Bauordnung, which has redefined residential use and limits short-term rentals in residential areas. In a 2024 reform, a limit of 90 days per year was introduced with no exceptions; anything above that threshold requires a special business permit and carries significantly harsher penalties to prevent the conversion of residential properties into tourist accommodation [21, 22].

3 Methodology

In order to answer the research question, open data from Inside Airbnb [23] has been used, selecting two European cities: Rome and Vienna, that differ in their regulation regarding STR, which provided a final dataset of 126,621 observations after cleaning and removing extreme values. Data were extracted from three representative periods of the different seasons: low season (March 2025), high season (June 2025), and end of the high season (September 2025). With this, the effect of seasonality was incorporated into the analysis. Therefore, the period analysed includes the implementation of the 90-day limit for short-term rentals in Vienna (July 2024), reinforcing the importance of differences between seasons and allowing for a deeper examination of structural differences between urban markets. A quantitative approach with a binary logistic regression model has been used. To adapt the data, a rigorous data cleaning and quality control process was carried out, guaranteeing the consistency, integrity, and suitability of the data. Also, compliance with the regression assumptions and the absence of multicollinearity were

verified through the analysis of the descriptive statistics of the variables, and no violations that compromised the validity of the results were detected. Then, the variables that required it were transformed. The model was carried out using City as the objective variable and categorizing it as follows (Rome = 0, Vienna = 1). Numeric independent variables are standardized using StandardScaler, and categorical independent variables are encoded using OneHotEncoder, with drop = "first". Class imbalance is addressed using class_weight = "balanced". The model was trained with L2 regularization and the LBFGS solver. The C hyperparameter was optimized using GridSearchCV with three-way cross-validation. To evaluate performance, threshold-independent discrimination Area Under the Receiver Operating Characteristic Curve (ROC-AUC), class classification metrics, and detailed error analysis were combined through the confusion matrix. The results are presented as standardized coefficients and odds ratios.

4 Results

In this section, we present the findings of the Logistic Regression model trained with the city as the dependent variable, i.e., Rome (0) and Vienna (1). The predictor set is made up of six numerical variables: accommodates, availability 365, host listings, yearly reviews, distance to city centre, and log price; and three categorical variables: room type, property type, and period season. Together, these variables allow the model to probe whether Rome and Vienna are linearly separable and which characteristics of the advertisements contain the most relevant regulatory signal.

Table 1. Optimal model configuration

Parameter	Optimal Value	Notes
C (regularisation)	100	Weak regularisation, sufficient data to prevent overfitting
Penalty	L2 (Ridge)	Compatible with the L-BFGS solver
Best CV AUC-ROC	0.8079	Model tuning based on three-fold cross-validation (GridSearchCV)
Solver	with parameters optimised through L-BFGS	Optimal for large datasets with L2 regularisation
Scaling of numerical variables	StandardScaler	Necessary to compare coefficients across variables

For the implementation, we use scikit-learn. Three decisions shaped the configuration: first, for class imbalance (76% Rome, 24% Vienna; ratio 3.16:1), it was corrected by balanced weighting rather than resampling; second, all numerical predictors were scaled to a uniform range before adjusting; and third, categorical variables were digitized with

a reference category removed to avoid multicollinearity. The solver with parameters optimised through L-BFGS with regularization L2 (max_iter = 1,000) and the optimal regularization parameter C was identified by three-fold cross-validation (GridSearchCV) over {0.01; 0.1; 1; 10; 100}. Table 1 presents the resulting configuration.

Table 2 shows the model performance metrics for the test suite (n = 25,325). The model achieves an AUC–ROC of 0.8030 and an overall accuracy of 70.7%, placing it within an acceptable range (between 0.80 and 0.90) on the standard discrimination scale.

Table 2. Performance metrics

Class	Precision	Recall	F1-score	Support	AUC-ROC / Acc. (Accuracy)
0—Rome	0,90	0,69	0,78	19.239	AUC = 0,8030
1—Vienna	0,44	0,76	0,56	6.086	Acc. = 0,707
Accuracy			0,71	25.325	
Macro avg.(average)	0,67	0,73	0,67	25.325	
Weighted avg. (average)	0,79	0,71	0,73	25.325	

The class-wise analysis reveals an asymmetric performance pattern that is diagnostically informative about the nature of both markets. For the Rome class, the model achieves high accuracy (0.90) when predicting the city of Rome; it is correct in 90% of cases, but low in the Recall (0.69): misclassifying 5,957 Roman listings as Vienna se (31% of the class). On the other hand, for the Vienna class, the pattern is reversed: the Recall is acceptable (0.76), but the accuracy drops to 0.44. This implies that, for every correctly identified Vienna listing, the model produces 1.3 Vienna se false positives (i.e., Roman listings misclassified as Viennese).

Figure 1 presents the ROC curve of the model. With an area under the curve (0.8030) that exceeds the threshold of 0.80. This indicates that the linear model distributes its correct rankings more evenly across the entire range, reflecting lower confidence in assigning class membership scores and suggesting that a substantial part of market differentiation operates through mechanisms that a linear decision function cannot fully resolve.

With regard to the relative homogeneity of the markets, Table 3 presents the model's confusion matrix.

The most significant finding observed in the confusion matrix is the error rate for the Rome class: 5,957 Rome listings (31.0%) are classified as Vienna listings. This indicates that the operational signature of the Roman market, dominated by nonlinear relationships between distance from the city centre, price levels, and host scale, cannot be adequately captured by a linear decision function in log-odds space. For the Vienna class, the model makes 1,457 errors (23.9%), classifying this proportion of Viennese listings as Roman. This shows that these listings correspond to the sub-segment of professional Viennese operators with exceptional permits, whose operational profile is characterized

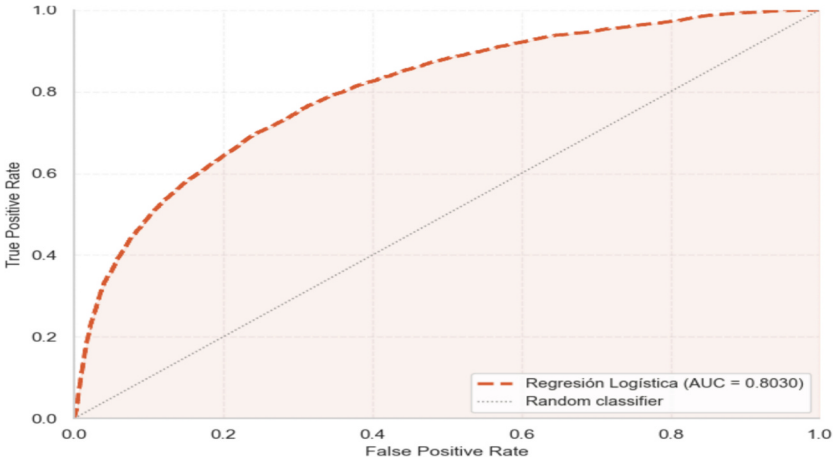

Fig. 1. ROC curve (AUC = 0.8030).

Table 3. Confusion matrix detail

	Pred. Rome	Pred. Vienna	Total actual	Recall
Actual Rome	13,282	5,957	19,239	69.0%
Actual Vienna	1,457	4,629	6,086	76.1%
Total predicted	14,739	10,586		Acc. 70.7%

by high availability, large scale, and price levels within the Roman range, which becomes operationally indistinguishable from the Roman market even for the linear model.

This finding is consistent with Hypothesis H2 and provides direct empirical evidence of a regulation-induced dual market structure within Vienna, where the majority of hosts operate within the 90-day limit with a distinctly Viennese profile, and a minority of large-scale operators with exceptional permits are operationally indistinguishable from the Roman market based on the available characteristics.

Table 4 below presents the twenty standardized coefficients with the highest absolute values. It shows the linear associations with each city through the standardized numerical variables (mean = 0, SD = 1), where coefficients are directly comparable by magnitude. In the model, Vienna represents the positive class (index 1), so positive values signal greater odds of Vienna, while negative ones point to higher odds of Rome in log-odds terms.

Table 4 presents the 20 highest coefficients in absolute value, showing that they correspond exclusively to property type, which indicates that the type of accommodation alone is sufficient to discriminate between the short-term rental markets of Rome and Vienna. The positive coefficients are dominated by Viennese guesthouses, hotel rooms, and serviced apartments, which reflect the strict delimitation of the Wiener Bauordnung between residential and commercial tourist use, this being a distinction absent in Rome.

Table 4. Top 20 standardised coefficients (positive class: Vienna)

Variable	Coefficient	exp(β) - Odds Ratio	Direction
Property type - Private room in pension	+11,819	136.120	Vienna
Property type - Private room in vacation home	−7,370	0,001	Rome
Property type - Room in bed and breakfast	−5,472	0,004	Rome
Property type - Shared room in home	−3,521	0,030	Rome
Room type - Hotel room	−3,500	0,030	Rome
Property type - Private room in private home	−3,440	0,032	Rome
Property type - Entire vacation home	−3,435	0,032	Rome
Property type - Private room in camper	+3,416	30,43	Vienna
Property type - Room in hotel	+3,159	23,54	Vienna
Property type - Camper/RV	−2,993	0,050	Rome
Property type - Private room in cycladic house	+2,943	18,99	Vienna
Room type - Private room	−2,934	0,053	Rome
Property type - Shared room in hotel	+2,866	17,57	Vienna
Property type - Shared room in guesthouse	−2,821	0,060	Rome
Property type - Private room in nature lodge	+2,792	16,31	Vienna
Property type - Entire cabin	−2,791	0,061	Rome
Property type - Entire bungalow	+2,739	15,47	Vienna
Property type - Room in boutique hotel	+2,688	14,69	Vienna
Property type - Private room in hostel	+2,687	14,67	Vienna
Property type - Room in serviced apartment	+2,556	12,89	Vienna

Negative coefficients, on the other hand, identify Roman private rooms in holiday homes, bed and breakfasts, shared rooms, and entire holiday homes, which corresponds to Italy's most permissive regulatory border between residences and tourist functions.

The clear separation in the probabilities observed at both extremes suggests an almost deterministic typological differentiation: accommodations belonging to these categories can be classified according to their city of origin with practically total precision, regardless of the rest of the variables. This provides direct evidence that regulatory frameworks generate structurally distinct typological configurations in short-term rental markets.

Figure 2 orders these coefficients from most negative to most positive, highlighting the asymmetry: Vienna's private room in pension exhibits the largest coefficient, followed by regulated commercial types; Rome displays a more heterogeneous profile with private room in vacation home and bed-and-breakfast rooms leading. The qualitative regulatory divergence between the cities is thus empirically manifest in their typological compositions.

Each hypothesis is examined below in light of the logistic model's results, drawing on both the AUC and classification metrics and the standardised coefficients.

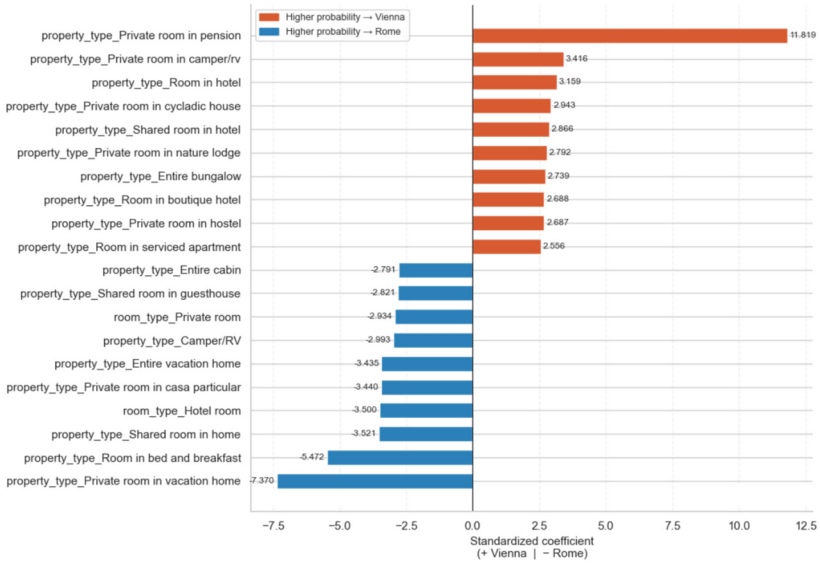

Fig. 2. Top 20 standardised coefficients

Table 5 summarises the hypothesis testing results derived from the logistic regression model, contrasting the empirical evidence obtained against the theoretical predictions and identifying the specific limitations of the linear framework for each dimension of analysis.

Table 5. Summary of hypothesis testing

H	Group	Evidence in LR	Limitation of the linear model
H1	Physical attributes	All top 20 coefficients belong to property type; Viennese and Roman typologies are linearly separable	Well, captured by this model, categorical relationships are linearly separable
H2	Structural distinctiveness	AUC = 0.8030 surpasses the 0.80 threshold; 1,457 Viennese listings identified with a Roman operational profile	Non-linear dynamics and threshold effects limit the model's full discriminant capacity

The LR confirms H1 with the most direct evidence in the result set: all twenty coefficients with the largest absolute magnitudes belong to property type, demonstrating that accommodation typology is the only linearly separable discriminating mechanism available to the model. The typologies associated with Vienna, pensions, camper/rv

accommodations, boutique hotels, bungalows, and nature lodges correspond to categories governed by their own legal regime under the Wiener Bauordnung, whose legal distinction between ordinary residential use and authorised commercial tourist use generates a quantifiable typological diversity that the LR captures with high reliability. The typologies associated with Rome, vacation homes, bed-and-breakfasts, private homes, and shared rooms in private dwellings reflect the greater informality and heterogeneity of the unregulated market, where the permeable boundary between uses produces categories that are practically non-existent in Vienna.

The LR achieves an AUC of 0.8030, surpassing the threshold established for H2 (>0.80) by a narrow margin. This confirms that the two markets are structurally distinguishable even under the assumption of linearity. Nevertheless, the model presents limitations in capturing the full range of differentiation mechanisms, given that certain market dimensions, such as host professionalisation and the spatial gradient of supply, operate through non-linear dynamics and threshold effects that a linear decision function cannot fully resolve. With regard to the dual market, the model identifies 1,457 Viennese listings with a Roman operational profile (23.9%), confirming the existence of a subsegment of professional operators who, having obtained exceptional permits, are operationally indistinguishable from the Roman market on the basis of the available characteristics.

5 Discussion and Conclusions

The main contribution of the logistic regression model is in its signed coefficients, which allow the relationship between the types of accommodation and each city to be clearly identified. Negative values are almost exclusively associated with typical Rome categories, such as private rooms and holiday accommodation, reflecting greater flexibility between residential and tourist uses. On the other hand, accommodation such as hotels, guesthouses, and tourist apartments predominates in Vienna, in line with stricter regulation separating the two uses.

These patterns clearly reflect the regulatory frameworks of each city: Vienna's regulated business categories are virtually non-existent in Rome, while Rome's characteristic informal accommodations have no place in Vienna. This marked typological separation shows that regulation leaves a direct structural footprint on short-term rental markets.

Methodologically, the moderate performance of the model suggests that these differences are not explained only in a linear fashion. Much of the regulatory influence operates through more complex dynamics, such as interactions and nonlinear effects, which the model fails to fully capture. This implies that linear tools may underestimate the actual impact of regulation, highlighting the need for more advanced approaches in public policy analysis.

The analysis identifies three main limitations of the logistics model. First, the dataset does not include variables related to the reputation or professionalization of hosts, which makes it impossible to assess the weight of these factors in the model. Secondly, the elimination of a reference category in the categorical variables conditions the interpretation of the results, which must be understood in relative and not absolute terms. Finally, the

extremely high coefficient associated with pensions suggests an almost perfect separation, as this category is virtually exclusive to the Viennese market. This can generate numerical instability and could require a higher level of regularization.

The limitations identified relate to the integration of short-term rentals (STR) activity into land-use dynamics and the distribution of local economic interest. In the cities analysed, land use transcends its spatial dimension to shape an institutional filter that determines which houses are suitable for conversion to tourist use and the conditions under which such conversion is authorized. In a context where regulations facilitate the transition, properties tend to be reconverted more easily, accelerating the functional transformation of central neighbourhoods. This repurposing process can widen the gap in rental prices, increasing the incentive to change the use of properties and deepening the market segmentation.

Our logistic regression analysis of Rome and Vienna's short-term rental markets show that, the type of accommodation is the main differentiating factor in linear terms. The predominant categories in Vienna, such as hotels, guesthouses, and tourist apartments, are clearly associated with its stricter regulatory framework, while in Rome more flexible accommodations stand out, such as private rooms and bed and breakfasts. This difference generates an almost deterministic typological separation between the two markets.

Also, the model confirms the existence of structural differentiation, albeit with a moderate margin. The presence of a subset of Viennese accommodations classified as Roman suggests the existence of a more professionalized segment that operates similarly in both contexts. Finally, the limitations of the model provide relevant information. Their inability to capture aspects such as the professionalization of hosts or spatial effects shows that part of the regulatory influence responds to nonlinear dynamics that linear models fail to capture. This implies that the impact of regulation may be underestimated, justifying the need to employ more advanced approaches in analysis. In this line, future research should explore interpretable nonlinear models that allow better capturing of threshold effects and complex interactions between variables, while maintaining explanatory capacity.

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A Checklist-Based Framework for Assessing the Functional Conversion Potential of Existing Buildings for Healthcare Uses

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Abstract. The COVID-19 pandemic exposed structural and organizational vulnerabilities in healthcare systems, highlighting the urgent need to strengthen community-based care provision. In Italy, Mission 6 of the National Recovery and Resilience Plan (NRRP) promotes the development of Community Health Facilities (CHFs), where the adaptive reuse of existing buildings represents a strategic yet technically complex solution. However, such interventions are often undertaken in the absence of integrated and operational evaluation frameworks specifically tailored to this context. This study proposes a checklist-based decision-support framework for the ex-ante assessment of the suitability of existing buildings for conversion into low-complexity healthcare facilities. The model is developed through the systematic integration of scientific literature, regulatory requirements, and technical standards, ensuring both methodological consistency and practical applicability. It is structured as a hierarchical multicriteria system focused on the intrinsic building characteristics, encompassing key dimensions including building flexibility, state of conservation and maintenance, environmental safety, accessibility, fire safety compliance, and energy performance. Each criterion is operationalized through discrete scoring scales grounded in applicable technical standards and regulatory references, enabling standardized, transparent, and comparable evaluations. The proposed framework supports the identification of critical constraints and enhances the consistency, replicability, and robustness of public decision-making processes in the context of healthcare infrastructure planning.

Keywords: Community Health Facilities (CHFs) · Decision-support systems (DSS) · Checklist-based assessment · Ex-ante evaluation · Building performance · Public decision-making

1 Introduction

The COVID-19 pandemic exposed significant structural, organizational, and managerial vulnerabilities in healthcare systems worldwide [1]. In many contexts, emergency responses were constrained by infrastructural limitations, technological gaps, and a limited capacity to rapidly adapt healthcare facilities and organizational models [2]. In Italy,

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the pandemic represented a major stress test for the National Health Service (NHS), highlighting longstanding structural weaknesses—particularly the condition of the healthcare building stock, often characterized by obsolescence, spatial rigidity, and limited functional adaptability [3–5]—while making explicit a structural imbalance between hospital-based and community-based care, which led to the progressive overloading of hospital facilities and a significant reduction in continuity of care for chronically ill and vulnerable patients [6]. Strengthening community-based healthcare has therefore emerged as a key priority for enhancing system resilience, understood as the ability to respond to shocks while ensuring continuity of care [7–9].

This imbalance reflects a long-term structural evolution of the NHS: since the 1990s, reforms aimed at improving financial sustainability progressively favored hospital-based services, while community-based care historically lacked equally structured evaluation and financing systems [10]. The pandemic made these weaknesses fully explicit, as hospitals became the primary access point for care, leading to overloaded emergency services and delays in routine and chronic care pathways [11–13]. In response, strengthening proximity-based healthcare has become a central objective in European and national policy agendas, and the Italian NRRP, supported by Next Generation EU, identifies Mission 6 (Health) as the vehicle through which to pursue this goal, with Component 1 focused on the reorganization of community healthcare networks [14, 15].

Among the newly introduced facilities, Community Health Facilities (CHFs) represent the central node of the community healthcare network and constitute the unit of analysis of this study. Due to their limited functional complexity and modest scale, these facilities are particularly suitable for adaptive reuse interventions. Ministerial Decree No. 77/2022 [16] provides for two implementation pathways: new construction and the conversion of existing buildings. While the latter represents a strategic solution in terms of sustainability, cost efficiency, and reduction of land consumption, it introduces significant decision-making complexity. Within the implementation of NRRP Mission 6, decisions regarding the conversion of existing buildings have often been conducted on a case-by-case basis, lacking standardized and transparent evaluation frameworks [17], with potential implications in terms of allocative inefficiency and suboptimal resource use. The present study aims to address this gap by proposing a structured, checklist-based multicriteria framework for ex-ante assessment of the suitability of existing buildings for conversion into CHFs.

2 Aim

This study aims to develop a structured decision-support framework for the ex-ante assessment of the functional conversion potential of existing buildings for community-based healthcare functions. The research proposes a multicriteria, checklist-based evaluation model designed to operationalize the assessment of buildings' technical, functional, and performance characteristics. The framework is intended to support public decision-makers by providing a transparent, consistent, and replicable tool for the comparative evaluation of reuse scenarios. It focuses specifically on the assessment of the intrinsic suitability of existing buildings, isolating building-related constraints and potentials within the broader decision-making process.

The study contributes to healthcare planning research by extending the focus beyond new construction and explicitly addressing the evaluation of existing building assets within adaptive reuse processes. From a methodological standpoint, it introduces a structured and scalable model for organizing and operationalizing heterogeneous evaluation criteria within a unified multicriteria framework, providing an operational tool for public administrations involved in the implementation of community-based healthcare policies. The application domain is limited to low-complexity healthcare facilities, with particular reference to CHFs, as defined by Ministerial Decree No. 77/2022. High-complexity hospital facilities are excluded, as they require different evaluation approaches.

3 Methodological Framework

The adaptive reuse of existing buildings is increasingly acknowledged as a relevant strategy in healthcare planning, as it enables the expansion of service capacity through the valorization of the existing building stock, while simultaneously reducing land consumption and implementation time compared to new construction. However, converting buildings for healthcare purposes entails significant technical and functional complexities, since such assets are typically characterized by spatial configurations, structural systems, and building services not originally designed to accommodate healthcare functions. While adaptive reuse represents a potentially more sustainable and cost-effective alternative to new construction [18], this option cannot be considered universally viable, as conversion projects may be constrained by unsuitable structural or dimensional characteristics, excessive refurbishment costs, or stakeholder conflicts [19, 20]. For this reason, a structured ex-ante assessment becomes essential to ensure technical and economic feasibility and to prevent allocative inefficiencies.

Despite the growing relevance of this topic, the academic literature on healthcare planning remains largely focused on the development of new hospital facilities and on location-allocation models. By contrast, the adaptive reuse of existing buildings for low-complexity facilities such as CHFs remains underexplored. This gap is especially evident in the context of M6 – Component 1 of the Italian NRRP, where decisions concerning the reuse of existing assets have often been carried out on a case-by-case basis, in the absence of structured evaluation tools, resulting in limited transparency, consistency, and replicability.

In response to this gap, the present study proposes a structured methodological approach aimed at the ex-ante assessment of the adaptive reuse potential of existing buildings through a checklist-based evaluation model. The framework was developed through the systematic integration of scientific evidence, regulatory references, and technical standards to ensure both methodological robustness and practical applicability. In a first phase, an international literature review was conducted on adaptive reuse and building performance assessment. Given the limited availability of studies specifically addressing the conversion of buildings into healthcare facilities, the review was extended to the broader field of functional conversion. This approach enabled the identification of key evaluation dimensions relevant to assessing reuse potential, while reducing the risk of overlooking critical factors that could compromise project outcomes. The literature analysis highlights that the evaluation of reuse potential should first consider the

dimensional and spatial characteristics of the building, in order to verify its coherence with the intended function. At the same time, the state of conservation and maintenance emerges as a critical indicator, as it directly influences the extent and cost of the interventions required. In this regard, Diana et al. [21] propose a qualitative assessment approach based on the systematic analysis of building components and technical systems, while Langston et al. [22] emphasize the role of physical condition and maintenance in determining reuse feasibility. Alongside these aspects, structural and spatial flexibility—understood as the building's capacity to accommodate new layouts—represents a fundamental prerequisite for successful adaptive reuse processes. Another key dimension concerns energy performance, in line with European sustainability objectives. The building sector accounts for approximately 40% of total energy consumption and 36% of greenhouse gas emissions in the European Union, making the improvement of existing building stock a strategic priority [23, 24]. Within the Italian regulatory framework, the Energy Performance Certificate (EPC), governed by Legislative Decree No. 192/2005 and subsequent amendments, provides a standardized indicator for classifying building energy performance and can therefore be effectively incorporated into comparative evaluation models.

The evidence derived from the literature review made it possible to identify a set of key dimensions that are crucial in assessing the adaptive reuse potential of existing buildings. These dimensions are particularly significant, as deficiencies in these areas typically translate into costly interventions that may ultimately compromise the feasibility of the project. The criteria identified through the literature were subsequently subjected to a process of selection and adaptation to ensure alignment with the research objective and with the specific requirements of low-complexity community healthcare facilities. This process enabled the exclusion of non-relevant dimensions and the reorientation of the framework toward assessing the intrinsic suitability of buildings for healthcare use. The model was further integrated with the Italian technical regulatory framework, incorporating mandatory references concerning accessibility [25], fire safety [26, 27], and energy performance [28]. Additional sources—including the ITACA Protocol and parameters adopted by the Italian Revenue Agency—contributed to the structuring of specific performance criteria and scoring scales.

The discrete scoring scales adopted for each sub-criterion were constructed according to a hierarchical referencing logic. Where mandatory regulatory thresholds exist, the scoring levels directly reflect degrees of compliance with applicable standards: accessibility requirements are grounded in DM 236/1989, fire safety in the Ministerial Decree of 3 August 2015 and DM 29 March 2021, and energy performance in D.Lgs. 192/2005. Where regulatory thresholds are absent, scoring levels were derived from technical planning guidelines—specifically DM 77/2022 and the Agenas/Politecnico di Milano "Quaderni del Metaprogetto"—which define minimum spatial and dimensional requirements for CHFs, or from established building assessment methodologies in the scientific literature [21, 22]. For the state of conservation and maintenance, the three-level classification (critical / intermediate / good condition) aligns with the operational categories adopted by the Italian Revenue Agency for building condition assessment, ensuring a consistent and verifiable classification basis.

The resulting framework takes the form of a hierarchical checklist of criteria and sub-criteria, with each sub-criterion associated with a discrete scoring scale representing increasing levels of suitability. The checklist-based approach translates technical observations into a structured evaluation, ensuring transparency, replicability, and comparability of results. The underlying evaluation logic is based on the coherence between building characteristics and the requirements of the intended healthcare use, enabling the identification of criticalities, estimation of intervention levels, and comparison of alternative options. It is important to note that the framework is intentionally bounded to the intrinsic characteristics of the building, and does not incorporate territorial or locational variables—such as proximity to public transport, presence of services in the catchment area, or urban accessibility indices. These dimensions, while relevant to the overall feasibility of CHF implementation, are considered distinct from the building-specific assessment and can be addressed in complementary evaluation phases, for instance, through GIS-based spatial analysis tools.

4 Structure and Articulation of the Checklist-Based Assessment Framework

The checklist developed in this paper is designed to assess the degree of compatibility of an existing building for its functional conversion into a healthcare facility, with particular reference to low-complexity community-based services (e.g., CHFs). From this perspective, the tool supports the decision-making process by directing attention toward buildings that require a lower level of structural, technical systems, and spatial interventions. The checklist is structured as a hierarchical framework composed of criteria and sub-criteria, enabling the systematic assessment of the main technical, functional, and performance-related dimensions of the building. In particular, it is organized into six main criteria, each representing a distinct analytical dimension relevant to the evaluation of adaptive reuse potential (see Fig. 1): i) building flexibility, ii) state of conservation and maintenance, iii) presence of contaminants and hazardous materials, iv) accessibility, v) compliance with fire safety regulations, and vi) energy performance.

Before applying the proposed framework, it is necessary to clarify that the assessment of a building's suitability for functional conversion into CHFs is carried out only after the verification of a set of preliminary feasibility conditions. These conditions represent requirements for the admissibility of the evaluation, ensuring that the analysis is conducted exclusively on potentially eligible assets. In particular, the application of the checklist presupposes: i) the verification of urban planning compatibility, namely the coherence of the intended healthcare use with the land-use regulations defined by the relevant planning instruments; ii) the absence of restrictive constraints related to landscape protection and hydrogeological risk, which may preclude or significantly limit transformation interventions; and iii) a preliminary verification of dimensional compatibility. With specific reference to the latter, the planning guidelines developed within the "Quaderni del Metaprogetto" for CHFs—promoted by Agenas in collaboration with Politecnico di Milano—indicate that an overall gross floor area of approximately 600 m^2 represents a reference threshold for ensuring adequate service provision. This condition does not imply a rigid threshold, but rather a preliminary screening criterion aimed at

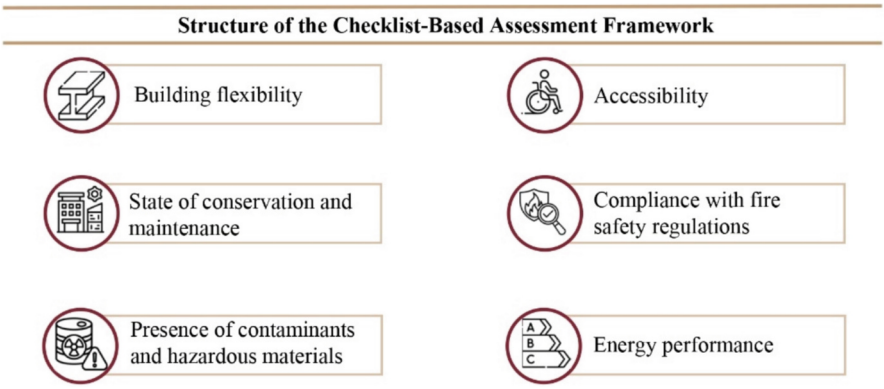

Fig. 1. Structure of the Checklist-Based Assessment Framework. Source: authors' elaboration.

excluding clearly unsuitable cases and ensuring the coherence of the subsequent multicriteria assessment. These preliminary conditions are themselves expressions of the territorial and spatial dimension of feasibility. Urban planning compatibility directly reflects the regulatory and land-use context in which the facility will operate, while the dimensional threshold of 600 m^2 is calibrated against the service catchment area and population demand parameters established by DM 77/2022. The connection between building-level and territorial-level assessment is therefore acknowledged as a relevant integration point, which future extensions of the framework may address through complementary spatial analysis tools. The following sections provide a detailed description of each criterion and the corresponding structure of the evaluation checklist.

4.1 Building Flexibility

The *Building Flexibility* criterion assesses an existing building's ability to accommodate a new intended use through modifications to its spatial layout and/or building systems, without requiring invasive or excessively costly structural interventions. This assessment is central to adaptive reuse processes, as it enables evaluation of the building's structural, spatial, and technical predisposition to accommodate new functions. The criterion is articulated into three main sub-criteria: i) structural system; ii) spatial configuration; iii) building services provisions (Table 1).

Table 1. Assessment scheme for the Building Flexibility criterion. Source: authors' elaboration

Building Flexibility		
Aspect to be assessed	**Score**	**Technical implications**
Structural system		
Load-bearing masonry with dense structural grid (continuous walls; spans < 4–5 m)	**0**	Layout non-modifiable; reconfiguration requires major structural intervention. Negligible flexibility.
Hybrid system (frame + masonry; localized load-bearing elements or structural cores)	**1**	Layout partially modifiable via lightweight partitions and localized openings. Moderate flexibility.
Regular frame structure (RC/steel; spans > 5 m; no internal load-bearing walls)	**2**	Layout fully reconfigurable without structural intervention. High flexibility.
Spatial configuration		
Predominance of rooms < 12 m²; irregular geometry; dense compartmentalization; inefficient circulation (e.g., tortuous corridors, pass-through or non-ventilated spaces)	**0**	Layout incompatible with healthcare functions; requires extensive demolition and full redesign. High cost and time.
Some rooms > 12 m² but irregular distribution or geometry; discontinuous or absent circulation	**0.5**	Limited compatibility with CHF layout; major reconfiguration needed to achieve functional modules (e.g., outpatient rooms ≥ 14 m²).
Rooms ≥ 14 m², partially contiguous or aggregable; partially organized layout; potential main corridor	**1**	Adaptable through selective demolition and internal reconfiguration. Functional baseline achievable.
Regular rooms ≥ 16 m²; partial contiguity; existing or easily achievable main corridor; mainly lightweight partitions	**1.5**	Layout largely compliant; minor interventions required. Low implementation cost.
Regular and contiguous rooms ≥ 16 m²; clear central circulation; lightweight partitions; efficient layout	**2**	Fully compatible layout; no structural intervention required. Immediate adaptability.
Building services provision		
No provisions for systems integration; absence of suspended ceilings and shafts; clear height < 2.80 m	**0**	New systems require invasive structural works and demolition. No integration capacity.
Adequate clear height (> 3.30 m) but no existing provisions; no ceilings or shafts; non-load-bearing partitions	**0.5**	Limited system integration (exposed installations or minor wall chases).
Partial provisions; suspended ceilings (20–60%); vertical shafts along at least one axis; systems partially divisible; at least one technical room per floor	**1**	System expansion feasible without structural works. Moderate flexibility with minor disruptions.
Good provisions; ceilings ≥60% (service zone > 35 cm); continuous shafts; horizontal distribution paths; systems divisible by functional areas	**1.5**	Complex system reconfiguration feasible with limited interventions. High adaptability.
Fully integrated and accessible systems; ceilings ≥90% (service zone > 40 cm); dense access points; continuous vertical and horizontal distribution	**2**	Plug-and-play adaptability. No demolition required. Minimal intervention.

The ***Structural System*** sub-criterion assesses the building's capacity for spatial reconfiguration as determined by its load-bearing structure. Load-bearing masonry systems with continuous walls and limited spans constrain layout modifications, whereas regular frame structures (reinforced concrete or steel) allow greater adaptability. The assessment is based on a three-level scale (0–2), reflecting increasing degrees of structural flexibility and associated intervention requirements. The ***Spatial Configuration*** sub-criterion assesses the current layout's compatibility with the CHF's functional and dimensional requirements. It considers room size, geometric regularity, spatial continuity, and circulation efficiency, capturing the extent of reorganization needed for functional adaptation. The evaluation is conducted through a five-level scale (0–2), designed to reflect progressive conditions of layout compatibility and corresponding transformation effort. The ***Building Services Provision*** sub-criterion assesses the building's capacity to accommodate, integrate, and reorganize technical systems. It focuses on the presence and accessibility of service infrastructure (e.g., ceilings, shafts, distribution paths) as key enablers of system adaptability. The assessment adopts a five-level scale (0–2), reflecting increasing levels of infrastructural readiness and decreasing intervention intensity.

Overall, the Building Flexibility criterion provides an integrated evaluation of the building's structural, spatial, and infrastructural adaptability, capturing its intrinsic capacity to support functional conversion with varying levels of intervention.

4.2 State of Conservation and Maintenance

The *State of conservation and maintenance* criterion assesses the level of degradation and the functional efficiency of the main building components and technical systems. Based on the integration of academic literature and regulatory references, the criterion is structured into 9 sub-criteria, covering structural components, envelope elements, internal finishes, and main technical systems, allowing for a comprehensive evaluation of the building's overall condition. Each sub-criterion is evaluated using a discrete three-level scoring scale, consistent with the operational categories adopted by the Italian Revenue Agency for building condition assessment and with established component-based assessment approaches in the literature [21], as detailed in Sect. 3: i) 0—critical condition: extensive degradation or failure, components require replacement or major rehabilitation; ii) 1—intermediate condition: localized degradation or partial functionality, minor or moderate interventions required; iii) 2—good condition: fully functional components with no significant maintenance requirements. This scoring system enables a consistent and comparable assessment of building conditions, supporting the identification of critical elements that may significantly affect the technical and economic feasibility of adaptive reuse interventions (Table 2).

The articulation of the State of conservation and maintenance criterion enables the quantification of the building's degradation level and supports the prioritization of intervention areas requiring rehabilitation or upgrading.

Table 2. Assessment scheme for the State of conservation and maintenance criterion. Source: authors' elaboration

State of conservation and maintenance		
Aspect to be assessed	**Score**	**Technical implications**
Load-bearing structure (beams, columns, walls, slabs)		
Structural damage (cracks, deformation, detachment, corroded reinforcement)	**0**	Compromised structural integrity; detailed assessment and strengthening required
Localized, non-critical damage; no stability issues	**1**	Minor inspections and localized maintenance required
No visible damage; structurally sound and stable	**2**	Fully compliant; no structural intervention required
Roof		
Active leaks, widespread degradation, damaged roofing layers	**0**	High risk of deterioration; full refurbishment required
Irregular condition, worn materials, no active leaks	**1**	Functionally acceptable; localized maintenance required
Intact roof, no leaks or defects	**2**	Fully functional; no intervention required
Faąades (plaster, cladding, cornices)		
Detachment, cracks, unsafe elements	**0**	Safety risk; urgent repair required
Surface degradation (cracks, stains, mould), no structural issues	**1**	Aesthetic/functional degradation; maintenance required
Uniform, well-maintained surfaces	**2**	No intervention required
Windows and doors (condition and thermo-acoustic performance)		
Damaged or non-functional frames; air/water leakage	**0**	Inadequate performance; full replacement required
Functional but inefficient (poor insulation, outdated systems)	**1**	Replacement or upgrading recommended
Fully functional, good insulation performance	**2**	Suitable for use; no intervention required
Internal finishes (walls and ceilings)		
Widespread degradation (moisture, mould, detachment)	**0**	Unsuitable for use; rehabilitation required
Localized degradation; no hygiene issues	**1**	Repairable with minor interventions
Intact, dry, washable surfaces	**2**	Suitable for healthcare use; no intervention required
Flooring		
Damaged, non-hygienic or unsafe flooring	**0**	Full replacement required
Usable but worn or outdated surfaces	**1**	Medium-term refurbishment recommended
Continuous, resistant, hygienic surfaces	**2**	Fully compliant, no intervention required

(*continued*)

Table 2. (*continued*)

Electrical system		
Non-functional or unsafe system; exposed or obsolete wiring	**0**	Critical safety condition; full system replacement required
Partially functional or outdated system	**1**	Upgrading required (e.g., panels, wiring)
Compliant and fully functional system	**2**	Suitable for use; no intervention required
Plumbing system		
Non-functional system; leaks, damaged pipes, no water points	**0**	Full replacement required
Partially functional; outdated components	**1**	Upgrading required; limited reliability
Fully functional and compliant system	**2**	Suitable for use; no intervention required
HVAC system		
Absent or non-functional system	**0**	Full installation required
Obsolete or inefficient system	**1**	Upgrading required; limited performance
Efficient and compliant system	**2**	Suitable for continuous use

4.3 Presence of Contaminants and Hazardous Materials

The *Presence of hazardous materials and contaminants* criterion introduces an evaluative dimension related to the environmental and hygienic safety of the building, accounting for potential critical issues associated with the presence of hazardous substances or materials subject to mandatory remediation. These factors may significantly affect the implementation time, intervention costs, and overall technical feasibility of the conversion process. The criterion aims at assessing the environmental suitability of the building in compliance with the applicable regulatory framework. The evaluation is based on a discrete scoring scale (0–2), reported in Table 3.

Table 3. Assessment scheme for the Presence of hazardous materials and contaminants criterion. Source: authors' elaboration

Presence of hazardous materials and contaminants		
Aspect to be assessed	**Score**	**Technical implications**
Widespread presence of hazardous contaminants (e.g., friable asbestos, hydrocarbons, PCB, lead, mould, soil contamination) or materials requiring mandatory remediation	**0**	Mandatory environmental remediation required. Reuse feasibility severely compromised
Localized or non-friable contaminants; materials potentially containing hazardous substances (e.g., encapsulated asbestos, sealants, tanks) removable without invasive works	**1**	Reuse feasible, subject to targeted removal or environmental verification. Impacts on costs and implementation
No documented or visible evidence of contaminants; previously remediated or certified materials	**2**	Environmentally suitable. No remediation required

4.4 Accessibility

The *Accessibility* criterion evaluates the level of physical usability of the building by verifying the absence of architectural barriers that may hinder access, circulation, and use of spaces by users with disabilities or reduced mobility—a fundamental requirement for healthcare facilities to ensure safe, autonomous, and inclusive use. The criterion assesses the degree of compliance with the dimensional and performance requirements established by Ministerial Decree No. 236/1989, while identifying any necessary upgrading interventions. It is structured into four sub-criteria: i) main building access; ii) vertical circulation; iii) horizontal circulation; iv) sanitary facilities. Each sub-criterion is assessed through a discrete scoring scale, allowing the progressive classification of accessibility levels from critical conditions to full regulatory compliance. The scoring scales are differentiated according to the specific technical complexity associated with each sub-criterion (Table 4). This approach allows the evaluation to account for the specific technical characteristics of each component, avoiding oversimplification.

Table 4. Assessment scheme for the Accessibility criterion. Source: authors' elaboration

Accessibility		
Aspect to be assessed	**Score**	**Technical implications**
Main building access		
Presence of architectural barriers preventing access (stairs >1.10 m without lift; entrance doors <0.75 m; no ramp)	**0**	Inaccessible entrance; major interventions required (lift installation and/or doorway widening)
Stair >1.10 m; entrance door ≥0.85 m; no ramp	**0.5**	Partially accessible; ramp installation or lift required
Stair >1.10 m; entrance door <0.75 m; no ramp	**1**	Limited adaptation required (door widening); vertical accessibility feasible
Stair ≤1.10 m; entrance door ≥0.75 m; non-compliant ramp (slope >8%, width <0.90 m)	**1.5**	Partially compliant; ramp upgrading required
Compliant ramp (slope ≤8%, width ≥0.90 m) and accessible entrance	**2**	Fully accessible; no intervention required
Vertical circulation (lifts/platform lifts)		
No lifting systems; level differences only via stairs; no predisposition or space for future installation	**0**	Complete vertical inaccessibility; structural interventions required
Lift present but non-compliant: cabin < 0.80×1.20 m; landing < 1.40×1.40 m; manual doors; platform lift absent or non-functional	**0.5**	Severe functional limitations; accessibility strongly compromised; replacement or alternative solutions required
Lift present with cabin ≥ 0.80×1.20 m but critical issues: reduced landing (<1.20×1.20 m), missing signaling devices or automatic opening	**1**	Partial accessibility; possible upgrades without full replacement; localized interventions on devices and spaces
Lift compliant with DM 236/1989: cabin ≥ 1.10×1.40 m; landing ≥ 1.40×1.40 m; automatic doors; acoustic/visual/tactile signals; controls at compliant height	**1.5**	Full accessibility ensured; no intervention required; independent use guaranteed
Horizontal circulation		
Corridors ≤1.00 m; doors <0.75 m; presence of steps or level differences	**0**	Severe mobility limitation; major structural interventions required
Corridors ≥1.10 m but ≤1.20 m; doors ≥0.75 m but <0.85 m; limited maneuverability	**1**	Partial accessibility; selective widening and layout adjustments required
Corridors ≥1.20 m; doors ≥0.85–0.90 m; no steps; adequate maneuvering space	**2**	Fully compliant; no significant barriers
Sanitary facilities		
No accessible restroom; insufficient space (<1.40×1.40 m); inadequate door width; no maneuvering space	**0**	Not suitable; full redesign required
Restroom present but partially compliant (adequate size but missing equipment or insufficient door width)	**1**	Adaptation possible with fixture replacement; no major structural works
Fully compliant accessible restroom (DM 236/1989: adequate space, equipment, maneuverability)	**2**	Fully accessible; no intervention required

4.5 Compliance with Fire Safety Regulations

Compliance with fire safety regulations represents a mandatory requirement for the authorization of healthcare activities. Within the proposed framework, this criterion assesses the building's ability to ensure adequate safety conditions in the event of fire, with particular reference to the usability of escape routes and the fire resistance of materials and structural elements. The methodological approach is based on the Italian Fire Prevention Code (Ministerial Decree of August 3, 2015, and subsequent amendments) and on the Ministerial Decree of March 29, 2021 (Vertical Fire Safety Regulation for healthcare facilities). Although outpatient healthcare facilities are characterized by a lower risk level compared to inpatient hospital units, they remain subject to minimum mandatory requirements concerning means of egress, fire reaction and resistance of materials, and emergency management. Accordingly, the criterion is structured into two sub-criteria: i) means of egress; ii) fire resistance of materials and structures. Each sub-criterion is evaluated through a discrete scoring scale (0–2) directly reflecting degrees of regulatory compliance with the applicable normative framework (Table 5).

Table 5. Assessment scheme for Compliance with the fire safety regulations criterion. Source: authors' elaboration

Compliance with fire safety regulations		
Aspect to be assessed	**Score**	**Technical implications**
Means of egress		
Single exit per floor; width <0.80 m; no direct access to a safe place (no protected staircase or external exit)	**0**	Critical condition; high evacuation risk. Major interventions required (new stairs, route adaptation)
Two exits present but not independent (same compartment) or insufficient width (<0.80 m)	**1**	Partial safety; upgrades required (compartmentation, door widening)
Two independent, clearly marked exits; compliant dimensions (≥1.20 m); protected staircase or direct access to a safe place	**2**	Fully compliant; safe evacuation conditions ensured
Fire resistance of materials and structures		
Widespread combustible materials (light structures, false ceilings, non-certified partitions); no fire resistance certification	**0**	High fire vulnerability, rapid spread, and structural risk. Major upgrading required
Partially combustible materials; incomplete or missing fire resistance documentation	**1**	Intermediate condition; improvement possible through material replacement and certification
Non-combustible materials; structure with certified fire resistance (REI ≥60); no hazardous finishes	**2**	Fully compliant; no intervention required

4.6 Energy Performance

The Energy performance criterion aims to evaluate the overall energy performance of the building within the assessment framework. The evaluation is based on the Energy Performance Certificate (EPC), a standardized and legally recognized indicator that synthesizes the energy efficiency of both the building envelope and the main technical systems, ensuring an objective and comparable assessment regardless of typological or dimensional differences among buildings. In accordance with Legislative Decree No. 192/2005 and subsequent amendments, the scoring scale directly reflects the 10 EPC energy classes defined by law, ranging from G (lowest performance, score = 0) to A4 (highest performance, score = 4.5), with each class associated with a progressively increasing score proportional to the energy performance level (Table 6).

Table 6. Assessment scheme for the Energy performance criterion. Source: authors' elaboration

Energy class (EPC)	Score
G	**0**
F	**0,5**
E	**1**
D	**1,5**
C	**2**
B	**2,5**
A1	**3**
A2	**3,5**
A3	**4**
A4	**4,5**

5 Aggregation and Interpretation of Results

A structured and comparable interpretation of the evaluation results requires the definition, for each criterion, of the range of achievable scores, identified by establishing the minimum value (set to 0) and the maximum value derived from the sum of scores associated with the respective sub-criteria. Table 7 reports, for each of the six criteria, the extent of the evaluation scale and the corresponding maximum attainable score.

Table 7. Scoring ranges and maximum attainable values for each evaluation criterion based on the aggregation of sub-criteria. Source: authors' elaboration.

CRITERIA	MIN SCORE	MAX SCORE
Building flexibility	0	6
State of conservation and maintenance	0	18
Presence of contaminants and hazardous materials	0	2
Accessibility	0	7,5
Compliance with fire safety regulations	0	4
Energy Class (EPC)	0	4,5
Total	**42**	

Once the overall score for each criterion has been determined, the results are normalized using a Min–Max linear transformation, made possible by the finite and homogeneous numerical structure of the adopted scoring system. The minimum value min(x) always corresponds to 0, while the maximum value max(x) varies depending on the criterion. The linear transformation is defined as follows:

$$I_i = \frac{x_i}{\max(x)}$$

where x_i represents the score obtained by the building for criterion i, and max(x) corresponds to the theoretical maximum score for the same criterion. The normalized indicators assume a standardized quantitative form ranging between 0 and 1, expressing the degree of suitability of the building for conversion into a CHF, while enabling the identification of critical areas (values close to 0) and higher-performing aspects (values close to 1). In addition to the criterion-level analysis, an overall synthetic measure is obtained through score aggregation: the total score ranges between 0 and 42, and its normalization—obtained by dividing by 42—expresses overall building performance on a 0–1 scale. This dual level of interpretation supports both the identification of specific technical and functional criticalities and the comparison of alternative options, facilitating public decision-making processes.

6 Conclusion and Future Insights

The increasing centrality of strategies aimed at strengthening community-based healthcare, particularly evident during the COVID-19 pandemic, has highlighted the need for operational tools capable of systematically supporting decision-making processes related to proximity healthcare facilities. In this context, the adaptive reuse of existing building stock represents a strategic solution, although one characterized by significant technical and decision-making complexity [29]. This study proposes a decision-support framework for the ex-ante assessment of the suitability of existing buildings for conversion into CHFs, configured as a structured multicriteria system based on a hierarchical checklist integrating technical, functional, and performance-related criteria derived from

scientific literature, regulatory frameworks, and operational practice. The use of discrete evaluation scales, combined with the normalization of results, enables the translation of qualitative observations into standardized quantitative indicators, ensuring transparency, replicability, and comparability.

From a methodological perspective, the main contribution lies in the development of an operational tool that isolates and evaluates the building component within the decision-making process through the assessment of intrinsic suitability, allowing a clear distinction between technical-functional building conditions and other decision dimensions—locational, economic, and organizational. From an applied perspective, the model assists public decision-makers in identifying key technical criticalities and comparing alternative options, promoting a more efficient allocation of resources.

Despite these strengths, some limitations remain. The absence of a weighting system implies equal contribution of all criteria, without reflecting decision priorities or contextual specificities. In this regard, it is worth noting that certain criteria may function as practical deal-breakers in real-world decision-making contexts: a score close to zero on fire safety compliance or on the presence of hazardous contaminants would likely undermine overall conversion feasibility regardless of performance on other dimensions, such as energy class or spatial configuration. A sensitivity analysis testing the stability of the overall suitability index under alternative weighting schemes—assigning greater importance to safety-critical criteria—is therefore identified as a priority for future methodological development. Moreover, the framework currently focuses exclusively on intrinsic building characteristics, excluding territorial, economic, and managerial variables that may significantly affect overall feasibility.

Future developments may extend the model toward a more comprehensive decision-support system integrating additional evaluation dimensions. The introduction of multi-criteria weighting techniques aligned with decision-makers' preferences [30] and integration with GIS-based tools for spatial analysis appear particularly relevant in this regard. Furthermore, the integration of the proposed checklist into BIM (Building Information Modelling) or Digital Twin environments represents a promising avenue aligned with current trends in Healthcare 4.0 [31], enabling dynamic updating of evaluation data and more efficient management of decision-making workflows in adaptive reuse planning. It should be noted that the framework has not yet been applied to empirical case studies: its validation through the systematic assessment of a heterogeneous set of existing buildings—spanning different typologies, construction periods, and maintenance conditions—is identified as the most urgent step toward demonstrating its operational reliability and identifying potential refinements. Overall, the proposed framework represents a first step toward the development of operational evaluation tools supporting policies aimed at strengthening community-based healthcare, contributing to bridging the gap between theoretical approaches and practical applications in healthcare planning.

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Assessing the Existence Value of Cultural Heritage. The Economic Evaluation of the "Scuola Grande di San Giovanni Evangelista" in Venice

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Abstract. The economic evaluation of cultural heritage has traditionally focused on use values, often neglecting non-use components such as existence value. The current contribution investigated the "Scuola Grande di San Giovanni Evangelista" in Venice as a case study to explore how existence value can be integrated into economic assessment framework. The research combined traditional real estate valuation methods with approaches derived from welfare economics, including demand estimation and proxy indicators of collective appreciation. Two alternative scenarios are analyzed, namely a private investment model and a public-oriented cultural system, interpreted as mechanisms for revealing different components of total economic value. The results show that, beyond market value, the asset generates a significance existence value linked to its historical symbolic, and identity-related dimensions. The study contributes to the ongoing debate on the economic justification of heritage conservation by proposing an integrated framework capable both use and non-use values in high-tourism urban contexts.

Keywords: Existence value · Cultural heritage economics · Economic evaluation

1 Introduction

The economic valuation of cultural heritage has been grounded in economic approaches that privilege measurable and market-based dimensions of value. However, the increasing recognition of the multidimensional nature of heritage has led to a progressive redefinition of evaluation frameworks, incorporating concepts derive from welfare economics and environmental valuation. Within this evolving paradigm, the notion of existence value has emerged as a crucial component for understanding the full contribution of cultural assets to society [1].

Existence value refers to the benefit that individuals derive from the mere knowledge that a cultural good continues to exist, regardless of any direct interaction with it. This form of value is particularly relevant in contexts where heritage plays a central role in shaping collective identity and cultural continuity. In cities such as Venice, where the

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urban fabric itself constitutes a living archive of history, the preservation of heritage assets generates benefits that extend far beyond their immediate use [2].

Despite its theoretical relevance, existence value remains difficult to operationalize within standard evaluation procedures [3]. Traditional valuation methods, such as market comparison or income capitalization, are inherently limited in their ability to capture intangible and symbolic dimensions. This limitation has led to the development of alternative approaches, including contingent valuation, choice modelling, and various forms of revealed preference analysis. As a result, public decision-making processes often rely on partial assessments that underestimate the social benefits of conservation [4–6].

The present study addresses this gap by proposing an integrated framework for the assessment of existence value, applied to the "Scuola Grande di San Giovanni Evangelista" in Venice (Italy). The research adopts a hybrid methodological approach that combines economic estimation with spatial and demand-based analyses, aiming to approximate non-use values through observable indicators. By interpreting different development scenario as mechanisms for revealing latent preferences, the paper contributes to bridging the gap between theoretical constructs and applied valuation practices.

2 The Existence Value in Cultural Heritage

Understanding he many different aspects of value that are related with cultural heritage can be accomplished through the utilization of the Total Economic Value (TES) concept, which offers a comprehensive framework, According to this, the value of a product is not linked only to its direct application; rather it encompasses a variety of components that reflect both real and possible interactions that are non directly related to the use of the product itself [7–10].

The meaning beyond the "use value" often refers to both direct consumption, such as going to a museum, and indirect advantages such as the economic spillovers that are generated by the tourism phenomena. The option value indicated the wish to retain the possibility of future usage, whereas the value of a bequest conveys the desire to pass on heritage to subsequent generations. Existence value, on the other hand, is distinct in that it is not based in any way on any type of utilization; rather, it is founded on ethical, symbolic, and identity-related factors [11].

A strict relationship is between the significance of existence value and the intrinsic value in the realm of the cultural heritage economics. Intrinsic value acknowledges the significance of cultural assets as goals in themselves, rather than solely as a means of earning economic rewards, Taking into account the existence value as element to bring into decision-making frameworks reflects that the heritage is regarded to be a reservoir of collective memory and social meaning [12].

The accounting of the existence value shows remarkable challenges from a methodological point of view. Across the existing literature, a several methods and empirical approaches were proposed and tested in the perspective to determine the economic significance that the people are capable to give to heritage assets [13]. These approaches, such as the stated preference methodologies (e.g. contingent valuation), are often characterized by remarkable biases and limits associated with imaginary scenarios and strategic behavior [14]. By means of diverse collateral approaches that are oriented to capture the

intrinsic connected to the symbolic value, the economic value of the existence depends on the capacity from the collectivity to estimate that product in accordance with the relative productive performance [15–19]. Recent scholars have investigated the contamination that came from using canonical accounting approaches whit other ones that depend by using location data, behavioral indicators. In line with this, the current contribution proposed a methodology the read patterns of accessibility, demand, and urban centrality as indirect manifestations of communal valuation. This meta-analytical approach provide proxy evidence concerning the economic value of the cultural heritage existence.

3 Materials and Valuation Protocol

3.1 Description of the Case of Analysis

As a case of study the "Scuola Grande di San Giovanni Evangelista" in Venice is considered. It serves repository of historical-cultural capital that bridge late-Medieval devotion with Renaissance architectural innovation. This appraisal evaluates the dual-track objective of maximizing the asset's direct income potential while preserving its intrinsic existing value and indirect use value. As a high-prestige asset in a globally saturated tourism market, The "Scuola Grande di San Giovanni Evangelista" requires ah hybrid valuation approach that combine the maximization of use value with the preservation requirements of a historical asset.

The missions centers on a conservative restoration of architectural surface and a systematic enhancement of public accessibility. By refining the formal quality of the Quattrocento interventions and safeguarding he Trecento craftsmanship, the project aims to optimize the site's functionality as cultural node of Venice. The renewal intervention is designed to ensure the highest standards of public enjoyment, in coherence whit Italian legislative on the valorisation of national heritage.

In the following Fig. 1 and Fig. 2 the characterization from an architectural and spatial perspective of the case of study is proposed. The Fig. 3 represent the spatial distribution of public and private properties in Venice; rather, the Fig. 4 the functional localization of most significant attractors in the city.

3.2 Merging Market and Non-market Valuation: An Hybrid Assessment Protocol

The proposed hybrid valuation protocol oriented to capture the economic significance of existence value is characterized by the integration of traditional economic assessment frameworks with collateral approached aimed at capturing non-market values. The analysis is built according to parallel scenarios, which are not seen as mutually exclusive options but rather as complementary perspectives for revealing different components of value.

The first decision-making frame of study consider a private investment perspective, and it is focused on the appraisal of market value and potential income streams. This first one is based on applying consolidated methodology likely the direct comparison and income capitalization, providing a measure of exchange value that are observable by the lengths of the market data. The second scenario, in contrast, is based on the

Fig. 1. Architectural and urban characterization of the case of analysis.

concept of a diffused museum, where the accessibility, cultural interaction, and the connection with the urban system assume significance and importance for conserving the cultural asset considered in Venice. A core item of the method consists of the using of spatial information related to the accessibility, due to its relative connection with the tourist pressure and cultural activity. Demand modeling is also employed to estimate the number of potential visitors, in accordance to similar institutions.

The proposed assessment approach, on one side, provides evidence connected to the use value, on the other one, indirect manifestations of the broader societal interest,

Fig. 2. Inside rooms of the historical property.

Fig. 3. Public and private properties in Venice, respectively in green and violet.

Fig. 4. Localization of the main functional properties in Venice.

which can be interpreted as a proxy existence value, The integration of these two diverse lengths of reading give a more comprehensive assessment of a historical cultural asset, by bridge the market and non-market evaluation.

In the following section the result of the above descripted assessment protocol are described. Then, the conclusions of the study are reported.

4 Results

By the application of the proposed integrated methodology a market value is estimated, reflecting the structural, locational, and architectural characteristics of the property within the Venice real estate context. This estimate derived through a direct comparative approach, calibrated by means of adjustment coefficients that accounts for both intrinsic attributes, such as the state of conservation and historical artistic quality, and extrinsic factors, including accessibility and proximity to primary urban attractors. In analytical terms, the estimated unit value can expressed as a function of the average market benchmark adjusted by a vector of hedonic parameters, thereby situating the asset within the upper segment of the historic property market while incorporating penalties related to the absence f premium features such as direct frontage on the Canal Grande. This value represents the exchange component of the asset and provides a robust baseline for subsequent economic evaluation.

The estimation of rental income further supports this assessment by applying a capitalization framework base on observed yield rates within comparable market segments. From a financial perspective their reinforces the feasibility of a private investment strategy, particularly in relation to adaptive reuse scenarios oriented toward cultural events and temporary uses.

While the market-based evaluation provides a clear measure of the use value, the analysis of demand under the public-oriented scenario reveals a broader and more complex dimension of value. More specifically, the estimation is based on an interception function relating the effective population present within a defined catchment area to observed visitation rates, thereby capturing the interaction between spatial context and cultural consumption behavior. This result indicates a significant level of cultural interest and engagement, reflecting not only the intrinsic attractiveness of the site but also its functional integration within the wider cultural system of Venice [20–22].

The interpretation of these findings in terms of existence value requires a shift from a purely quantitative framework toward a more comprehensive evaluative perspective grounded in welfare economics. The discrepancy between market value and the broader set of benefits associated with the asset highlights the presence of significant non-use components. This can be inferred through the divergence between measurable economic returns and the wider social significance of attributed to the asset [23, 24].

By combining market indicators with spatial and demand-based proxies, the study develops an indirect estimation framework for existence value that is consistent with observable data while remaining theoretically grounded. The integration of geomarketing analysis, accessibility metrics, and demand modeling allows for the identification of patterns that reflect collective preferences and social valuation processes. In this sense, existence value is not treated as an hypothetical construct, but rather as an emergent property of the interaction between the asset and its socio-spatial context [25–43].

5 Conclusions

The study proposed an integrated and multidimensional framework for the assessment of the existence value in cultural heritage, combining traditional economic evaluation techniques with spatial analysis and demand-based modeling. By bridging methodologies derived from real estate appraisal, welfare economics, and geomarketing, the proposed approach aims to overcome the limitations of conventional valuation practices, often liked to market-based indicators. The study highlights the relevance of non-use components within the broader structure of the TEV theory, showing how existence value can be approximated by means with indirect and empirically grounded indicators.

The research opens several directions for further developments. Future studies may enhance the analytical rigor of the proposed approach through the integration of econometric modeling, such as hedonic pricing models or discrete-choice models. The incorporation of stated preference methods including contingent valuation and choice experiments, could allow for a more explicit monetary estimation of existence value, complementing the proxy-based approach adopted in this study. Expanding the empirical basis through the analysis of multiple case studies across different urban and cultural contexts would further strengthen the generalizability of the framework and enable comparative assessments of value structures.

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Urban Regeneration and Real Estate Transformation: A Case Study of Parque Fundidora in Monterrey

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Abstract. Urban regeneration projects have become key strategies for the transformation of former industrial areas and the creation of new public spaces in contemporary cities. These initiatives are often promoted as mechanisms for revitalizing urban environments, improving environmental conditions, and fostering social interaction. However, the spatial and economic secondary effects of these interventions, particularly those related to surrounding real estate dynamics, are not always evaluated after their implementation. This paper examines these processes through the case of Parque Fundidora in Monterrey, México, a former industrial complex that ceased operations in the late twentieth century and was later transformed into a large public park. Through a regeneration initiative, the site preserved part of its industrial infrastructure for the use of spaces with new uses with educational and leisure approaches, such as museums, libraries, pavilions, auditoriums and extensive open green areas. Over time, the park has become one of the most important recreational and cultural spaces in the city, attracting many visitors and becoming an iconic place for diverse urban activities. The study explores how specific interventions in places like this can reshape patterns of accessibility, public use, and real estate development in their surrounding urban environment. This document presents an approach to the ways in which the transformation of large industrial sites into public spaces can generate new pressures and opportunities within the local real estate market. By examining the dynamics phenomena emerging around Parque Fundidora, the paper seeks to contribute to the understanding of the broader urban and economic transformations associated with large-scale regeneration projects.

Keywords: Urban Regeneration · Real Estate Dynamics · Public Space · Urban Planning

1 Introduction

Monterrey has served as a canvas for multiple waves of urban regeneration throughout its history, each of which has contributed to shaping the city's identity by redefining its urban landscape and dynamics. Drivers such as the recovery of obsolete industrial spaces,

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the renewal of infrastructure aimed at enhancing user experience, and the revitalization of social fabric are commonly presented as the main arguments for promoting this type of interventions [1, 2].

Despite the benefits that are often assumed to be implicit in these ideals, the scenarios accompanying such transformations can become discouraging. Intrinsically, these processes involve periods in which spaces are restricted and disabled for use, indefinitely in many cases. These phenomena range from disruptions in urban connectivity to modifications in the social dynamics that take place within these environments. In such scenarios, the implementing agents usually argue that such discomfort will decrease as the projects progresses, and that the profit will surplus the temporary discomfort and losses experienced by users. However, these scenarios are rarely evaluated to determine whether such metrics are met, or whether the temporary restrictions of spaces lead to more notable and serious consequences. In some cases, represent the loss of something in concrete, an intangible element value that is not captured for those who propose the plans and make decisions. These indicators are often linked to patterns of appropriation, use, and the daily experience of space by the users [3].

Parque Fundidora covers a space of more than 140 ha, that stood on the grounds of the "Fundidora de Fierro y Acero de Monterrey", company that went out of business in 1986. Fifteen years later, that place was transformed into a public park through an urban regeneration initiative. This process proposed the original industrial infrastructure to accommodate spaces with main purposes for culture and public recreation, including museums, libraries, multipurpose halls, recreational outside areas, a 3.4 km circuit, and grassed areas, while also maintain connection with emblematic recreation spaces from the city [4].

Today, nearly forty years after the closing of the company and several decades of its transformation, Parque Fundidora has undergone a series of transformations associated with the emergence of new patterns of use. While many of these interventions have been justified under the previously mentioned objectives, there appears to be a relationship with how they respond to the new forms of management and exploitation of the site, linked to broader processes of urban space commodification [5]. These changes have led to modify usage dynamics in the park also have even produced forms of segregation that affect certain groups of users.

At the same time, these dynamics have generated new pressures on the surrounding environment, responding to emerging needs that differ from those considered in the original planning framework, which prioritized public use over economic interests. Among the most notable effects is the activation of the real estate market, reflected in changes in land use and in the value of nearby properties [6].

In this context, it becomes pertinent to question the phenomena associated both with the project's initial premises and with those arising from the evolving needs of a space in constant transformation, as their analysis makes it possible to identify which variables acquire greater prominence in the use of the park and, consequently, how interaction dynamics between users and space are configured. Among the phenomena that warrant consideration in this reflection are: 1.- The level of accessibility of the park and the redefinition of it over time. 2.- The potential forms of exclusion derived from the mixed management schema. 3.-The grade of segregation resulting from the management of use

in massive events. 4.- A new conception of an equitable vision of benefit distribution among the different performers of the urban activity. 5.- Visibly the resilience of the users among the incorporation of the implemented dynamics of use that implies the integration of economic factor. 6.- The influence of public investment initiatives taking place in the park periphery.

This study aims not only to identify, demonstrate, and measure the effects associated with the implementation of large-scale urban regeneration projects in public spaces, but also to distinguish those that emerge intrinsically from the intervention process from those that catalyzes to additional transformations. These effects are examined in the urban dimension of space, but also in real estate dynamics and in the practices of residents, users, and other actors who recognize this space as part of their everyday lives. In that way, the study raises the question of when the original objectives become distorted and how they may be redirected toward a more balanced outcome.

The present study aims to analyze how contemporary patterns of use in Parque Fundidora have reconfigured its character as a public space, the effects derived from the implementation of large-scale private events and their relationship on the development with real estate transformation in the surrounding areas. The study examines the motivations driving such interventions, the dynamics which by they are projected, and those that are expected to emerge from the everyday interactions on the surrounding environment, users, and the development of the project itself. The recognition of primary and collateral effects on these phenomena allows new perspectives, understanding how diverse actors, dynamics, and scales leads and contributes to the shaping of urban landscapes and how this in fact influences important factors that affect citizens living conditions and life quality.

2 Materials and Methods

2.1 Study Approach

This research adopts a case study approach to the contemporary dynamics of urban regeneration in large-scale public spaces, specifically Parque Fundidora in Monterrey, Mexico. The case was selected from its unique transformation from a private industrial use to a public park with multiple developed sub-spaces, which currently operates under a hybrid management model. Combining open public access and private spaces with payment of access fees. Also, a contemporary system of restricted zones on specific dates due to temporary events, a sort of segregation areas that turns spaces from public to private by a large-scale events agenda.

The study considers spatial and social dimensions related to accessibility, patterns of use, and user experience within the park. Also, incorporating quantitative data associated with the frequency, scale, and spatial impact of private events held within the park over time and the evolution of the outlaying area properties and urban public equipment.

This approach shows how different forms of space utilization coexist and interact with the users, and the perspective of the citizens about this space. Emphasizing how these dynamics have a leading role forming the shape in the urban and real estate modifications in the surrounding area and the park itself. Approaching the analysis to examine the

relationship between public space management and market-driven activities, the study aims to explore the implications this has for urban development.

2.2 Conceptual Framework

Urban regeneration is a process that has gained prominence in recent decades, it has deep social, economic and political implications. As noted by François Merlin, "The absence of a rigid definition reflects the fact that urbanism operates not only as a technical discipline but also as a form of praxis". Urban regeneration encompasses integrated visions designed to address urban challenges while improving economic, physical, social, and environmental conditions [7].

The term urban regeneration is approached through an integrated perspective inspired by the document "Carta de Toledo", which was created for the better-established practices for the process that seeks to balance social, environmental, and urban structures while preserving existing urban capital, recognizing it as one of the core values of civilization. This perspective accents the interdependence between spatial configurations, social dynamics, and economic activity, the critical importance of the regeneration processes beyond focusing solely on the immediate outcomes [8].

Regeneration practices in the present are frequently triggered by market-oriented project dynamics, where the economic profit becomes the principal driver of the action. David Harvey argued that urban space is formed gradually by processes inherent to capital accumulation, which can lead to exclusionary outcomes even though they began as initiatives aimed at improving public spaces and a better quality of the user experience. These concepts are related to the concept "right to the city," originally proposed by Henri Lefebvre, which recognize the active action of the collective to access, use, and define the urban landscape [3, 5].

In practice, urban regeneration is not only intended for spatial improvement. When these planning approaches are implemented, they can establish patterns in value distribution within the city. These patterns of behavior among participating agents prioritize economic profit over addressing the impacts they generate, such as shifts in value perception and the creation of value blocks. This analysis illustrates how regenerated spaces operating under hybrid public-private models can become unbalanced. When these spaces are treated primarily as assets, developers often retain the economic benefits rather than reinvesting them into the site. Consequently, funding is typically limited to repairing the physical damage caused by commercial activities failing to account for the loss of "use value", a critical intangible element. It is observed that improvements to the environment and facilities serve primarily as a marketing asset for these projects rather than benefiting the intended original users. The access to these spaces is often restricted, and no provisions are made for the affected area during their implementation, in fact, these interventions are often out of sync and incongruent with the most pressing needs of the average citizen.

2.3 Notable Comparative Case Studies

Parque Fundidora is not an isolated example of industrial regeneration; there are two internationally recognized examples of site regeneration that recall similar projects: the

High Line in New York and the Landschaftspark Duisburg-Nord in Germany. Both cases involve an obsolete industrial site repurposed for public use, preserving the original infrastructure and maintaining respectful renovations to adapt it to its new purpose. However, the two cases have significant differences in terms of the development logic and the socioeconomic outcomes they produced for their cities and residents.

The High Line in Manhattan, New York is a 1.5-mile public linear park built on a former elevated railway from the 1930's. Since its 2009 debut, it has become an iconic place in the city, always recognized for its great design that attracts millions of visitors. However, its presence has sparked an intense real estate boom, characterized by luxury residences and mixed-use developments that have dramatically reshaped the urban fabric and redefined the neighborhood's socioeconomic composition [9].

The Landschaftspark Duisburg-Nord in Duisburg, Germany was a production plant of steel and coal. It was abandoned due to economic reasons, after the industrial operations ceased, the site was left with contaminated soil. In 1991, after the social pressure of the citizens, the decision to preserve industrial memory led the efforts to maintain the place with a new objective, turning it into a public landscape focused on cultural, recreational, and ecological functions. The project kept the industrial structures and restored the health of the soil by applying phytoremediation. The park evokes a sense of calm and respect for the industrial heritage that the residents fought to preserve, and it does not conflict with urban development interest, as its location is far from being a development hub [10].

Although these two cases are based on the same strategy of repurpose the space and land, reuse the industrial equipment and enrich the cities, depending on their urban, economic, and territorial contexts, the results are unique. High Line demonstrates the potential of the regeneration processes to catalyze real estate transformation according to the environment where the project is developed and Landschaftspark Duisburg-Nord shows a completely different environment develop because the strong character of the citizens who took it upon themselves to preserve and lead the way it regenerated the space for the benefit of all the users recalling the sense of place.

2.4 Data Collection and Processing

The collected data for this study were reconstructed through a triangulation of independent sources. To ensure a reliable longitudinal dataset, information was gathered from journalistic archives, music industry blogs, the private organizations of the events official pages, press releases and personal interviews with key stakeholders involved in event -related activities and a longitudinal documentation of events held at Parque Fundidora. To validate these sources, each entry was cross-referenced with secondary evidence and the validation with geospatial analysis using Google Earth measure and dron flight footage. This method of reconstruction was necessary to fill the gaps in public transparency due to the diffuse nature of administration, resulting in a database that covers from the first documented large-scale events to the present. The target data focused primarily on large-scale events, particularly music festivals, due to their significant spatial and operational impact on the park. Furthermore, the study accounted for event frequency, assistance, prices and the overall scale for each one [11].

In addition, qualitative information was incorporated including reports, media coverage and direct on-site observations before, during, and after events. These were used to objectively verify logistical requirements such as installation periods, infrastructure deployment, and user experience during both active and inactive phases. These diverse inputs were examined in detail to ensure an objective perspective on the findings.

The data describing changes in properties and real estate are based on direct physical observation and research conducted in digital media. The northern boundary of Parque Fundidora runs along Francisco I. Madero Avenue, this section spans nearly one kilometer, providing a direct view of numerous real estate developments. These properties are still listed for sale on official websites, and their availability can be physically verified through advertisements displayed on the buildings themselves. Searches were conducted on different platforms for buying, selling and leasing properties.

To analyze the social impact of the park's transformation, a perception survey was conducted among diverse user groups (athletes, families, casual visitors,). The instrument was designed to capture the perception of the users between regular park use and event-active periods. The synthesis of the user feedback yielded three primary insights concerning the impact of event logistics.

Experience displacement: Statistically, the data shows a 75% drop in user satisfaction. While the park is rated 7.6/10, under "normal" conditions, this score collapses to 1.9/10 during event periods. This quantitative drop reflects a mismatch between the park's primary purpose and its temporary private use.

Temporal and spatial friction: While official event timelines are limited to specific dates, approximately 90% of users report that accessibility restrictions and spatial disruptions persist for days or even weeks. Revealing how the logistical burden of staging and dismantling creates a temporal friction that far exceeds the duration of the events themselves. The survey data specifically identifies the closure of the main track circuit and green areas as the primary drivers of user frustration and eventual abandonment of space.

Perceived privatization: Accessibility and free recreation are the most degraded factors according to 70% of participants. This shift converts a public asset into a restricted "bottleneck", where saturation and physical barriers force the displacement. Qualitative responses reflect a recurring sentiment: the transition from a "public park" to a "private venue". Users explicitly mention that the park has become "inaccessible" and "saturated", leading to a forced change in their use habits. This feedback evidence that the current management model prioritizes event-related revenue over the continuity of the public realm. The resulting displacement affects the local citizens indiscriminately: while non-participants lose their right to the city, even event attendees report a degraded experience due to the saturation and physical barriers thar compromise the park's basic functionality.

3 Results

3.1 Intensification Use and Public Space Inaccessibility on the Park

The data collected shows a clear increase in the intensity, frequency and scale of the events held in the park. From an economic standpoint, prices have also risen, although these increases are not always gradual and do not always correspond to what is offered. Recent events have reached an attendance exceeding 300,000 people and nearly 70% of the park's open public space has been occupied during the preparation and execution of the events (Figs. 1 and 2) (Table 1).

Delimitation of the Different Areas in Parque Fundidora According to Use

Green: Indicates public access areas that may vary according to the park's agenda.

Orange: Indicates permanent restricted-access paid areas.

Blue: Indicates areas temporarily reserved for private use during festivals.

(Figure 3 indicates the minor recorded area allocated for such events, Fig. 4 depicts the maximum.)

A 20-day restriction period is estimated based on the average duration of setup, execution, and dismantling activities, as documented in press reports and on-site observations. Calculating these days for each event reveals how the park operates under conditions of limited space and obstruction caused by these activities and the subsequent repairs dimension required [12–14] (Fig. 5) (Table 2).

3.2 Peripheral Development and Real Estate Property Transformation

The intensification of activities at Parque Fundidora has led to a notable transformation along Francisco I. Madero Avenue. Property development in the area shows a trend toward businesses that benefit from the park's management shift and infrastructure improvements. These businesses can offer services to event-goers without having to invest in the events themselves.

Once a commercial corridor of moderate importance composed of auto repair shops, educational centers, banks and small convenience stores, it has now been converted into a developing corridor of hotels and mixed-use buildings. In some cases, leasing offers targeted specifically at demographic profile can already be found on platforms such as Airbnb [15, 16].

Table 3 presents data on the current and previous uses of properties developed along Francisco I. Madero Avenue. The most prominent private development "Novus Fundidora" is situated within the park itself. This illustrates how real estate dynamics are not limited to the surrounding urban fabric but have begun to integrate directly into the park's spatial structure. When searching for information regarding the apartments available within the complex, it is common to find conflicting statements about whether these areas were "ceded" or if they officially belonged to the park. It is where the opacity of the public-private management model becomes most evident. However, promotional advertising for these spaces frequently uses slogans and catching phrases such as: "The project that connects us to Fundidora", "Fundidora is my future", "Your apartment in Fundidora", this information is provided by official sources within the complex's administration that makes it clear the park's role is to promote itself as an amenity [17] (Fig. 6).

Table 1. Historical record of massive events. *Source*: Own elaboration.

Year	Day/Month	Name of the event	Registered Attendance (Persons)	Ticket Cost (USD)	Park area used (ha)
2008	08/11	Coca-Cola Zero Fest	15,000	$27.48–$56.09	10.3
2013	24/03	Machaca	14,000	$14.02–$19.63	1.78
	09/11	Pa'l Norte	52,000	$28.04–$44.87	12.8
2014	24/05	Machaca	24,000	$30.85–$61.69	10.8
	5,6,7/09	Monterrey City Festival	65,000	$25.24–$112.17	9.31
	31/10, 1/11	Pa'l Norte	104,000	$33.37–$122.83	17.9
2015	24,25/04	Pa′l Norte	114,000	$33.37–$134.60	17.9
	29,30/05	WISH	50,000	$58.89–$224.34	14.2
	13/06	Machaca	50,000	$22.43–$168.26	10.8
	20/06	Indio Unión Libre	30,000	$11.22–$39.26	10.8
	29/08	Hellow Festival	67,000	$33.37–$50.42	20.4
	10/11	Fusión Ska	5,000	$21.31–$50.48	1.78
	12/12	Tecate live out	27,000	$42.06–$75.72	17.7
2016	15,16/04	Pa'l Norte	134,000	$36.17–$168.26	19.2
	21/05	WISH	50,000	$39.26–$67.30	14.2
	18,19/06	Machaca	80,000	$22.43–$131.80	16.3
	20/08	Hellow Festival	68,000	$32.53–$95.34	24.0
	01/10	Heineken Live Out	40,000	$30.85–$66.18	16.4
	12/11	Northside Corona	32,000	$33.65–$168.26	6.5
2017	31/03, 01/04	Pa′l Norte	170,000	$70.67–$126.75	26.1
	27/05	WISH	50,000	$39.26–$84.13	14.2
	17,18/06	Machaca	90,000	$56.65–$90.86	16.3
	26/08	Hellow festival	76,000	$39.26–$112.17	28.2
	07/10	Mother of All	36,000	$81.32–$165.45	22.0
	21/10	Heineken Live Out	62,000	$47.67- $84.13	17.7
	28/10	Northside	19,000	$43.75- $84.13	14.8

(*continued*)

Table 1. (*continued*)

Year	Day/Month	Name of the event	Registered Attendance (Persons)	Ticket Cost (USD)	Park area used (ha)
2018	10/03	Beyond Wonderland	53,000	$42.06–$109.37	16.0
	20,21/04	Pa′l Norte	210,000	$81.88–$188.45	32.7
	26/05	WISH	55,000	$44.87–$95.34	14.2
	23/06	Machaca	40,000	$33.65–$215.93	26.2
	25/08	Hellow festival	55,000	$61.64–$280.37	24.1
	20/10	Tecate Live Out	55,000	$50.48–$92.54	17.7
	03/11	Mother of All	67,500	$131.80–$258	18.1
2019	22,23/03	Pa′l Norte	210,000	$93.10–$281	35.2
	25/05	WISH	35,000	$61.69–$112.17	14.2
	24/08	Hellow festival	78,000	$70.11–$308.47	36.0
	19/10	Tecate Live Out	53,000	$44.87–$84.13	17.5
	22/10	Machaca	60,000	$89.74–$153.39	31.0
	5/11	Beyond Wonderland	100,000	$44.87–$103.76	19.2
2021	12,13/11	Pa′l Norte	128,000	$124–$785.19	40.6
	11/12	Nortex	20,000	$56.09–$148.63	31.0
2022	1,2/04	Pa′l Norte	160,000	$121–$886.15	40.6
	21/05	Power Fest/WISH	45,000	$89.74–$151.43	14.2
	25/06	Machaca	90,000	$92.54–$187.89	31.4
	15/10	Tecate Live Out	57,000	$47.67–$100.67	17.5
	5/11	Beyond Wonderland	80,000	$50.48–$103.76	19.2
	10/12	Nortex	18,000	$49.36–$148.63	18.1
2023	7/03	Dale Mixx	60,000	$67.30–$196.30	37.0
	31/03, 1,2/04	Pa'l Norte	240,000	$190.80–$1,290	40.6
	24/06	Machaca	65,000	$101–$224.34	31.4
	1/07	Miller Lite Grill Together	N/D	$67.30	3.0
	21/11	Heineken silver Live Out	60,000	$67.30–$134.60	17.5

(*continued*)

Table 1. (*continued*)

Year	Day/Month	Name of the event	Registered Attendance (Persons)	Ticket Cost (USD)	Park area used (ha)
2024	29,30,31/03	Pa′l Norte	300,000	$222.66–$1,346	40.6
	6/07	Miller Lite Grill Together	N/D	$67.30	3.0
	17/08	Dale Mixx	60,000	$75.72–$280.43	37.0
	12/10	Tecate Live Out	60,000	$81.32–$168.26	17.5
	2/11	Hasta los huesos	15,000	$84.13–$373.53	1.78
2025	04,05, 06/04	Pa'l Norte	300,000	$245–$1,570.40	43.8
	7/06	BANDIDOS Festival	70,000	$111.22–$231	17.9
	16/08	Dale Mixx dos equis	35,000	$78.52–$308.47	37.0
	7, 8/11	ARRE Pepsi Black	100,000	$70–$286.32	37.0
2026	27,28,29/03	Pa'l Norte	330,000	$257.43–$1,571	46.1

Attendance is calculated as the sum of all daily attendees throughout the event.

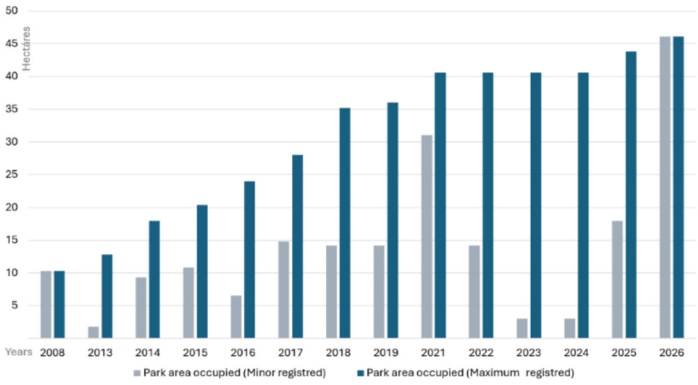


Fig. 1. Minor and maximum park area occupied per year.

The construction of a new elevated metro line traversing the park announced in 2023 coupled with a new station in front of "Novus Fundidora" plus upgrades of another existing metro station in 2025 near the area, reflects a trend of leveraging and exploiting public infrastructure interventions to maximize private real estate value. Rather than responding to the actual needs of those who integrate into the park's daily dynamics or taking care of the needs of the park users. These projects, temporary or permanent, appear to serve external interests. They leverage the benefit of public investment to

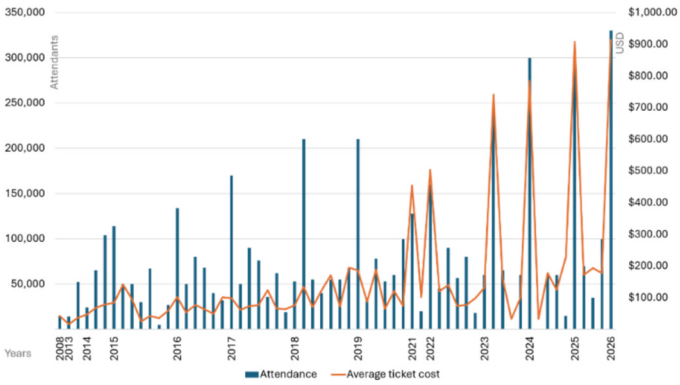


Fig. 2. Relationship between attendance and average ticket cost

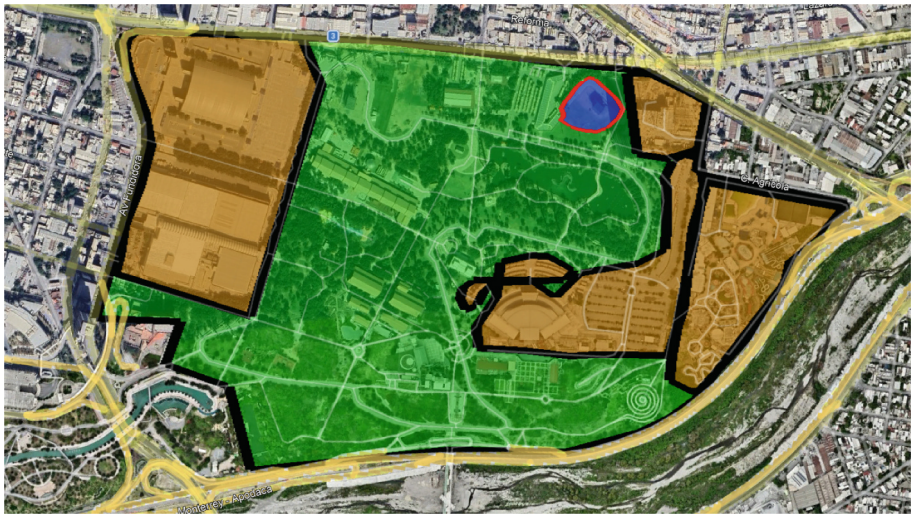


Fig. 3. Parque Fundidora. Source: Own elaboration based on a Google Earth image taken in April 2026.

add value to private properties or event offerings without direct reinvestment into the park itself and fail to provide and restore the intangible value to those who shape the space through daily interaction, instead capturing the profits from public projects and producing an artificial form of space [18] (Fig. 7).

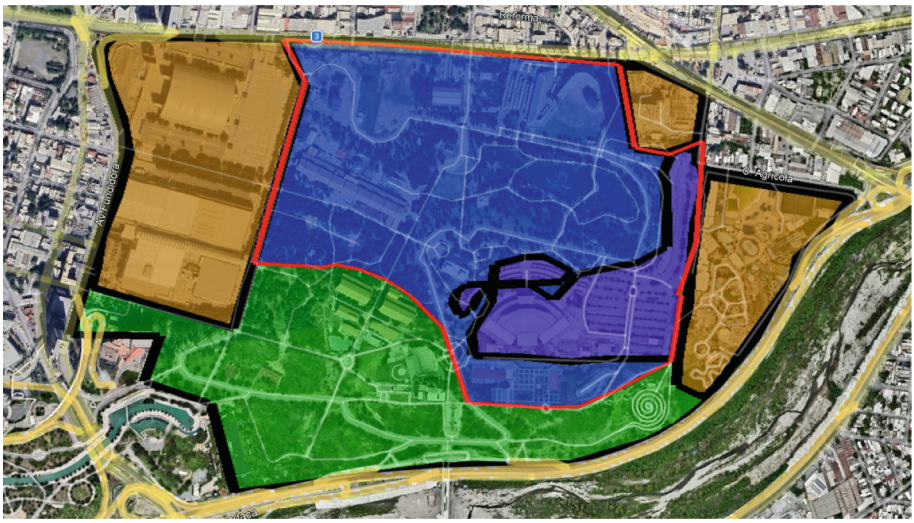


Fig. 4. Parque Fundidora. Source: Own elaboration based on a Google Earth image taken in April 2026.

Table 2. Periods of spatial obstructions. *Source*: Own elaboration.

Year	Estimated days with limited access or obstructions	Annual impact of accessibility and optimal use (%)
2008	21	6%
2013	42	12%
2014	126	35%
2015	189	52%
2016	168	46%
2017	189	52%
2018	168	46%
2019	148	41%
2021	63	17%
2022	147	40%
2023	147	40%
2024	147	40%
2025	147	40%
2026(1Q)	63	17%

Fig. 5. Parque Fundidora. Damaged area of the park 3 days after a festival event and new elevated metro line. Source: Own elaboration. Dron flight, May 6, 2026.

Fig. 6. Yellow figures represent real estate and land transformations. From left to right described in Table 3 by order of appearance. Green line delimits Parque Fundidora. Source: Own elaboration based on a Google Earth image, September 2026.

Table 3. Transformation of properties and land use. *Source*: Own elaboration.

Previous use	Current use	Building Name	Building year	Units/ Scale	Average cost (USD)
Auto repair shop	Hotel	Hotel Myst 4	2020	35 Rooms	$85.00
Educational center	Hotel	Tru by Hilton 4.5	2019	120 Rooms	$85.00
Restaurant	Mixed-use	Arena Vive el parque	2020	154 Units + Retail	$280 M
Part of Parque Fundidora	Mixed-use	Novus Fundidora Departamentos Hotel	2020	700 Units. 200 Rooms 16,500 m2 Retail	$297 M

Fig. 7. Elevated metro line structure and new station under construction in front of Novus Fundidora complex. Source: Own elaboration, dron flight, May 6, 2026.

4 Discussion and Conclusions

An effort to regenerate this industrial site and convert it into a public space for its citizens has been turned into a mixed-purpose area, combining private events with real estate developments. The actions taken to upgrade the park remarks a clear connection between these dynamics and the immediate outcomes that benefit them, failing to establish a balanced distribution of those benefits and a sustainable management framework that allows for the preservation of the park's integrity while maintaining a balanced exploitation of its resources.

Several indicators emerged linking the phenomena of exploitation and segregation to the new management dynamics adopted by Parque Fundidora. The surrounding areas have been transformed into a product designed to serve those seeking to commercialize the space. These actors face a unique opportunity: guiding urban interventions as amenities that enhance the appeal of their commercial offerings.

The intensification of events has not only increased the occupation of space within the park but has also normalized extended periods of unusable spaces due to equipment installation and dismantling operations. As a result, users who do not participate in these activities (whether by choice or due to economic constraints) are systematically displaced from the everyday use of the park. Although it could be argued that not all spaces must cater to every user, the continuous prioritization of event-oriented dynamics creates an imbalance where the non-consuming user is no longer considered, weakening the park's public character.

This transformation is closely linked to the evolution of the surrounding urban environment. These changes reflect a shift toward functions aligned with high-intensity, event-driven demand. In a deeper sense, the park operates not only as a recreational space but as a catalyst for real estate valorization. However, a significant side effect emerge when such developments occur. When changes are implemented, rather than responding to natural behavior there's a lack of desirability in the products, rooted in the incongruence of the "ideal buyer" profile. The reality is that demand for these units is low. The sale and promotion of these spaces is related to mismanagement in pre-sales and other underlying issues; developers have failed to position them as desirable products within the real estate market. While this fact is worth mentioning, it is far from the main reason for the principal phenomenon. The resulting non-demand effect, where unsold units languish at prices far exceeding market willingness to pay, creates an imbalance, corrupting local valuation criteria through artificially inflated supply.

The marketing strategies that lead developments to explicitly capitalize on their proximity to the park (framing it as an amenity that enhances real estate value) reveals a cyclical relationship between public space and private value creation. The existence and maintenance of Parque Fundidora as a public asset contribute directly to the economic potential of surrounding developments. In this sense, public space operates as a value generator that is subsequently captured and capitalized by private actors [19]. However, as this process intensifies, the conditions that enable this value (namely accessibility, openness, and collective use) begin to erode. As access becomes increasingly conditioned by event programming and economic participation, the public function of the space is progressively limited, leading to a paradox where the success of the public realm contributes to its own dissolution. The park's mixed-management model facilitates this phenomenon. By 2026, the interior of the park has increasingly become a "pay to play" environment, where financial expenditure is a growing prerequisite for enjoying its amenities. Long pathways lacking public water fountain, the strategic and only placement of functional restrooms near commercial areas, and the aggressive expansion of food and snack franchises have transformed the park into a space of economic consumption rather than one of hospitable recreation. This shift undermines the user's freedom of choice, effectively forcing consumption as a necessity to successfully carry out any activity withing the grounds.

The purpose of comparing international cases is allow a deep reflection on aspects we may be overlooking in the development of our urban landmarks. The High Line in New York does not deny the fact that the development of a popular, well-trafficked and well-maintained public space can serve as an attraction that benefits nearby private entities. However, it demonstrates an ideal approach: providing intrinsic value through its very presence in the urban fabric (a value appreciated by those who enjoy space without invading or restricting interaction between the public and private realms. In this way, both sides enhance each other through their presence, composition and shared value. Landschaftspark Duisburg-Nord, despite its isolated location and the challenging conditions for its restoration, priories the creation and preservation of a space dedicated to landscape rehabilitation and public enjoyment. Parque Fundidora does not fully align with either model; instead, it reflects a trend where private entities exploit public spaces for their own benefit. These actors not only avoid investing in the improvement of the space but also by steering public regeneration efforts under the guise of user improvements. Ironically, these users long ago stopped expecting better treatment, resigned themselves to deficient public amenities that show no sign of improvement based on user-experience criteria. Furthermore, this self-interest creates flaws in the real estate system by implementing products that also fail to meet specific needs [20].

The political implications behind the park's management, operating as a decentralized organism with direct ties to the state, has adopted a corporate logic that prioritizes cash flow over citizens rights and freedom. This administrative autonomy has served as a mechanism to justify the commodification of public land: the park is no longer managed as a common good, but as a financial asset that must be profitable. Under this pro-growth governance model, the administration acts more as a lessor of spaces than as a custodian of urban heritage, allowing economic success of festivals to be built on the externalization of cost onto the user, who ultimately pays the social price through exclusion, noise and the physical fragmentation of their own space and market.

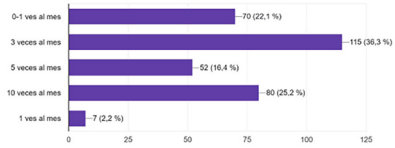
Disclosure of Interests.. The authors have no competing interests to declare that are relevant to the content of this article.

Attribution of the parts of the text is the result of the joint work of all authors and will be attributed in equal parts.

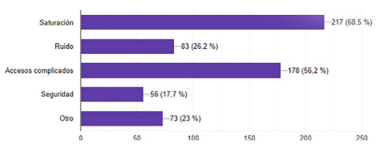
Appendix A. Survey instrument and methodology.

The survey was conducted digitally in April and May 2026.

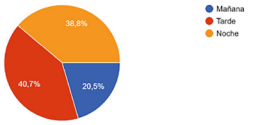
¿Con que frecuencia visitas el parque fundidora durante el año?
317 respuestas



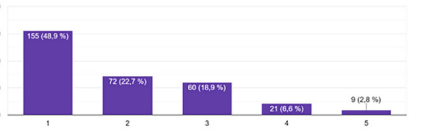
¿Por qué?
317 respuestas



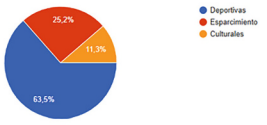
¿En qué horario sueles asistir? (Selecciona la más frecuente)
317 respuestas



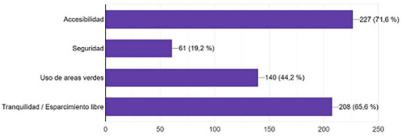
¿Cómo cambia tu experiencia en el parque cuando hay eventos?
317 respuestas



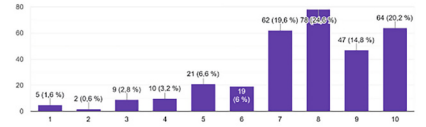
¿Qué actividades realizas regularmente en el parque? (Selecciona la más frecuente)
318 respuestas



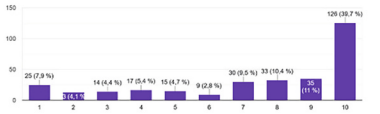
¿Qué aspectos de tu experiencia en el parque se ven más afectados cuando un evento masivo se agenda?
317 respuestas



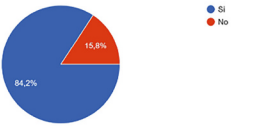
En condiciones normales, (Sin la intervención de un evento masivo) ¿Cómo calificarías tu experiencia en el parque?
317 respuestas



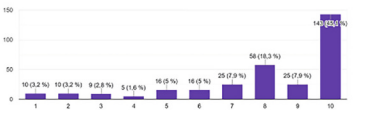
Las actividades que buscabas realizar en el parque se vieron afectadas y/o modificadas debido a la logística de montaje y/o desmontaje de los escenarios de los eventos masivos
317 respuestas



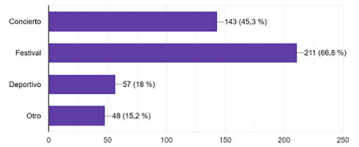
¿Has visitado el parque durante eventos masivos?
317 respuestas



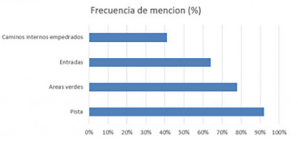
¿Haz encontrado obstáculos o áreas restringidas en el parque fundidora en alguna visita cercana a la realización un evento masivo?
317 respuestas



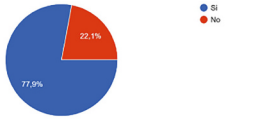
¿Qué tipo de evento era?
316 respuestas



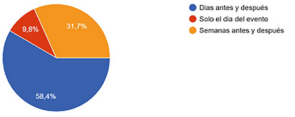
Según tu experiencia ¿Qué zonas del parque se vuelven inaccesibles durante eventos?
302 respuestas



Durante eventos masivos, ¿has considerado dejar de visitar el parque fundidora?
317 respuestas



Según tu percepción ¿Cuánto tiempo dura la afectación del parque en consecuencia a estos montajes y desmontajes y uso del parque para eventos masivos?
315 respuestas



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Evaluating the Multi-dimensional Impacts of the 10% Biodiversity Net Gain Requirement: A Methodological Proposal for Public Administrations

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Abstract. Biodiversity Net Gain (BNG) has been introduced in England as a mandatory planning requirement to reverse biodiversity loss and mobilize private investment in nature recovery. From February 2024, most new developments are required to deliver a measurable improvement of at least 10% in biodiversity value. With the start of BNG implementation, positive and negative externalities are emerging and since it is still in its early implementation phase, no widely validated academic framework currently exists that comprehensively evaluates its multi-dimensional impacts. In this context, we propose using the COSIMA (Composite SIgnificance and Multicriteria Assessment) framework as a tool for a holistic ex-ante evaluation of BNG projects. COSIMA integrates traditional cost-benefit analysis (CBA) with multicriteria decision analysis (MCDA) to generate a composite index called the Total Rate of Return (TRR). In this context, this framework ensures that the priorities of developers, government agencies, and local communities are reflected in the final evaluation by including a variety of criteria, both monetizable and non-monetizable. The framework was developed through a structured three-phase methodology combining an exploratory and a systematic scoping review, a stakeholder analysis, and a structured expert validation procedure involving multi-domain specialists to finalize a set of impact indicators spanning environmental, economic, social, and governance dimensions. COSIMA enables transparent, evidence-based comparison of alternative scenarios and provides public administrators and policymakers with a flexible tool to support stakeholder dialogue and optimize the BNG policy.

Keywords: Environment Act · Mitigation hierarchy · Impact assessment

1 Introduction

Biodiversity is the foundation of ecosystem functioning and provides critical ecosystem services, from food security and water purification to climate regulation and human well-being [1]. It holds both intrinsic ecological value and irreplaceable socioeconomic

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importance for human societies [2]. Despite this, biodiversity is declining at accelerating rates globally, driven by economic growth and development [3]. This trend makes it increasingly important to assess the likely ecological, economic, and social effects of biodiversity-related interventions at an early stage.

England is currently among the most nature-depleted countries in the world, having lost more than half of its native biodiversity due to centuries of urban development, habitat destruction, and intensive agriculture [4]. To reverse this trend, the UK government introduced Biodiversity Net Gain (BNG) as a mandatory requirement under the Environment Act 2021. This policy requires that most new construction projects must leave the local environment in a demonstrably better state than before construction. Specifically, the Statutory Biodiversity Metric (SBM) is used to ensure a minimum 10% gain [5, 6], a rule that has applied to most English construction projects since February 2024. This move marks a significant transition from the previous "No Net Loss" (NNL) approach, which focused on pure offsetting, towards a more proactive framework for ecological improvement [7].

BNG is in its early implementation phase and its implications at this stage are insufficiently studied, with several operational challenges already beginning to emerge. However, as a policy that only came into force in 2024, there is currently no widely validated academic framework currently integrates ecological, economic, social, and governance dimensions into a unified and stakeholder-driven assessment of the multidimensional impacts of BNG [8, 9–12].

To develop such a framework, it is necessary to examine the methodologies traditionally used for comparable initiatives. The evaluation of similar concepts to BNG such as broader environmental policies and nature-based interventions has employed a range of assessment tools. Among these, cost-benefit analysis (CBA) and multicriteria decision analysis (MCDA) have emerged as the most widely applied. CBA is formally prescribed by the UK Government's Green Book [13] and by European Commission as the main appraisal methodology for public policies [14], based on the monetization of direct costs and benefits. However, it systematically underestimates non-market ecological, social, and cultural values [15] which are critical to BNG's objectives. On the other hand, MCDA captures qualitative and multidimensional trade-offs between different stakeholder values, but lacks the economic interpretability required for public financial evaluation [16].

To address this gap, this paper proposes COSIMA (COmposite SIgnificance and Multicriteria Assessment), as an integrated decision-support framework for the ex-ante evaluation of BNG interventions. COSIMA was originally developed by Barfod and Salling for transport appraisal [17] and was later adapted for ecosystem services assessment by Oppio et al. [16]. In this study, COSIMA is extended for the BNG context by integrating into a unified Total Rate of Return (TRR) indicator [16]. The proposed framework is structured around three core stakeholder perspectives of developers, local government bodies, and local communities and based on a rigorous dual-stream review and validated by an expert panel. The scope of this paper is limited to the conceptual and methodological development of the COSIMA-based assessment framework. Its empirical application to the Italian planning context will be addressed in a subsequent research phase.

Following the definition of our research objectives, Sect. 2 reviews the current BNG policy landscape and highlights where existing assessment tools fall short. Section 3 details our methodology. Section 4 presents the final, validated list of these indicators. Section 5 discusses preliminary findings and practical policy implications. Finally, Sect. 6 summarizes the main contributions, acknowledging their limitations and suggesting future perspectives.

2 Literature Review and Policy Context

2.1 Evolution of Biodiversity Compensation

The BNG introduced by the Environment Act 2021 [5] requires new construction projects in England to increase local biodiversity by at least 10% [18]. This requirement is based on a measurable net improvement in biodiversity value, rather than on simple compensation for ecological loss. This legislation marks an evolution from the previous concept of NNL [19]. While NNL aimed simply to offset damage to maintain the status quo, BNG transforms development into an active tool for environmental restoration (Fig. 1).

The implementation of BNG is based on two key pillars. The first requires developers to give absolute priority to avoiding ecological damage, intervening with improvements only where the impact is unavoidable. The second is based on the SBM, developed by DEFRA and Natural England [20, 21]. This tool assesses the health of the environment before construction begins. By analyzing the size, quality, and characteristics of habitats, SBM provides a transparent and measurable method to ensure that the claimed benefits are real and monitorable over time. In short, BNG shifts the focus from simply limiting damage to creating long-term benefits, making the construction sector directly responsible for ecosystem regeneration.

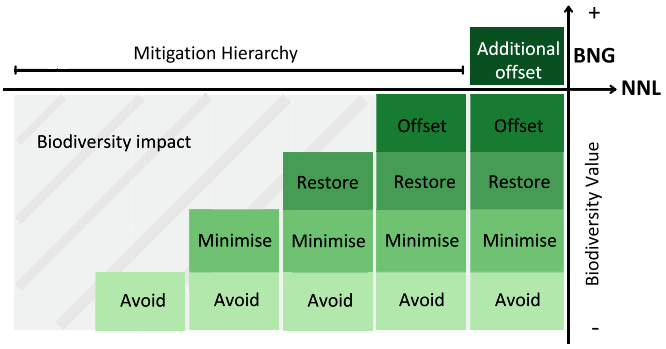

Fig. 1. Previous No Net Loss policy and the new BNG approach to mitigate biodiversity loss during development. Redrawn by the authors based on [18]

2.2 Evaluation Standards and Assessment Framework

A range of methodological frameworks have been applied in the scholarly and policy literature to assess environmental policies and nature-based interventions, including Environmental Impact Assessment (EIA), Cost-Effectiveness Analysis (CEA), MCDA, and CBA. Among these, CBA and MCDA have emerged as the most widely applied tools for capturing impacts. CBA is formally prescribed by the UK Government's Green Book as the core appraisal methodology for public policies [13]. MCDA is recommended for complex interventions involving multiple objectives and diverse groups of stakeholders. Together, these two approaches provide the methodological basis for assessing both monetizable and non-monetizable impacts, which is particularly relevant in the case of BNG. A review of grey literature has shown that the specific actions used to deliver biodiversity gain include the creation of new habitats through Nature-Based Solutions (NBS), interventions that use natural processes to deliver environmental and social benefits, and Green Infrastructure (GI), as well as the enhancement of existing habitats [6, 10]. Evidence from these similar concepts, including Ecosystem Services (ES), NBS, and GI, which share BNG's core characteristics confirms that neither CBA nor MCDA alone is sufficient. Monetary methods fail to capture social and ecological values, while qualitative approaches lack the economic rigor required for public appraisal. CBA excels at monetizing direct costs and benefits and enables transparent financial accountability. However, it systematically under-represents non-market values, including social well-being, ecological quality, and institutional trust [13, 22], that are central to BNG's objectives. MCDA captures qualitative, multi-dimensional trade-offs and incorporates diverse stakeholder values. However, it lacks the economic rigor required for public financial appraisal and can be sensitive to subjectivity in weight elicitation [16].

Stated preference methods, such as contingent valuation and choice experiments, offer a partial bridge by translating selected non-market values into monetary estimates. However, their reliance on hypothetical scenarios introduces uncertainty and limits their applicability in complex, multi-stakeholder contexts such as BNG [23].

Beyond project-level appraisal tools, several internationally recognised frameworks have also been developed to account for the values of biodiversity and ecosystem services at broader scales. The System of Environmental-Economic Accounting (SEEA EA) constitutes a statistical framework for tracking ecosystem changes at national scale [24], and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) produces scientific assessments of biodiversity at the supranational to global scales to inform international policy [2]. However, these frameworks share a common limitation in the context of BNG project appraisal. They primarily operate as accounting or assessment frameworks and are less suited to project-level ex ante option appraisal [25]. Crucially, none of these frameworks produces a single composite indicator capable of capturing how each stakeholder group experiences the impacts of a BNG project differently. Moreover, they do not provide a decision-making structure for comparing how alternative project options may affect different stakeholder groups before implementation.

2.3 Current Implementation Challenges

The implementation of the BNG program is facing significant challenges that could jeopardize the achievement of its objectives. On the one hand, the market for biodiversity units has had a slow start. By July 2024, only a few sites, totaling less than 300 ha, had been included in the Register of Biodiversity Enhancement Sites. This falls substantially short of the government's target of 6,700 ha per year [10]. On the other hand, developers are struggling to comply with the BNG. In the first five months of the policy's implementation, only 0.5% of planning applications included provisions related to the BNG. The main problem appears to be that the new rules are simply too complex to manage. The amount of paperwork and the financial burden of managing the sites for decades pose huge obstacles for developers. It is not just private developers who are struggling. The public sector is also having a difficult time. Local planning authorities are legally required to oversee BNG, but most local councils lack the resources to monitor sites and ensure compliance [12, 26].

The challenges are not only administrative and management-related. At a societal level, although local communities may benefit from improved green spaces and improved ecological quality, they may be excluded from decision-making processes regarding the location and methods of habitat creation outside the sites. This can result in biodiversity gains being concentrated in some areas, while losses occur in others, leading to an unequal distribution of benefits among different population groups [27]. These multidimensional challenges suggest that BNG may generate complex and often uneven impacts on different stakeholder groups, particularly between developers and local communities, impacts that cannot be captured through a single assessment approach.

3 Methodology

3.1 Research Design

The research adopts an integrated methodological design organized into three main phases. The approach begins with a stakeholder analysis (SA), which provides the conceptual foundation for the framework. This phase is crucial in the context of NBSs, which, as in all complex decision-making problems, involves a diverse set of actors with potentially conflicting interests. Specifically, SA allows for the identification of actors and helps clarify their roles and the ways in which they are influenced by policy.

In parallel, a review is conducted that combines grey and policy literature, with a systematic analysis of academic and scientific sources. The grey literature review contributed to understanding the actions used in implementing NBSs and their impacts, the real emerging challenges, externalities, and the starting point for future research and analysis. We also examined the academic literature to identify potential indicators from previous studies on ecosystem services and NBSs. The next step involved a validation process of the initially identified set of indicators, involving a panel of experts. This rigorous filtering made our framework practical for real-world use. After the final list was approved by reviewed by the expert panel, we moved to the final step. Here, we use the total rate of return (TRR) [17] as a performance indicator derived from the COSIMA approach. The TRR combines CBA and MCDA into a single tool. As Fig. 2 shows, this

process provides us with a clear way to calculate performance and compare different BNG scenarios. As noted above, the present methodological phase focuses on building the assessment structure, while an application will be used later to test its empirical implementation.

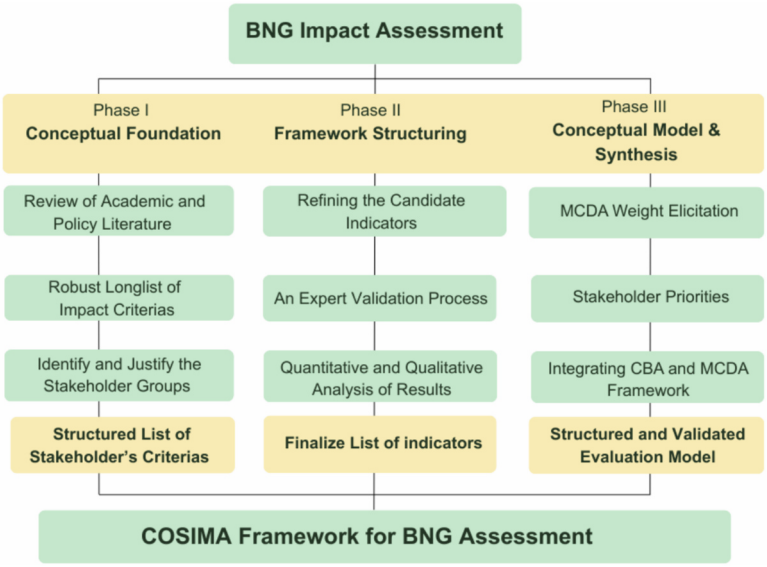

Fig. 2. Three-phase research workflow for COSIMA development.

3.2 Stakeholder Analysis

As mentioned above, the first step of the framework involves SA. In this phase, we identify the main actors affected by BNG decisions and consider how their different interests and values can be represented in the assessment framework [16]. This is important for identifying the set of indicators in the first place. But it is also relevant for the application of the MCDA, which seeks to capture real, intangible, and extra-economic priorities and trade-offs, rather than simply considering monetary aspects. This way, we can obtain a more complete picture and consider aspects that would otherwise be excluded by applying CBA alone.

To identify stakeholders, we relied on two existing frameworks. First, the NECR502 assessment plan [29] groups actors based on their proximity to the project. "Primary" stakeholders, such as developers and planning authorities, have legal responsibilities. "Direct" stakeholders, such as ecologists and contractors, are responsible for technical execution. Finally, "indirect" actors, including universities and civil society, shape the broader policy debate. We combined this insight with the BNG and ENG stakeholder map [30]. This second tool tracks who is involved at each stage of a project. It includes a wide range of actors, from funders and legal teams to service providers and local residents.

This mapping informed the selection of the three main stakeholder perspectives later discussed in Sect. 4.1.

3.3 Indicator Selection Process

To better understand how the BNG policy works, we examined policy documents, technical guidance, and grey literature reports, including materials from Natural England and the Green Finance Institute. We used this information to select several key indicators for the next stage that would demonstrate the policy's effectiveness. These indicators are important because they help us understand whether the policy is having the desired impact against its objectives. By analyzing both academic research and practical aspects, we can gain a more complete picture of the policy's performance.

In parallel, a systematic review of the scientific and academic literature was conducted. The database used in this preliminary analysis phase was ScienceDirect, updated in August 2025, based on ten Boolean search queries predefined by the authors. Following the PRISMA-ScR protocol, the initial search yielded 3,259 results. These were subsequently refined through a multi-stage filtering process based on English language, document type, journal articles only, and a publication period defined between 2020 and 2025. We cleaned the search results by eliminating duplicates and analyzing titles and abstracts. This led to 23 relevant products. A matrix including authors, title, evaluation methodology (monetary and non-monetary), and indicators used was created to gather all the information. From this selection, we extracted specific indicators directly from 18 articles that explicitly reported assessment criteria or measurable indicators, creating an initial list. Then, we began filtering. We combined the overlapping ideas and eliminated anything that was difficult to measure ex ante (before a project begins). Ultimately, we arrived at 26 practical indicators, grouped by stakeholder and dimension.

3.4 Expert Review Procedure

To assess the relevance, clarity, and practical applicability of the indicators to be included in the model, we asked a panel of experts to review them. We selected individuals with a combination of academic research in decision support and practical experience in the public and private sectors in environmental assessment. This validation was conducted in two phases. First, the experts rated each indicator on a scale of 1 to 5 in terms of relevance and clarity, using a Likert scale. This allowed us to initially determine whether the selected indicators were meaningful and aligned with the objective. They also provided feedback and comments, which we used to simplify and refine the list. Once the indicator list was refined, the same panel weighted the MCDA criteria. The method used was the 100-point method. In detail, experts allocated 100 points across the MCDA indicators within each stakeholder category, according to their professional judgment. This approach supports transparency in the validation process and provides an initial consolidation of the model, although the results remain limited by the small size of the expert panel.

3.5 The COSIMA Framework

CBA handles financial data well. It easily tracks investment costs, maintenance, and monetizable ESs. However, it does not account for social and environmental values that do not have a direct market price. COSIMA solves this problem by integrating CBA parameters with a multi-criteria analysis module based on multi-attribute value theory (MAVT). COSIMA allows for the aggregation of monetary and non-monetary performance by calculating the total rate of return (TRR) for each alternative A_k using Eq. 1:

$$TRR(A_k) = \frac{TV(A_k)}{C_k} = \frac{1}{C_k} \cdot \left[\sum_{1=1}^{n} V_i(X_{ik}) + \alpha \cdot \left(\sum_{j=1}^{m} w_j \cdot V_j\left(Y_{jk}\right) \right) \right] \quad (1)$$

where A_k represents the specific project option under review. $TV(A_k)$ stands for its Total Value, which gathers all the benefits together. On the expense side, C_k tracks the Total Cost. This includes both the upfront investment and 30 full years of maintenance. The next terms break down the actual benefits. $V_i(X_{ik})$ calculates the Net Present Value for everything that has a strict financial price (the CBA impacts). On the extra-economic side, $V_j(Y_{jk})$ provides the score for a specific non-monetary criterion j, while w_j is the exact weight our experts assigned to that goal. Before aggregation, the non-monetary indicators are converted into comparable value scores through criterion-specific value functions. Finally, α acts as a sliding scale. It lets us test how much the MCDA scores should influence the final result. Setting to 0% gives us a traditional financial CBA, while pushing it to 100% fully integrates both economic and social values [16, 17].

4 Stakeholder Perspectives and Indicator Validation

4.1 Core Stakeholders

Building on the stakeholder mapping described in Sect. 3.2, the COSIMA framework assesses BNG impacts from three main perspectives: developers, local authorities, and local communities. The first concerns developers, who, as the primary delivery actors, are responsible for managing upfront costs, biodiversity credits and long-term maintenance obligations extending over 30 years [7, 31].

A second perspective focuses on local authorities, whose oversight and enforcement roles are often constrained by limited institutional capacity, as well as by the need for consistent and rigorous monitoring to ensure public value [27, 32].

Finally, the framework considers the perspective of local communities, with particular attention to the distribution of social and environmental co-benefits. This includes aspects such as access to green spaces, wellbeing and the broader quality of the local environment [27, 33].

4.2 Outcomes of the Expert Review

As anticipated, an expert panel was formed to review the indicators identified in the literature and carefully selected by the authors. This panel consisted of four members

with diverse professional backgrounds, including research, national policies, and local government, each with their own area of expertise. This ensured that all aspects of BNG implementation were considered and a diverse range of perspectives were provided. The composition of this expert panel is shown in Table 1.

When the experts examined the indicators, they found that they were overall relevant, but that different groups had different priorities. For developers, the indicators focused on economic aspects, such as the cost of on-site construction and 30-year maintenance. The experts also considered off-site costs and registration fees. However, they did not consider the legal incentives to be that important, using them only when strictly necessary. Feedback on government incentives was mixed. This was because the rules for combining and adding incentives were too restrictive. Experts believed that having well-integrated policies and plans was very important, simplifying administration and contributing to environmental protection.

Table 1. Expert panel composition

Expert profile	Country	Field of expertise
Public Sector / Agency	UK	Ecology, BNG policy, monitoring & evaluation
Practitioner / Consultancy	UK	Environmental planning, local authority BNG support
Academia	Italy	Real estate evaluation, multidimensional assessment
Academia	Italy	Urban planning, green infrastructure

From the municipalities' perspective, the focus was on broader policy outcomes that had a community impact. For example, they believed that preventing flooding in cities and absorbing carbon were very important because they helped cities adapt to climate change. The experts also emphasized the importance of ensuring that the actions taken aligned with local priorities. This way, the money invested would have a real impact at the local level. When they analyzed what matters to local communities, a key aspect emerged. The experts interviewed stated that being in contact with nature is good for both the body and the mind. They believe that ensuring everyone has access to these benefits is essential to creating equity, which is what we mean by environmental justice.

4.3 Resulting Indicator Set

Following the preliminary expert-informed validation, the initial indicators were refined by cross-referencing the Likert-scale ratings and feedback with the MCDA weights. This step distinguished between core indicators valid for all cases and context-dependent indicators specific to certain implementation scenarios. Furthermore, four new indicators were proposed and discussed with the experts: Ecosystem Services Provided (C5), Protected Species and Sites (C6), Nature Recovery and Ecological Connectivity (C7), and Local Planning System Capacity (C8). These indicators were added to better capture ecological quality, access to nature, and institutional capacity, which emerged as important dimensions during the expert review. The resulting indicator set, organized by

stakeholder and dimension, is shown in Tables 2, 3 and 4. Some data sources reported in these tables refer to their potential use in a future Italian application of the framework, specifically in the City of Turin, and are included to illustrate transferability rather than to report empirical results.

Table 2. Developer related indicators for COSIMA BNG assessment.

ID	Indicator	Dim.	Type	Main Data Source	Unit
B1	Cost of BNG Delivery (On-site)	Eco	CBA-Cost	DEI – Construction Cost Manuals; Regional Price Lists; City of Turin – Public Works Department	€/m^2, €/tree, €/unit
B2	Cost of BNG Delivery (Off-site)	Eco	CBA-Cost	ISPRA – Land Consumption & Restoration Reports; LIFE Projects Database	€/ha or €/m^2
B3	Statutory Biodiversity Credit Price	Eco	CBA-Cost	Credit prices from analogous environmental markets (e.g., carbon) or engineering cost estimates	€/unit
B4	Site Registration Fee	Eco	CBA-Cost	Regional / Municipal administrative fee lists (SUAP, VIA, VINCA)	€/application
B5	Maintenance Cost (30-year)	Eco	CBA-Cost	DEI – Maintenance Cost Manual; City of Turin – Green Plan / Contracts	€/m^2/year or €/tree/year (NPV 30 yrs)
B6	Government Incentives / Subsidies	Eco / Gov	CBA-Benefit	MASE – Funding and Incentive Programs; PNRR – Mission 2; LIFE and PSR grants	€/project or grant
B7	BNG Uplift Ambition	Env	MCDA-Criterion	% net gain above statutory 10% minimum; scored on expert-validated scale	% biodiversity net gain
B8	Policy / Plan Congruence	Gov	MCDA-Criterion	Qualitative alignment with Local Plans and national policy frameworks	Performance scale

Note: Dim. stands for Dimension. The dimensional abbreviations used are: Eco (Economic), Env (Environmental), Gov (Governance), Soc (Social), Cul (Cultural), and Hea (Health).

Table 3. Municipality related indicators for COSIMA BNG assessment.

ID	Indicator	Dim.	Type	Main Data Source	Unit
C1	Urban Flood Risk Mitigation	Env	CBA-Benefit	Hydrological models; damage cost databases	€ (from m^3 retained)
C2	Carbon Sequestration	Env. / Eco	CBA-Benefit	EU ETS / Voluntary Carbon Markets; DEI – Green Works / Ecological Engineering	€/tCO_2e or €/ha habitat creation
C3	Achievement of Strategic Policy Targets	Gov	MCDA-Criterion	% of policy objectives achieved; scored against policy documents and project reports	% achievement; Score [1–3]
C4	Job Opportunities	Soc / Eco	MCDA-Criterion	Quantitative count of employment opportunities created; expert-validated scale	no. jobs created
C5	Ecosystem Services Provided	Env. / Eco	MCDA-Criterion	Composite qualitative score of ES bundle delivered; expert-weighted criterion	Performance scale
C6	Protected Species / Sites	Env	MCDA-Criterion	Qualitative assessment of contribution to protected species recovery; ecologist expert score	Performance scale
C7	Nature Recovery and Ecological Connectivity	Env	MCDA-Criterion	GIS Connectivity Analysis	Landscape Connectivity Index; Score [1–3]
C8	Local Planning System Capacity	Gov	MCDA-Criterion	Qualitative assessment of LPA administrative and monitoring capacity	Performance scale

Note: Dim. stands for Dimension. The dimensional abbreviations used are: Eco (Economic), Env (Environmental), Gov (Governance), Soc (Social), Cul (Cultural), and Hea (Health).

Table 4. Local community related indicators for COSIMA BNG assessment.

ID	Indicator	Dim.	Type	Main Data Source	Unit
D1	Property Value Uplift	Eco	CBA-Benefit	Academic literature (WTP, Travel Cost); Real estate data	€/m^2 or % uplift

(*continued*)

Table 4. (*continued*)

ID	Indicator	Dim.	Type	Main Data Source	Unit
D2	Urban Cooling (Heatwave Mitigation)	Eco	CBA-Benefit	Microclimate models; energy price data	€ energy savings from Δ°C reduction
D3	Recreation Value	Soc / Cul	CBA-Benefit	Academic literature (WTP, Travel Cost)	€/visit or €/year
D4	Access to Green Space	Soc / Hea	MCDA-Criterion	GIS analysis: % residents within 300 m of accessible green space; WHO benchmark scoring	% residents within 300 m
D5	Inclusion in Decision-Making	Soc / Gov	MCDA-Criterion	Procedural equity indicator; n° stakeholders engaged in weighting phase	Performance scale
D6	Social Inclusion and Cohesion	Soc	MCDA-Criterion	Proxy metrics: n° community events enabled; expert-validated scale	Performance scale
D7	Place Attachment and Cultural Identity	Cul	MCDA-Criterion	Community input or cultural mapping; qualitative score based on design documentation	Performance scale
D8	Opportunities for Social Relations	Soc	MCDA-Criterion	Design feature assessment; qualitative score based on project design documents	Performance scale
D9	Outdoor Activities	Hea / Soc	MCDA-Criterion	Diversity of outdoor uses provided; n° different activity types enabled by BNG design	no. activity types
D10	Places for Meditation and Psychophysical Well-being	Hea / Soc	MCDA-Criterion	n° dedicated spaces for quiet contemplation; quantitative count from project design	no. spaces

(*continued*)

Table 4. (*continued*)

ID	Indicator	Dim.	Type	Main Data Source	Unit
D11	Educational Activities	Soc / Cul	MCDA-Criterion	n° educational opportunities created (e.g. learning trails, school programmes)	no. opportunities
D12	Aesthetic Perception	Cul	MCDA-Criterion	Subjective aesthetic value; qualitative score based on structured expert or community assessment	Performance scale

Note: Dim. stands for Dimension. The dimensional abbreviations used are: Eco (Economic), Env (Environmental), Gov (Governance), Soc (Social), Cul (Cultural), and Hea (Health).

5 Discussion of Findings and Practical Application

5.1 Integration of COSIMA and Alternative Scenario Evaluation

The COSIMA framework enables structured comparison of alternative BNG scenarios, directly addressing the Green Book's requirements for robust options appraisal. As set out in the Green Book, public sector interventions must be assessed through a sequential process of establishing a clear Business As Usual (BAU) baseline, generating a longlist of options, and conducting detailed shortlist appraisal to identify the preferred approach that optimizes public value [13]. In practical terms, COSIMA requires the comparison of at least two scenarios: a baseline or BAU scenario, representing the existing condition, and a project scenario, representing the proposed intervention. Further BNG delivery options can then be added as alternative scenarios. COSIMA makes these requirements assessable in the BNG context by providing a unified framework capable of evaluating multiple scenarios, against a common set of validated indicators. To illustrate this potential use, a local planning authority could compare the existing condition with a proposed biodiversity-enhancement scenario and, where relevant, with additional BNG delivery options such as on-site habitat creation, off-site compensation, or credit purchase. In a future application of COSIMA, the authority could calculate a TRR for each alternative by monetising CBA indicators and scoring MCDA criteria using the expert-informed indicator set. The resulting TRR scores could provide a transparent, evidence-based basis for selecting the preferred option, making explicit the trade-offs between financial efficiency and broader ecological and social value. At the core of this capability is the TRR formulation, which integrates CBA with MCDA analysis, by aggregating stakeholder-weighted indicators into a composite score.

The expert validation process strengthens the credibility of the framework, while the variation in MCDA weights assigned by individual experts reflects the genuine plurality of values that characterise BNG decision-making [34, 35].

A recognised sensitivity of MCDA-based frameworks concerns the influence of stakeholder weighting choices on final results. Within COSIMA, different stakeholder groups are likely to assign different weights reflecting their distinct priorities, which will in turn produce different TRR scores for the same project alternative. Future applications of COSIMA could incorporate formal sensitivity analysis by systematically varying the α parameter and stakeholder weights to observe how TRR rankings respond under different value assumptions.

By revealing these tensions explicitly, COSIMA supports more informed and defensible option selection, providing public authorities with a transparent basis for negotiation between stakeholders with divergent priorities [35] and directly operationalising Green Book principles for evidence-based appraisal.

5.2 Policy Implications

COSIMA addresses a clear need for rigorous, transparent appraisal tools as mandatory BNG requirement is progressively adopted.

For local planning authorities, it provides a practical and evidence-based tool to evaluate developer proposals against validated set of ecological, social, and economic indicators. This strengthens the technical credibility of planning decisions.

Beyond its technical function, COSIMA framework also creates a space for structured dialogue between stakeholders. This dialogue is particularly important when interpreting indicators such as property value uplift. Although this indicator is included as a potential economic benefit for local communities, it should not be read as an unqualified positive outcome. In some urban contexts, environmental improvements and new green infrastructure may contribute to green gentrification, increasing property values and living costs and potentially reducing the ability of vulnerable residents to remain in the area [36, 37]. For this reason, COSIMA should support not only the identification of aggregate benefits, but also a discussion of their distribution across different social groups.

6 Conclusion and Future Perspectives

6.1 Summary of Contributions

The main contribution of this research is the integration of CBA and MCDA in the context of BNG. An additional contribution of this study is the systematic development and preliminary expert-informed validation of a comprehensive set of indicators. The framework is grounded in a three-phase methodology that integrates a grey literature review, a systematic analysis of academic sources, stakeholder analysis, and expert validation. Finally, the expert review provided an initial assessment of the relevance, clarity, and practical usefulness of the indicators for the ex ante evaluation of BNG impacts.

6.2 Limitations

This study has limitations, which clearly indicate some areas where further exploration is needed. First, the validation process involved a small panel of four specialists covering

fields such as ecology, environmental economics, urban planning, and conservation. While they provided a good starting point, such a small group may represent a limited perspective. Therefore, the expert validation should be interpreted as preliminary and not statistically representative. To make our research more robust and inclusive, we will need to expand this group in the future and organize workshops to gather input from a broad range of stakeholders. Another limitation of our study is that we considered only practically measurable indicators. This excluded some complex variables, such as the cultural benefits of ecosystems or the equitable distribution of benefits among different groups. These values, often considered intangible, are difficult to quantify, whether on a monetary or qualitative scale, which made it difficult to include them in our framework. The framework also does not consider some long-term impacts, such as the influence of BNG on climate resilience, as these effects may emerge after the standard 30-year maintenance period. Future research should address these missing dimensions and explore how they can be integrated into the framework. A further limitation is that the framework does not include a specific indicator for green gentrification risk. While property value uplift is considered as a possible benefit, higher property values may also have negative effects, especially if they increase housing costs or make it harder for vulnerable residents to remain in the area. Future research should therefore explore how this risk can be considered in ex-ante evaluation.

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

Crowdsourced Data for Urban Planning: Evaluating OpenStreetMap Categorization Reliability in Historical Urban Centres

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Abstract. The contemporary shift toward proximity-based urban planning relies heavily on high-resolution spatial data. Although Volunteered Geographic Information (VGI) platforms such as OpenStreetMap (OSM) provide extensive and free datasets, the quality of commercial POIs in dense historic centres has not yet been thoroughly examined through a functional taxonomy. This study assesses the spatial and semantic reliability of crowdsourced commercial data by comparing it with ground-truth surveys in the historic centres of Pisa and Lucca (Tuscany, Italy). Using a 23-tier meso-category classification framework, this research examines the degradation of VGI data through quantitative metrics and an analysis of mapping mismatches. The results reveal significant gaps in data coverage and a marked imbalance in Points of Interest (POIs) in both contexts: whilst tourism-oriented and food-related services are systematically over-represented, traditional retail suffers from severe under-mapping. Expanding spatial matching tolerances yields negligible improvements, confirming that the main constraint is a significant time lag rather than GPS inaccuracy. In both cities, the mapping community must contend with the rapid turnover of urban retail: the accumulation of 'digital ghosts' – fuelled by 'excess' and 'replaced/inconsistent' nodes – highlights a systemic failure to eliminate obsolete data. At the same time, a clear spatial-semantic dichotomy emerges: when a physical entity is actually mapped, its semantic categorisation proves to be remarkably accurate, in direct correlation with the ontological clarity of the object. Ultimately, this article suggests that, within these two densely touristic historic centres, OSM currently functions more as a cumulative historical record than as a real-time synchronised digital twin. This finding cautions against the potential structural risks of integrating unverified VGI into advanced urban computational models without accounting for the friction of urban commercial turnover.

Keywords: Volunteered Geographic Information (VGI) · Spatial Reliability · Retail Categories

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1 Introduction

The contemporary landscape of urban planning relies heavily on computational models and advanced spatial analytics, which require high-resolution data regularly refreshed. As planners and policymakers work to implement sustainable, proximity-based frameworks – most notably the "15-min city" concept [1, 2] – the demand for accurate mapping of essential services, retail nodes, and public amenities has increased. This information is essential for evaluating pedestrian access and simulating how urban environments react to transformative policies [3, 4].

Concurrently, the proliferation of Volunteered Geographic Information (VGI) and crowdsourced platforms, such as OpenStreetMap (OSM), has provided researchers with large amounts of geospatial data at no cost. The consequent assumption that "Big Data" inherently equates to reliable data is deeply flawed and represents a critical issue that urban planners must face: when computational algorithms process unverified crowdsourced data to inform urban policy, the propagation of spatial and categorical errors can lead to misdiagnosed urban deficits and misguided structural interventions [5, 6].

Previous literature has extensively documented the quantitative shortcomings of OSM, primarily focusing on geometric accuracy and coverage in comparison to authoritative datasets [7, 8]. Nevertheless, the dimensions of functional categorization and temporal maintenance of urban amenities remain largely underexplored with significant consequences: frameworks relying on broad functional umbrellas – such as grouping all retail into a generic "Commerce" macro-category [1] – fail to capture the functional diversity and the ontological nuances required for micro-urban analysis [9].

This study bridges this gap by merging rigorous spatial validation – comparing OSM records against exhaustive ground-truth surveys – with a refined functional taxonomy tailored specifically for commercial Point of Interest (POI) records developed by Mara et al. [6]. Focusing on the walled historical centres of Pisa and Lucca (Tuscany, Italy), this paper aims to dissect the specific typologies of errors inherent to VGI in these contexts. Specifically, we investigate the completeness and quality of the OSM database in terms of: (i) volumetric representation; (ii) spatial and semantic reliability; (iii) typologies of mapping mismatches (e.g., surplus, redundant, and replaced nodes); and (iv) categorisation correctness. Our ultimate objective is to critically assess whether crowdsourced mapping, in its current state, possesses the structural, temporal, and categorical integrity necessary to support advanced urban analytics in morphologically complex cities like Pisa and Lucca.

On this vein, the paper is structured as follows: Sect. 2 presents the analyzed case studies; Sect. 3 describes the adopted methodology – ranging from the construction of the two datasets to the processing steps performed for their comparison; Sect. 4 presents and discusses the results obtained; finally, Sect. 5 summarizes the key findings and outlines potential developments for future research.

2 Case Studies: Two Walled Historical Centres

The historical walled centres of Pisa and Lucca (Tuscany, Italy) provided an ideal, bounded laboratory for investigating digital geospatial data reliability, serving as a testing ground that challenges the mapping capabilities of crowdsourced communities. Unlike

sprawling suburban areas where commercial nodes are highly visible and segregated, these medieval urban cores are characterized by dense, mixed-use fabrics that foster social vibrancy, walkability, and commercial vitality in plazas and streets [10].

Divided by the Arno river, Pisa's historical centre acts as a primary commercial and cultural hub characterised by high pedestrian flows driven by tourism and a prominent university population. Lucca is completely encircled by its intact Renaissance walls and presents an extremely compact pedestrian environment where commercial amenities are deeply embedded within narrow street networks (Fig. 1).

Testing OSM's reliability in these areas highlights the vulnerability of crowdsourced data in environments where the rapid turnover of commercial activities, the high density of Points of Interest (POIs), and the frequent repurposing of historic ground-floor spaces create a highly volatile environment for digital mapping.

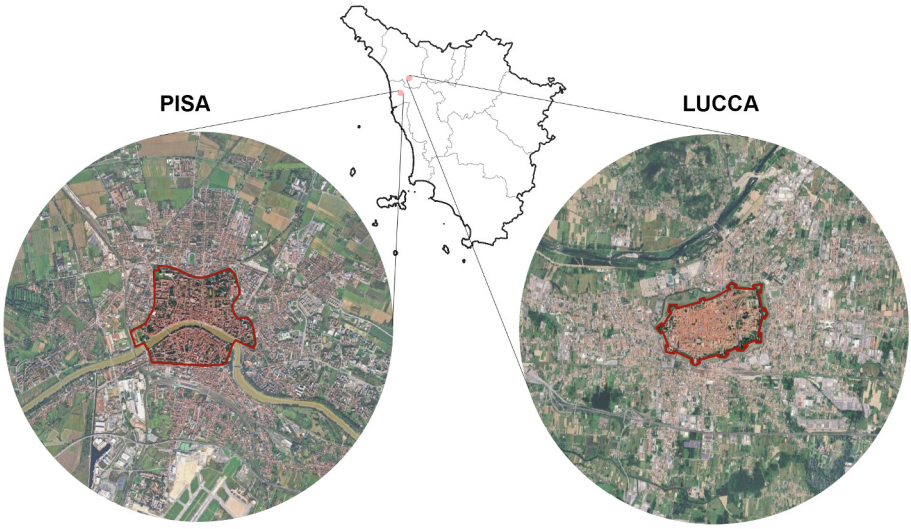

Fig. 1. Case studies

3 Methodological Framework

3.1 Data Acquisition: Ground-Truth vs. Digital Strata

The ground-truth database, which forms the basis of this study, was created specifically to overcome the limitations and privacy restrictions of official Italian business registers [11]. In line with the findings of Deri et al. [11] and Mara et al. [6], we conducted a systematic field mapping campaign focusing on commercial activities. Data collection was carried out independently by three surveyors on different weekdays during November 2025, strictly during normal working hours (approximately from 9:00 to 12:00 and from 16:00 to 19:00). The aim of this systematic approach was to obtain a representative snapshot of the active commercial landscape and to minimise discrepancies that might arise

from temporary shop closures. A comprehensive dataset was therefore created by integrating the collected records, which included the name, physical address, specific retail category and a unique alphanumeric identifier (ID) for each registered amenity. We then manually georeferenced the resulting dataset in QGIS, using Geoscopio orthophotos as the fundamental cartographic base.

In parallel with the field surveys, we extracted the OSM digital datasets by configuring geospatial queries using the QuickOSM plugin in QGIS to retrieve all point and multipolygon features tagged with 'amenity', 'shop', 'craft' and 'leisure'. The entire procedure was carried out in November 2025 to obtain data that were comparable with the surveys.

3.2 Spatial-Nominal Alignment

OSM entries do not contain complete address information; for this reason, aligning crowdsourced data with ground-truth records required a combined matching protocol based on geographical evidence and name information: an OSM entry was considered a 'match' if it fell within a 5-m spatial buffer of a real-world POI and shared a consistent business name. The choice of this radius was derived from two considerations: firstly, OSM data is generated by volunteers who mainly use smartphones [12] and the *Official US government information about the Global Positioning System (GPS) and related topics* states, based on research by Van Diggelen and Enge [13], that the GPS of smartphones is accurate on average within a 4.9 m radius under open sky. Furthermore, a test was previously conducted on the real database to evaluate the average distance between each business and its nearest neighbor. The Nearest Neighbour Index was found to be 0.075 which confirms the clustering of agglomerated points along shopping streets; the Observed Mean Distance presented a value of 10.31 m: the choice was therefore to fall within a 5-m buffer to prevent the search areas from overlapping with the adjacent activity.

Once matched, the OSM node inherited the corresponding real-world ID. If these criteria were not met, we assigned the unmatched OSM element a new, distinct unique identifier to formally record the absence of a corresponding real-world entity.

To analyse the nature of the data inconsistencies, we isolated and classified unmatched or problematic OSM entries into specific error types using a dedicated "mismatch" attribute:

- **Relocated/mislocated**: assigned when identical or equivalent business names appear in both datasets, but their spatial distance exceeds the 5-m threshold. In this case, the digital entry is linked to the real-world element via the same ID. This highlights the semantic presence on the one hand, whilst explicitly flagging the positional inaccuracy on the other, which likely stems from geocoding errors or the actual relocation of the business.
- **Replaced/inconsistent**: used when a digital POI shares the geographical location of a detected real entry but has a completely different name. This status reflects actual business turnover over time, as well as significant discrepancies in naming conventions.
- **Redundant**: when a single real-world activity is mapped multiple times in crowdsourced data (this can occur for both matching and non-matching records).

- **Excess**: reserved for 'ghost' web entries that have no corresponding real-world activity anywhere in the surveyed urban area.

3.3 The Meso-Category Taxonomy

The crux of this study lies in its approach to functional categorisation. Although useful for macro-scale models, the generic classifications often used in the literature obscure fundamental operational differences that are essential for micro-urban planning [1, 14]. To address this, Mara et al. [6] proposed an intermediate-level categorisation into 23 meso-categories to bridge the gap between overly generic classifications and the highly granular tags that typically describe geospatial data [15, 16]. By translating both the raw OSM data – via key-value tags – and the ground-truth observations into these 23 categories, it was possible to effectively demonstrate the platform's ability to accurately represent and maintain specific commercial sectors (Table 1). From a methodological point of view it is important to underline that, if an OSM node has been downloaded multiple times starting from different tags (e.g. shop = bakery and amenity = cafe which is a very common situation in the Italian context where hybrid premises with bar-pastry shops are frequent), each node was assigned to a single meso-category based on the specific tag with which it was downloaded. This procedure allowed us to avoid tag conflicts or multi-tag features. Next, during the matching phase and in particular during the assignment of the 'redundant' mismatch to one of the nodes, the meso-category was also considered to avoid distorting the Accuracy_cat results.

Table 1. Excerpt of the taxonomic alignment framework: correspondence between raw OSM tags (key = value), in-situ ground-truth labels, and the unified meso-categories used in this study

Meso-category	OpenStreetMap	Ground-truth retail category
Healthcare supplies and pharmacies	hearing_aids, medical_supply, pharmacy, herbalist, (…)	Farmacie (pharmacies), Parafarmacie (parapharmacies), (…)
Fuel	fuel	Carburanti (fuels)
Clothing and accessories	boutique, clothes, fashion, bag, fashion_accessories, (…)	Abbigliamento (clothing), Calzature (footwear), (…)
Private agencies	funeral_directors, travel_agency, storage_rental, money_lender, (…)	Agenzie immobiliari (real estate agencies), Agenzia viaggi (travel agency), (…)
Furniture and home furnishings	antiques, bathroom_furnishing, fireplace, bed, doors, (…)	Mobili (furniture), Cucine (kitchens), Letti (beds), (…)
Vehicles	atv, car, caravan, motorcycle, car_parts, fuel (shop), (…)	Autofficina (auto repair shop), Carrozzerie (car body shops), Autonoleggio (car rental), (…)

(*continued*)

Table 1. (*continued*)

Meso-category	OpenStreetMap	Ground-truth retail category
Workshops and crafts	agricultural_engines, atelier, bag_repair, bakery, (…)	Idraulici (plumbers), Fabbri (locksmiths), Falegnami (joiners), (…)
Home care	houseware, household_linen, dry_cleaning, (…)	Lavanderie (laundries), Casalinghi (housewares), (…)
Personal care	beauty, hairdresser, hairdresser_supply, massage, (…)	Parrucchieri (hairdressers), Estetista (beautician), (…)
Hardware and building supplies	hardware, key_cutter, insulation	Ferramenta (hardware store), Materiali edili (building materials), (…)
Electrical devices and sanitary equipments	electrical, security, energy (shop), hvac	Elettricisti (electricians), Materiale elettrico (electrical supplies), (…)
Bookshops, stationery and newsagents	books, paint, craft, stationery, copyshop, newsagent, kiosk	Librerie (bookstores), Cartolerie (stationery shops), (…)
Tobacco	lottery, tobacco	Tabaccherie (tobacco shops)
Photographic and optical equipments	photo_booth, camera, photo, photographer, photographic_laboratory, optician	Negozio di ottica (optical shop), Fotografia (photography), (…)
Miscellaneous items	cannabis, e-cigarette, gift, party, pyrotechnics, (…)	Articoli regalo (gift items), Bomboniere (party favours), (…)
Animals and plants	animal_boarding, animal_breeding, animal_training, (…)	Negozi di animali (pet shops), Fiorai (florists), Toelettatura animali (pet grooming), (…)
Technology and digital	electronics, radiotechnics, computer, printer_ink, (…)	Negozi di telefonia (mobile phone shops), Elettrodomestici (home appliances), (…)
Shopping malls	mall, general, wholesale, department_store	
Supermarkets	convenience, supermarket, variety_store, (…)	Supermercati (supermarkets), Minimarket (mini market / convenience store), (…)
Food and beverages	butcher, seafood, alcohol, beverages, water, wine, (…)	Macellerie (butcher shops), Pescherie (fish shops), Frutta e verdura (greengrocers), (…)

(*continued*)

Table 1. (*continued*)

Meso-category	OpenStreetMap	Ground-truth retail category
Restaurant services	food_court, restaurant	Ristoranti (restaurants), Pizzerie (pizzerias), Trattorie (traditional Italian restaurants), (…)
	fast_food, tortilla	Fast food (fast food restaurants), Kebab (kebab restaurants), (…)
Bars and clubs	bar, cafe, ice_cream, internet_cafe, pastry, (…)	Bar (bars), Caffetteria (cafés), Gelaterie (ice cream shops), (…)
Betting and gaming centres	casino, adult_gaming_centre, bookmaker, gambling, (…)	Agenzia scommesse (bookmaker), Sale gioco (arcades), (…)

3.4 Quantitative Evaluation

Using the unique ID as a join field, the two datasets were joined to generate a unified table comprising: (i) real-world activities successfully matched with OSM features; (ii) unmatched real-world activities; and (iii) all unmatched OSM features. This integrated table enabled a systematic comparison of the databases using the metrics defined in Table 2.

Following an overall assessment of OSM's reliability using the 'Amount' and 'Accuracy' metrics, we disaggregated the analysis by mesocategory to investigate two specific dimensions. Firstly, we examined how accurately real-world categories are reflected within the OSM database, with the aim of identifying potential trends relating to the specific type of goods sold or services provided. Subsequently, we assessed the accuracy of the categorisation of web entries to determine whether the degree of representativeness observed in the first phase translated into correct intrinsic categorisation within the OSM platform.

Table 2. Metrics analysed for assessing OSM reliability

Measure	Explanation	Equation
Amount	Assessment of the apparent data over- or under-estimation within the web platform	$A = \frac{N_{OSM}}{N_{real}}$
Accuracy	Measure of the actual digital platform capability to map existing ground-truth features…	$AC = \frac{M_{OSM}}{N_{real}}$
Accuracy_1	…including the relocated/mislocated entries	$AC\_1 = \frac{M_{OSM} + M_{OSM\_rel}}{N_{real}}$
Accuracy_cat	The proportion of successfully matched web entries that exhibit the correct functional categorisation	$AC\_C = \frac{M_{OSM\_cat}}{N_{real}}$

4 Results and Analytical Discussion

4.1 Overall Assessment

The initial quantitative assessment focused on the overall volume of data and its spatial validity. The on-site mapping campaign verified the existence of 1,236 active commercial entities within the historic walls of Pisa and 792 in Lucca. By contrast, the extraction from OSM yielded a significantly lower volume, with 837 nodes for Pisa and 407 for Lucca. An assessment of the Amount metric (OSM entries extracted relative to the total number of real-world entities) reveals a significant shortfall in data completeness: in Pisa, the dataset captures only 68% (A = 0.68) of the actual commercial fabric, whilst in Lucca coverage stands at 51% (A = 0.51).

Aware that volume alone is a misleading metric, we analysed the Accuracy – defined as the proportion of OSM entries that correctly corresponded to a physical commercial business (see Table 2) – which revealed another vulnerability: in both historic centres, Accuracy dropped significantly, reaching just 50% in Pisa (AC = 0.50) and 30% in Lucca (AC = 0.30). Even when increasing the matching tolerance to include incorrectly placed entries ('relocated/mislocated') as positive matches, the overall Accuracy scores show no substantial improvement (AC_1 = 0.51 for Pisa and AC_1 = 0.32 for Lucca).

The reasons behind this sharp decline from the initial Amount to the actual Accuracy become clear when examining the types of mismatches. Both case studies reveal an almost total absence of duplicate elements, with only 1% of OSM features extracted in Pisa and 3% in Lucca classified as 'redundant'. Similarly, no substantial differences are observed regarding non-existent digital records: 14% of OSM entries in Pisa and 11% in Lucca are labelled 'excess'. Conversely, records with completely divergent names show a different trend, with 'replaced/inconsistent' entries accounting for 9% in Pisa and 22% in Lucca.

Thus, the OSM dataset proves to be positionally robust, free from gross spatial errors and essentially devoid of extraneous elements. The 'noisy' portion of the data can in fact be attributed either to semantic errors during data entry into the platform or, more seriously, to a systemic temporal vulnerability inherent in participatory mapping when applied to these complex urban environments. This latter hypothesis is supported by the morphological and functional characteristics shared by the two case studies (Sect. 2): within the dense alleyways of these medieval cities, volunteers' mapping efforts structurally struggle to keep pace with the rapid turnover of small shops [17].

Ultimately, the main problem is a significant time lag rather than a mere spatial inaccuracy, which results in a data landscape cluttered with the 'digital ghosts' of businesses that have since closed down or become obsolete.

4.2 The Meso-Category Assessment

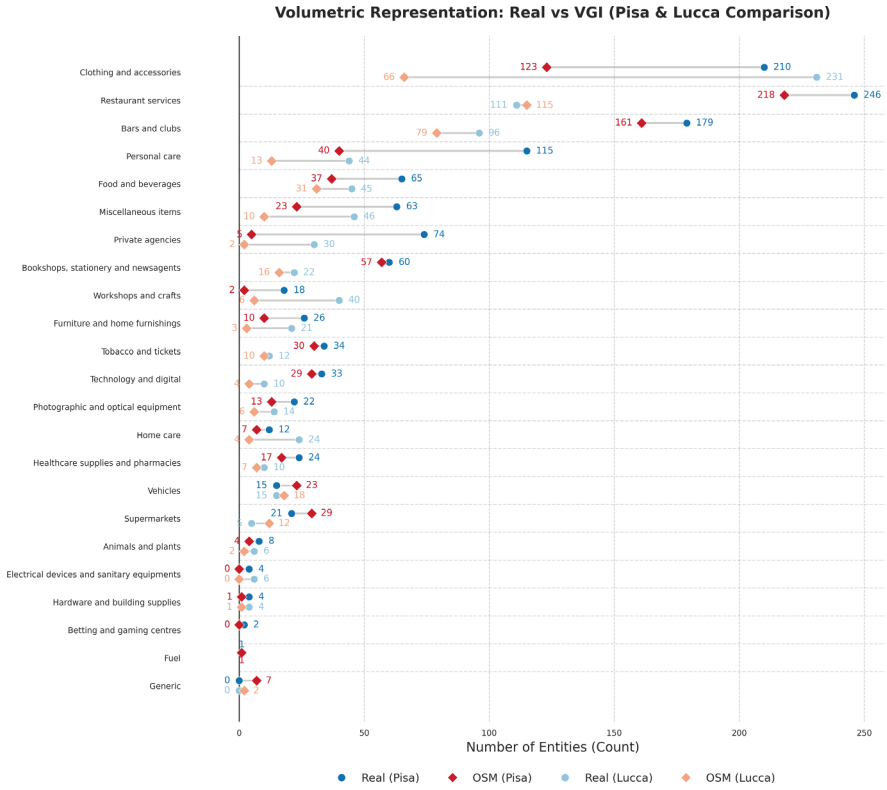

Fig. 2. Dumbbell plot illustrating the volumetric difference between OSM entries and ground-truth activities within the historical centres of Pisa and Lucca. The length of the grey line represents the magnitude of the gap between the two datasets: specifically, a circle positioned to the left of the diamond indicates an overrepresentation of entries in the OSM database, whereas a circle to the right denotes an underrepresentation

A detailed analysis at the meso-category level reveals a thematic imbalance in the mapping patterns of Volunteered Geographic Information (VGI), which is immediately evident when examining the Amount metric. In both Lucca and Pisa, the dataset shows widespread under-representation regardless of the type of shop. As illustrated in Fig. 2, the web data markers (diamonds) are consistently lower than the ground-truth counts (circles); overestimates occur only in a few isolated cases, such as the 'Supermarkets' and 'Vehicles' categories, which display Amount values greater than 1.0 in both contexts. The over-representation of these specific businesses within the analysed sample likely reflects a time lag in digital curation, linked in particular to the delayed updating or failure to remove obsolete data. This evidence suggests that the rapid physical turnover of these commercial businesses is not accompanied by an equally rapid maintenance of the web database, leading to an accumulation of obsolete records.

The categories with the highest coverage (A > 0.80) are 'Tobacco and tickets', 'Restaurant services' and 'Bars and clubs' – that is, highly frequented establishments that are vital both for the local social fabric and for the tourism economy. These patterns are strongly consistent with the academic literature on Points of Interest (POI) bias and thematic heterogeneity [18, 19], according to which VGI contributors tend to prioritise highly visible, heavily trafficked or socially significant urban amenities.

As already suggested in Sect. 4.1, relying solely on coverage indicators gives a false impression of completeness, as their interpretation must be supplemented by spatial reliability metrics. Accuracy values exceeding 0.50 confirm the results mentioned above: 'Restaurant services', 'Supermarkets', 'Bars and clubs', and 'Healthcare supplies' consistently emerge as the categories represented with the greatest precision in both case studies. Conversely, a stark contrast between high volumetric representation and poor spatial-semantic correspondence is exemplified by the categories 'Tobacco and tickets' and 'Vehicles' in Lucca: despite having significant volumes (A = 0.83 and A = 1.20, respectively), their accuracy drops to a mere 0.25 and 0.33 (see Table 3). This highlights that, in addition to a surplus of records, even the data points that would numerically overlap with real-world entities exhibit a serious qualitative deficit.

More broadly, particularly low Accuracy scores emerge across a clearly defined group of categories involving *comparison goods retail* [20]: sectors such as 'Clothing and accessories', 'Electrical devices and sanitary equipment', 'Hardware and building supplies', and 'Furniture and home furnishings' consistently show poor reliability in both case studies. This trend suggests that whilst VGI contributors readily map and update social or tourist-oriented services, traditional retail shops attract significantly less digital engagement.

The fact that Pisa outperforms Lucca in terms of overall data quality across most categories suggests a potentially more active local mapping community. Despite this, in both urban centres, expanding the spatial matching tolerance to include 'relocated/mislocated' entries (Accuracy_1) yields negligible improvements, confirming that the main issue within these historic districts is not simple GPS inaccuracy, but rather a complex combination of a complete lack of data and significant temporal lag (Table 3).

Mismatch Typologies. A detailed analysis of the types of mismatches provides key insights into the mechanisms underlying the deterioration of VGI data in the case studies examined, confirming that geometric imprecision is largely secondary to poor temporal and lifecycle management (Fig. 3).

Firstly, in both Lucca and Pisa, the vast majority of mapping anomalies fall into the 'excess' and 'replaced/inconsistent' categories. On closer inspection, however, it emerges that 'excess' records (surplus or ghost nodes) predominate in Pisa, whilst phenomena linked to actual business turnover or serious discrepancies in nomenclature ('replaced/inconsistent') are more widespread in Lucca. This suggests that in Pisa there is a prevailing failure to remove obsolete records, highlighting the locally additive nature of crowdsourced mapping: volunteer contributors demonstrate a strong proactive commitment to creating new spatial entities, but systematically neglect the subtractive maintenance required to remove closed or obsolete businesses. The city's strong focus on tourism and academia likely exacerbates this trend, particularly within highly dynamic

categories such as ‘Bars and clubs’, ‘Bookshops, stationery and newsagents’, ‘Clothing and accessories’, ‘Food and beverages’, and ‘Vehicles’.

On the other hand, Lucca appears to be affected by a more general lack of data updates, with a pool of local contributors that is less active and shows little inclination to add or update entries. Here too, the city’s economy, which is heavily tourism-oriented, may help to explain this phenomenon, which particularly affects categories such as ‘Bars and clubs’, ‘Clothing and accessories’, and ‘Restaurant services’.

Ultimately, in both urban contexts, the dataset functions more as a cumulative historical record than as a real-time synchronised digital twin.

Furthermore, the distribution of ‘redundant’ records is concentrated almost exclusively in the macro-domain of food service and in the ‘Vehicles’ category. Rather than mere random duplication, this likely reflects the functional complexity and hypervisibility of these venues. Indeed, very popular locations are often mapped by multiple independent users who may represent the same physical entity using different tags that nevertheless refer to the same functional sphere.

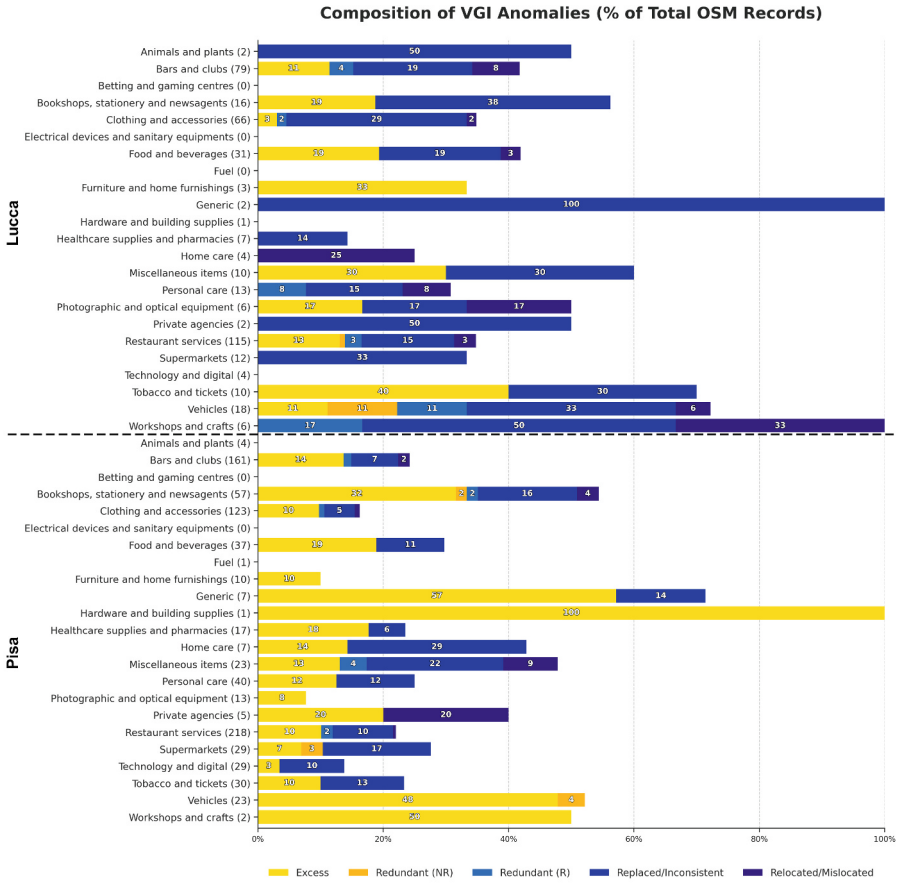

Fig. 3. Bar chart showing mismatch typologies by meso-categories. Data are normalized to the OSM values (shown in parentheses).

Table 3. Reliability assessment metrics for OSM dataset

Area	Meso-category	N_{real}	N_{OSM}	A	M_{OSM}	AC	M_1*	AC_1
Lucca	Animals and plants	6	2	0.33	1	0.17	1	0.17
	Bars and clubs	96	79	0.82	52	0.54	58	0.60
	Bookshops, stationery and newsagents	22	16	0.73	5	0.23	5	0.23
	Clothing and accessories	231	66	0.29	38	0.17	39	0.17
	Electrical devices and sanitary equipments	6	0	0.00	1	0.17	1	0.17
	Food and beverages	45	31	0.69	18	0.40	19	0.42

(*continued*)

Table 3. (*continued*)

Area	Meso-category	N_{real}	N_{OSM}	A	M_{OSM}	AC	M_1*	AC_1
	Furniture and home furnishings	21	3	0.14	2	0.10	2	0.10
	Generic	0	2		0		0	
	Hardware and building supplies	4	1	0.25	1	0.25	1	0.25
	Healthcare supplies and pharmacies	10	7	0.70	6	0.60	6	0.60
	Home care	24	4	0.17	5	0.21	6	0.25
	Miscellaneous items	46	10	0.22	8	0.17	8	0.17
	Personal care	44	13	0.30	9	0.21	10	0.23
	Photographic and optical equipment	14	6	0.43	4	0.29	5	0.36
	Private agencies	30	2	0.07	1	0.03	1	0.03
	Restaurant services	111	115	1.04	71	0.64	75	0.68
	Supermarkets	5	12	2.40	5	1.00	5	1.00
	Technology and digital	10	4	0.40	2	0.20	2	0.20
	Tobacco and tickets	12	10	0.83	3	0.25	3	0.25
	Vehicles	15	18	1.20	5	0.33	6	0.40
	Workshops and crafts	40	6	0.15	2	0.05	4	0.10
Pisa	Animals and plants	8	4	0.50	4	0.50	4	0.50
	Bars and clubs	179	161	0.90	135	0.75	138	0.77
	Betting and gaming centres	2	0	0.00	0	0.00	0	0.00
	Bookshops, stationery and newsagents	60	57	0.95	24	0.40	26	0.43
	Clothing and accessories	210	123	0.59	103	0.49	104	0.50
	Electrical devices and sanitary equipments	4	0	0.00	1	0.25	1	0.25
	Food and beverages	65	37	0.57	25	0.39	25	0.39
	Fuel	1	1	1.00	1	1.00	1	1.00
	Furniture and home furnishings	26	10	0.39	6	0.23	6	0.23
	Generic	0	7		0		0	
	Hardware and building supplies	4	1	0.25	0	0.00	0	0.00
	Healthcare supplies and pharmacies	24	17	0.71	13	0.54	13	0.54

(*continued*)

Table 3. (*continued*)

Area	Meso-category	N_{real}	N_{OSM}	A	M_{OSM}	AC	M_1*	AC_1
	Home care	12	7	0.58	5	0.42	5	0.42
	Miscellaneous items	63	23	0.37	24	0.38	26	0.41
	Personal care	115	40	0.35	31	0.27	31	0.27
	Photographic and optical equipment	22	13	0.59	11	0.50	11	0.50
	Private agencies	74	5	0.07	3	0.04	4	0.05
	Restaurant services	246	218	0.89	163	0.66	164	0.67
	Supermarkets	21	29	1.38	13	0.62	13	0.62
	Technology and digital	33	29	0.88	21	0.64	21	0.64
	Tobacco and tickets	34	30	0.88	21	0.62	21	0.62
	Vehicles	15	23	1.53	10	0.67	10	0.67
	Workshops and crafts	18	2	0.11	4	0.22	4	0.22

*M_1 denotes the sum $M_{OSM} + M_{OSM\ \_\ rel}$

Semantic Accuracy. Finally, assessing the correctness of the classification using the Accuracy_cat metric confirms that, despite the aforementioned volumetric inflation and spatial gaps, when a physical entity is successfully matched with an OSM node, the accuracy of its categorisation is remarkably high (Fig. 4). In both case studies, Accuracy_cat often records scores between 0.80 and 1.0 (14/23 categories in Lucca and 15/23 in Pisa), indicating a dichotomy in the quality of VGI: whilst volunteer mappers struggle to capture the full extent and update the spatial layout of the ever-evolving urban commercial fabric, their semantic classification of the nodes they actually choose to map appears highly reliable.

It is important to emphasise that this high level of semantic agreement is structurally facilitated by the meso-level categorisation framework adopted. It is, in fact, a reference that is neither overly granular nor too generic, and which effectively intercepts gross conceptual errors. It also allows for the harmonisation of internal tagging inconsistencies inherent to VGI – which frequently stem from the heterogeneous linguistic, cultural and socio-spatial contexts that guide contributors in the recognition and classification of local amenities [6]. Within this framework, it emerges that categories characterised by universally recognised and unambiguous physical profiles – such as 'Supermarkets', 'Healthcare supplies and pharmacies', 'Clothing and accessories', 'Vehicles', and 'Animals and plants' – consistently achieve near-perfect categorisation scores in both Lucca and Pisa; for these services, the semantic translation from a physical shopfront to a digital tag is likely straightforward for a volunteer mapper.

Conversely, categorisation accuracy decreases in two specific scenarios. Firstly, within the highly mapped macro-domain of food service (e.g. 'Bars and clubs', 'Food and beverages'), Accuracy_cat shows a slight variation, generally ranging between 0.60 and 0.95. This reflects the actual physical and functional hybridity of these venues, where volunteers correctly identify the broader function related to food but may diverge

conceptually from the ground-truth classification. Secondly, the lowest semantic accuracies – often ranging between 0.25 and 0.60 – are systematically recorded in conceptually broad or highly specialised sectors, such as 'Miscellaneous items' and 'Workshops and crafts'. In these cases, the lack of standardised visual cues and the ambiguous nature of the services make it challenging for the crowdsourcing community to classify the physical entity consistently. Ultimately, whilst extreme failures (such as 0% in 'Electrical devices') are simply statistical artefacts resulting from very small spatial matching sets, the broader trend confirms that the semantic reliability of VGI is directly proportional to the ontological clarity of the mapped object.

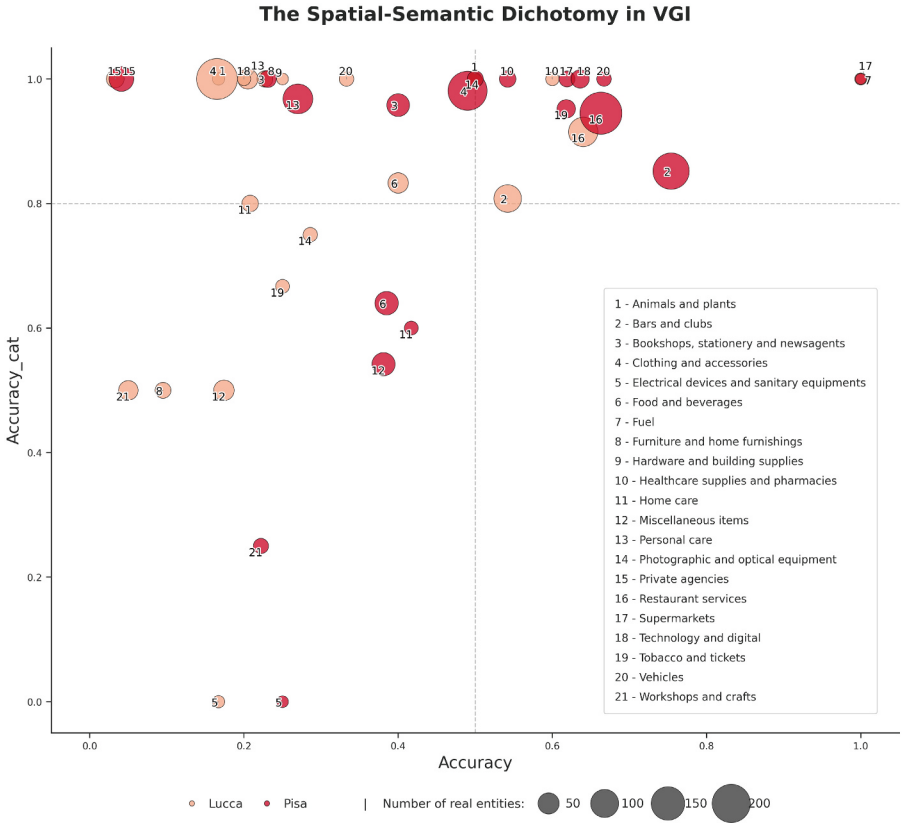

Fig. 4. Bubble scatter plot illustrating spatial accuracy against categorization reliability. The bubble size represents the absolute count of real-world activities. The predominant clustering within the upper section of the plot indicates that OSM entries are generally correctly categorized, regardless of their varying spatial accuracy values

5 Conclusions

As urban planning paradigms increasingly rely on granular spatial analyses to model proximity-based environments, the uncritical use of crowdsourced datasets entails significant methodological risks. This study, through a ground-truth validation in the historic centres of Pisa and Lucca, highlights the structural and behavioural limitations of OpenStreetMap in capturing the highly changeable commercial fabric of these complex urban centres. In particular, three key findings emerge from this research.

Firstly, VGI is intrinsically shaped by the thematic heterogeneity and bias of Points of Interest (POI). In both contexts, the mapping community systematically prioritises highly visible, socially relevant or tourism-oriented services (e.g., the food-related and mobility sectors), whilst neglecting ordinary, localised retail trade.

Secondly, the data reveal a stark contrast between spatial completeness and semantic reliability. The study shows that traditional commerce suffers from severe under-mapping attributable to a genuine lack of data rather than geometric imprecision (even relaxing spatial tolerances fails to bridge the gap), but it is also evident that successfully mapped nodes are classified with considerable accuracy.

Thirdly, and this is the most critical point, the analysis of the types of mismatches allows to hypothesize that OSM suffers from a serious lack of subtraction-based maintenance in both case studies. The prevalence of 'excess' and 'replaced/inconsistent' mapping anomalies confirms that crowdsourced platforms struggle to keep pace with the rapid turnover in the retail sector: volunteer contributors actively map new establishments, but fail to systematically record urban commercial churn. Consequently, the platform seems to function as an additive and cumulative historical record rather than as a real-time synchronised digital twin, leaving the digital landscape littered with 'digital ghosts' of relocated or closed businesses. To confirm this hypothesis, it is possible to conduct a subsequent in-depth analysis by verifying the timestamps of individual OSM records. At the same time, separating the contributions of never-mapped entities from stale-but-once-correct entities – which in this study were not isolated because they were marginal to the specific research question – would allow to outline different remediation strategies for web platform managers.

While the empirical analysis of this study is grounded in the cities of Pisa and Lucca, the general methodology extends beyond these specific geographical boundaries. The manual mapping and matching process means that the protocol in its current form is difficult to reproduce over large contexts, but future developments could automate the process to make it replicable at scale. In this way it would be possible to broaden the scope of investigation to include even more morphologically and functionally complex case studies, also in international contexts, to ascertain whether the trends and biases observed in Pisa and Lucca are intrinsic to the VGI platform itself rather than being purely place-based. Furthermore, the implementation of Artificial Intelligence-based tools will be crucial to systematically eliminate obsolete nodes and align digital layers with the relentless pace of urban evolution, ultimately bridging the gap between historical crowdsourced records and real-time synchronised digital twins.

In conclusion, although OSM remains an invaluable resource for mapping static infrastructure networks, its use in the dynamic analysis of urban retail must be approached with extreme caution [7, 21]. If unverified crowdsourced data is fed, for

example, into '15-min city' algorithms, the resulting models could overestimate the availability of hospitality services and drastically underestimate the retail services essential for daily life, leading to distorted accessibility metrics.

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Assessing the Availability of Crowdsourced Street-Level Imagery for Urban Perception Mapping

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Abstract. The integration of urban science with spatial artificial intelligence, referred to as Urban-AI or Geo-AI, is playing an increasingly important role in monitoring cities, supporting urban planning, and addressing urban challenges. In this context, investigating how cities are perceived by individuals and understanding the effects of urban environments on people have emerged as important research topics that can directly influence individuals' quality of life. In recent years, street-level imagery (SLI) has been widely used to evaluate urban perception through artificial intelligence-based algorithms. In particular, generative artificial intelligence offers growing potential for analyzing urban environments and supporting the development of spatial solutions. However, ethical risks such as algorithmic bias, socio-economic inequalities, and data representativeness issues remain important concerns. Therefore, before enabling generative AI-based systems to support transformations in urban environments, it is critical to investigate their functionality and development from a spatial data perspective. This study presents an empirical framework to evaluate the usability of crowdsourced SLI for urban perception research.

Keywords: Street-Level Imagery (SLI) · Urban Perception Mapping · Geo-AI · Crowdsourced Data · Data Representativeness · Spatial Data Quality

1 Introduction

With the intensification of global urbanization, challenges related to urban form, function, and sustainability are becoming increasingly complex and urgent [1, 2]. These interactions between urban science and artificial intelligence, referred to as UrbanAI or Geo-AI, enable high-resolution and dynamic monitoring and modeling of urban processes [2]. These emerging approaches highlight that traditional physical planning systems were not designed to address the crises of today's complex world and therefore require radical transformation [3]. Data-driven generative artificial intelligence (Generative AI) and large language models (LLMs) provide new opportunities not only to explain existing urban systems but also to invent new urban forms that optimize multiple criteria [4]. However, serious ethical concerns accompany these technological developments, including algorithmic bias, the deepening of social inequalities, and potential human

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rights violations [1, 5]. In particular, the training of urban AI systems on datasets reflecting "WEIRD" (Western, Educated, Industrialized, Rich, Democratic) values increases the risk of discrimination and exclusion on a global scale [5]. For the future of cities, an interdisciplinary approach that synthesizes urban science, computer science, and geographic information science (GIScience) is proposed [1]. This approach advocates balancing technological innovation with principles of social justice, sustainability, and human-centered design, ensuring that smart interventions are grounded in the real needs and experiences of urban residents [1, 6]. Consequently, it is essential to establish a comprehensive research framework that aligns emerging digital tools with societal needs and to structure these technologies within accountable governance mechanisms [1, 2, 6].

In the 21st century, the massive data generated by the widespread use of smartphones and applications together with satellite imagery, IoT sensors, social media, and Street-Level Imagery are regarded as major data sources for urban analytics [1, 2, 6]. Based on the idea that cities are computationally measurable, artificial intelligence technologies are widely recognized as important tools for making sense of data derived from these heterogeneous sources [1, 6].

Street View Imagery (SVI) typically refers to platform-specific, often panoramic and vehicle-based images such as those from Google Street View, whereas Street-Level Imagery (SLI) is a broader concept that includes images captured at street level from various sources and devices (e.g., Mapillary, KartaView, mobile cameras). In this study, the term SLI is preferred in sections beyond the literature review, as it provides a more comprehensive and inclusive framework.

SLI has become firmly established as an integral element of urban analytics and GIScience, with advances in artificial intelligence enabling the automation of geoinformation extraction and increasing the spatial coverage provided by data sources [7]. However, previous studies indicate that certain regions are disadvantaged in SLI based research due to limitations in spatial and temporal coverage. In particular, developing regions, rural areas, and parts of South America and Africa remain underrepresented, highlighting geographic inequalities in data availability and research focus [7]. Biljecki and Ito (2021) show that 80% of studies using SLI focus on only a single city. In addition, numerous SLI data sources exist; however, the majority offer spatial coverage limited to one or a small number of countries [7].

1.1 Studies in Türkiye

Building on the general literature, this study focuses on the Turkish context by presenting methods to assess the availability and usability of street-level imagery (SLI) in Türkiye, while also reviewing the existing body of SLI-related studies conducted in the country.

Kassab and Uzun (2024) examine urban segregation between two districts in Istanbul by combining semantic segmentation of street view images with perceptual scene ratings [8].

Gulnerman (2025) evaluates the ability of generative AI models (Gemini 1.5 Flash and LLaVA 13B) to assess urban perception from street-level images in a small central region of Ankara and finds that Gemini provides more consistent multilingual results, highlighting the potential of GenAI for automated urban perception mapping [9].

Küçükyağcı (2025) investigates changes in the green view index (GVI) at street level in a street in Kadıköy, Istanbul, using Google and Yandex street-level imagery, demonstrating that the green texture decreased due to urban transformation [10].

Iban et al. (2025) argue that available benchmark datasets for urban semantic segmentation are biased, as they are largely based on European and North American urban patterns (e.g., Cityscapes) and are primarily designed for navigation or driving purposes (e.g., KITTI, CamVid, BDD100K), limiting their applicability to diverse urban contexts. To address this issue, they introduce a new SVI dataset from Mersin that reflects diverse urban typologies in Türkiye [11].

Gönül and Durak (2025) evaluate human perception along a high street in Bursa adjacent to a historical area listed as a UNESCO heritage site, assessing changes following urban transformation between 2000 and 2022 using Google Street View (GSV) imagery from 2014, 2018, 2020, and 2023 [12].

Most studies conducted in the Turkish context focus on a limited part of a city or only a few streets. Among these, only the study by Iban et al. [11] adopts a comprehensive data collection approach, aiming to develop a semantic segmentation benchmark better aligned with Türkiye's urban morphology. The existing literature indicates that street-level imagery (SLI) research in Türkiye is still a relatively new and emerging field. Therefore, providing a preliminary assessment of data availability and quality in Türkiye is considered essential for guiding future research in this area.

1.2 SLI Assessment Studies in Literature

Studies evaluating SLI are systematically presented in Table 1 with respect to the data sources employed, the spatial scope of the analyses, and the methodological approaches adopted.

SLI is typically collected from a moving object (e.g., a motor vehicle, bicycle, or pedestrian), capturing images along the movement trajectory at a consistent angle (or panoramically) [19]. The resulting data has been evaluated in many studies in terms of spatial coverage [14, 16, 17]. This coverage is commonly assessed by examining whether images are present within specific road segments, grid cells, or point-based buffer zones. However, the presence and diversity of objects within the imagery have largely been overlooked in the literature. While the high availability of images along major roads provides valuable contributions to applications such as road perception for motorized travelers and the development of autonomous driving algorithms, these images alone are not sufficient to represent the urban perception of residents living in the area. Therefore, the content of the images and the capture perspective should be evaluated in accordance with the research theme, and a content-oriented perspective should be incorporated into coverage analyses.

1.3 Aim of the Study

This study aims to evaluate the usability, availability, and quality of crowdsourced SLI for urban perception research in Türkiye by proposing a methodological framework and providing a preliminary assessment to support future Geo-AI and urban analytics

Table 1. Street view imagery data assessment studies.

Author	Used SLI source	Geospatial scope	Methodology
Juhász and Hochmair [13]	Mapillary and GSV	Global evaluation for main roads, detailed analysis for 11 urban, rural and mixed areas in USA and Europe for various road types	User contribution pattern and spatial coverage analysis based on tile.
Quinn and León [14]	Mapillary, GSV, OpenStreetCam	24 major world cities and 25 differently sized cities in Brazil	Coverage analysis (qualitatively assessed by three analysts), along with comparisons between platforms and an examination of the reasons behind missing data regions.
Ma et al. [15]	Mapillary	Worldwide dataset covering 5 years (2014–2019)	Explorative analysis-User sequence-based contribution activity analyzed based on different photo collection modes (driving, walking, cycling)
Fry et al. [16]	GSV	371 cities in Latin America	Image availability, Image age, age variability (standard deviation) over points sampled 500 m intervals
Mahabir et al. [17]	Mapillary, OpenStreetCam	4 cities in USA	Coverage analysis with 1kmx1km grid (cumulative sequence based)
Biljecki and Ito [7]	>600 academic papers	80% of papers focus solely on one city	Review academic paper

(*continued*)

applications, which will be further supported by an exploratory analysis based on SLI data from Ankara.

Table 1. (*continued*)

Author	Used SLI source	Geospatial scope	Methodology
Hou and Biljecki [18]	Mapillary	The Kowloon area (Hong Kong) for a comprehensive evaluation, along with eight additional cities worldwide to assess selected quality elements (e.g., Singapore, Chicago, Santiago, Zagreb)	7 quality categories (including image, spatial, and temporal quality), comprising 48 quality elements.
Fan, Feng, Biljecki [19]	GSV	62% of buildings in London	Element-level SVI coverage estimation

2 Methodology

The methodological framework is structured around four main components: Spatial Distribution and Coverage Assessment, Temporal Data Assessment, Participation-Based Assessment, and Domain (Theme)-Based Assessment.

2.1 Spatial Distribution and Coverage Assessment

Spatial coverage is addressed within the context of the road network and incorporated into the analysis. OpenStreetMap (OSM) road data for the study area are retrieved using the OSMnx library and transformed into an analysis-ready format. The road network is divided into 100-m segments to establish comparable and homogeneous spatial units. Each SLI point is associated with its nearest road segment using a nearest neighbour approach, with the linkage defined based on a distance threshold ($\leq$100 m).

While no standard segment length is adopted in the literature, previous studies on street-level imagery commonly rely on spatial aggregation and proximity-based association methods to derive meaningful analytical units [17–19]. In this study, a 100 m segmentation was selected as a pragmatic balance between spatial resolution and analytical robustness.

Within this framework, the number of SLI points per road segment is calculated to define street-level coverage. The resulting values are classified using the K-means clustering method to identify different levels of data density. Segments with no associated data are retained within the analysis, enabling the identification and evaluation of spatial gaps in data coverage.

2.2 Temporal Data Assessment

Temporal characteristics of the SLI data are examined using metadata-derived timestamp information. The timestamp attribute, stored in milliseconds, is retrieved from

the database and converted into a standard datetime format to enable temporal analysis. Records with invalid or missing timestamps are excluded to ensure data consistency. Following this transformation, temporal attributes are extracted at the year level, allowing the distribution of SLI data over time to be systematically evaluated.

The number of images is aggregated for each year to identify temporal trends, data accumulation patterns, and potential gaps in data availability. This approach enables the assessment of data recency and temporal representativeness, providing insight into whether the dataset reflects current urban conditions or is dominated by imagery from specific time periods.

2.3 Participation-Based Assessment

To analyze the distribution of participation, the number of images produced per user is calculated and ranked according to contribution levels. This approach reveals whether data production is concentrated among a limited number of users. In addition, the representativeness of the data production structure is evaluated based on the most active contributors.

To assess the level of inequality in contribution, cumulative contribution shares of users are calculated and evaluated using a Pareto-based approach. This analysis identifies the extent to which data production is dominated by a small number of contributors and provides insight into the balance of participation.

To examine temporal participation dynamics, user contributions are disaggregated by year, and the yearly distribution of contributions by leading users is analyzed. This enables the evaluation of temporal continuity in data production, user-based contribution patterns, and potential periods of intensified activity.

This comprehensive approach aims to reveal not only the spatial characteristics of SLI data but also its participation-based production structure and representational equity.

2.4 Domain (Theme)-Based Assessment

Domain-based assessment is grounded in the analysis of the thematic content of SLI data through the objects and visual elements. In this context, image content is evaluated using computer vision-based methods, particularly semantic segmentation and object detection techniques.

Through semantic segmentation, key components of the urban environment (e.g., greenery, buildings, roads, sidewalks, sky, vehicles, and pedestrians) are identified at the pixel level. The proportional distribution of these classes is calculated for each image, enabling the quantification of thematic representation across the dataset.

Object detection is employed to identify the presence and frequency of specific urban elements. This approach provides complementary information on scene composition, allowing for a more comprehensive evaluation of thematic content. The resulting thematic indicators are associated with spatial analysis units such as road segments or grid cells. This enables the examination of spatial variations in thematic distributions as well as potential biases in data representation.

This methodological approach aims to reveal the extent to which SLI data represent the visual and functional characteristics of the urban environment and to assess its applicability for urban perception and Geo-AI-based analyses.

Mapillary provides semantic segmentation outputs for SLIs. Through the Mapillary API, geometric and descriptive information about objects present in the images was obtained. Using the image width and height, the pixel area of each detected object was calculated and expressed as a percentage of the total image area. These values were stored both at the detection level and as image-level summaries based on object classes. In this way, each image was represented not only by the presence of objects but also by the proportional area occupied by each object category. This structure formed the basis for deriving thematic components such as road, sidewalk, building, vegetation, sky, vehicle, and person, which were subsequently used in the calculation of the usability score.

The usability score (US) is based on three main indicators: urban visibility (UV), obstruction (OB), and diversity (DV). Urban visibility represents the proportion of key perceptual elements in the image; obstruction reflects the extent to which elements such as vehicles and people block the view; and diversity represents the number of different object groups present in the image. The proposed usability score does not directly follow an existing standardized metric in the literature. Instead, it was developed as a heuristic composite index based on semantic segmentation outputs and informed by previous studies on street view imagery quality, urban perception, and content-based evaluation frameworks (Hou & Biljecki, 2022; Ito & Biljecki, 2021).

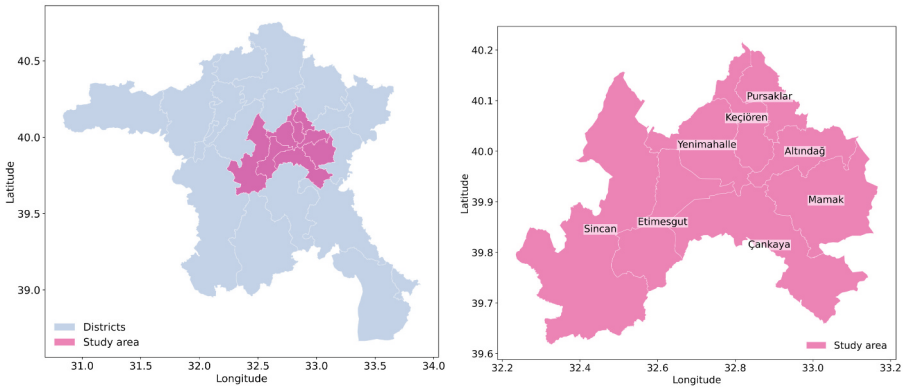
3 Case Study and Results

In this study, the city of Ankara was selected as the study area. Ankara is not only the capital of Türkiye but also the second most populous city in the country. Although many studies in the literature assessing SLI quality have focused on major cities worldwide, Ankara has not been included in these analyses. In this context, examining Ankara is considered to partially represent cities in Türkiye in terms of SVI quality.

Figure 1 illustrates all districts of Ankara and the spatial location of the study area. The study area is selected from districts characterized by an urban population density exceeding 500 persons per km^2, ensuring the representation of relatively dense urban environments.

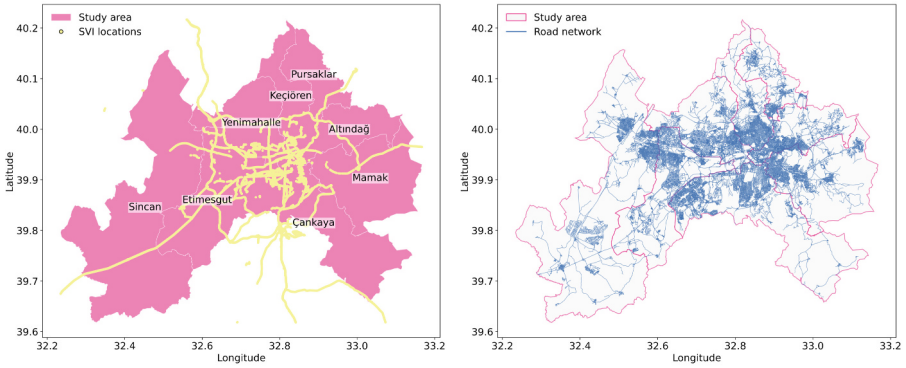
Mapillary SLI data were retrieved using the Mapillary API within the bounding box of the study area and subsequently refined through a spatial intersection with the study area boundaries. The resulting dataset is presented in Fig. 2(a). In addition, the road network within the study area was obtained from the OpenStreetMap (OSM) platform and visualized in Fig. 2(b). A partial spatial correspondence can be observed between these two datasets, particularly along primary road segments where SLI data are more consistently available. In contrast, the presence of SLI data along secondary roads appears to be limited and is mainly concentrated in areas closer to the urban core.

The spatial distribution of SLI data across the road network, classified using the K-means algorithm, indicates a highly uneven coverage structure (Fig. 3). A substantial portion of the road network contains no SLI observations, highlighting significant gaps in data availability. Primary arterial roads predominantly fall within low to moderate



(a) (b)

Fig. 1. (a) Administrative boundaries of all districts in Ankara; (b) districts selected as the study area.



(a) (b)

Fig. 2. Spatial distribution of (a) SLI locations and (b) road network across the area.

density classes (e.g., 1–16 and 16–50 images per 100 m segment), forming the main backbone of SLI data. In contrast, higher-density classes do not exhibit spatial continuity and are largely confined to short road segments or point-like clusters, particularly in areas close to the urban core. These findings suggest that while major transportation corridors are relatively well represented, the overall spatial distribution of SLI data remains fragmented and uneven. High-density observations tend to occur as localized concentrations rather than along continuous street networks, reflecting the opportunistic nature of data collection and the lack of uniform spatial coverage.

The temporal distribution (Fig. 4) shows a sharp peak in 2019, indicating a major data collection period, followed by a decline and a gradual increase in recent years. Overall, the dataset is temporally uneven, with a strong concentration in a single year.

Figures 5, 6, and 7 collectively reveal that SLI data production is highly concentrated among a limited number of contributors and exhibits notable temporal variability.

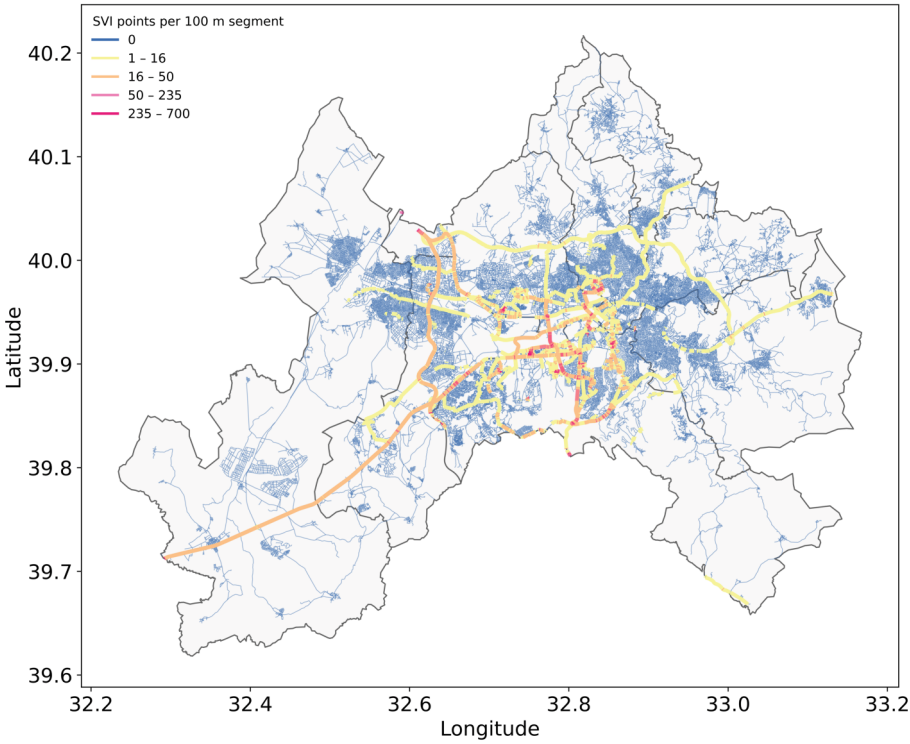


Fig. 3. SLI street-based coverage map.

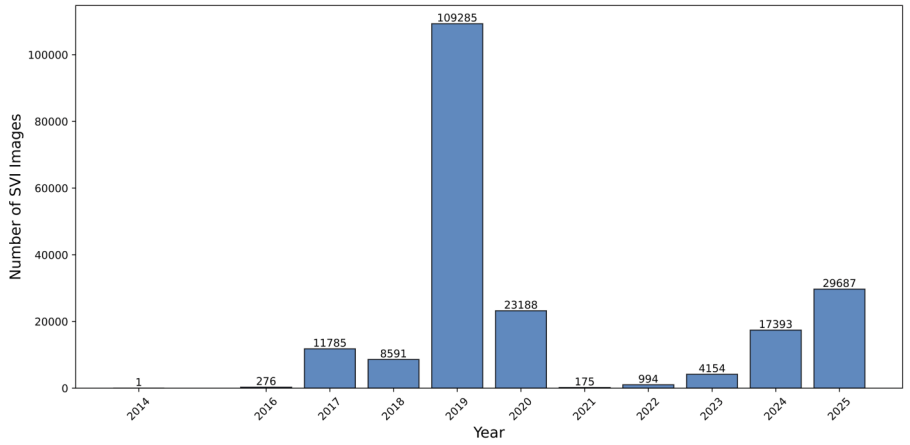


Fig. 4. Temporal distributions of SLI data by year.

Figure 5 shows that a small group of users produces a disproportionately large share of the total images, indicating an uneven participation structure. This pattern is further

confirmed by the cumulative contribution curve in Fig. 6, where a relatively small number of contributors accounts for the majority of the dataset, reflecting a clear Pareto-like distribution.

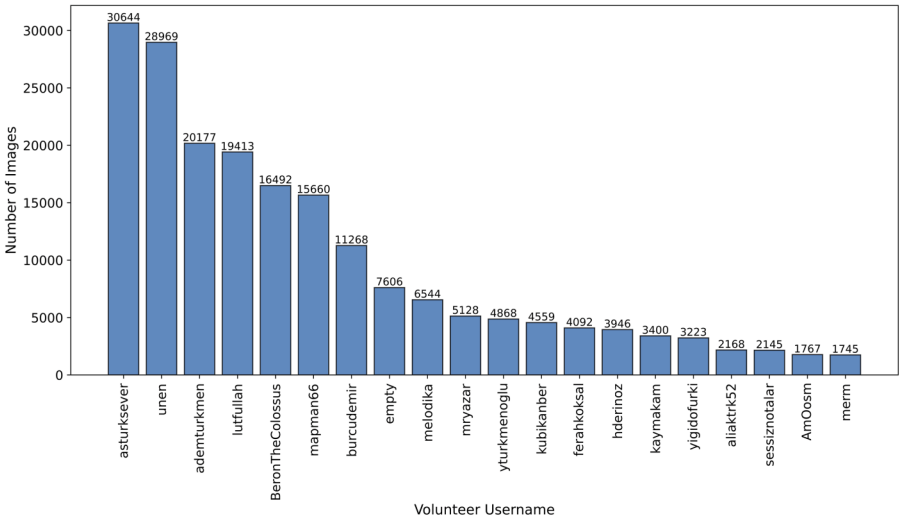


Fig. 5. Top Contributors by Number of SLI Images

Figure 7 adds a temporal dimension to this pattern, demonstrating that leading contributors dominate data production across multiple years, although their activity levels vary over time. This suggests that SLI data generation is not only user-dependent but also temporally inconsistent, relying on intermittent contributions from a core group of active users. Overall, these findings highlight that SLI data production is both participant-driven and unevenly distributed, raising important considerations regarding data representativeness and potential biases in urban analyses.

An object-based framework to evaluate the suitability of street-level imagery for urban perception analysis is applied. Using Mapillary data, detected objects are first grouped into perception-relevant categories such as road, building, vegetation, sky, vehicle, and pedestrian elements. For each image, the spatial composition of these categories is quantified based on their area coverage percentages. Building on this composition, a usability score is constructed using three main components: (i) urban visibility, representing the presence of key environmental elements such as roads, buildings, vegetation, and sky; (ii) diversity, reflecting the variety of perceptual cues within the scene; and (iii) obstruction, penalizing elements that reduce scene readability, such as vehicles and pedestrians. In addition, images with insufficient informative content are further penalized. The resulting score is normalized to a 0–100 range, and images are classified into different usability levels, enabling the transformation of raw street-level imagery into a dataset suitable for urban perception analysis.

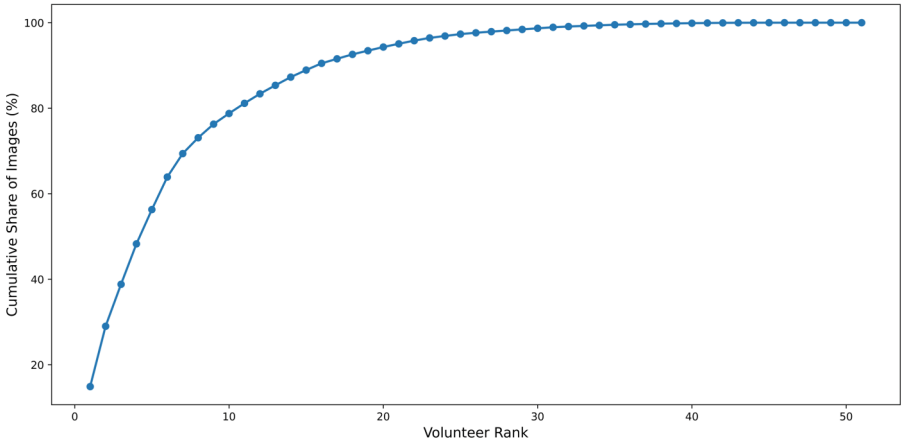


Fig. 6. Cumulative Contribution of Creators.

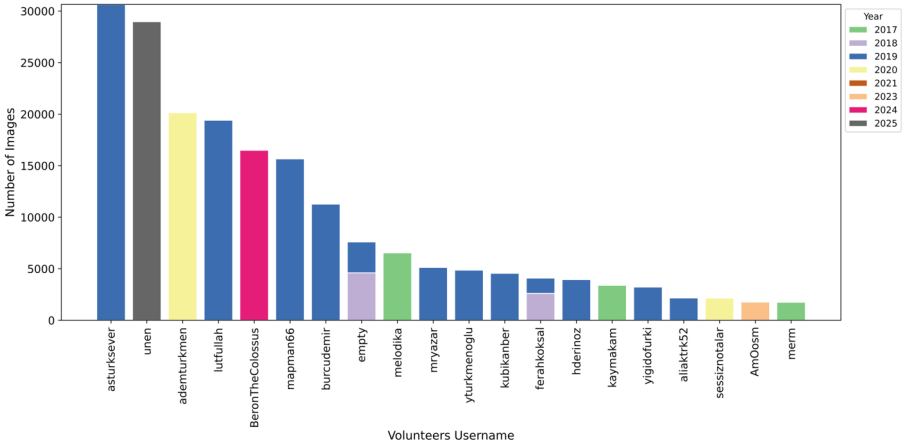


Fig. 7. Yearly Contributions of Top Volunteers.

The distribution indicates a strong concentration of images in the medium usability range, while a substantial proportion of images exhibit very low usability scores, highlighting the presence of noisy or non-informative observations in the dataset (Fig. 8(a)). The scatter plot (Fig. 8(b)) further demonstrates a strong negative relationship between obstruction and usability, confirming that visual occlusions significantly reduce the analytical value of SLI. However, the variability observed at low obstruction levels suggests that usability is not solely determined by occlusion, but also by the overall spatial composition of the scene.

The correlation analysis reveals that usability is primarily driven by scene openness and structural visibility, with sky and road coverage emerging as the strongest predictors (Fig. 9). Vegetation and vehicle presence also contribute positively, suggesting that both environmental quality and urban activity enhance scene interpretability. In contrast,

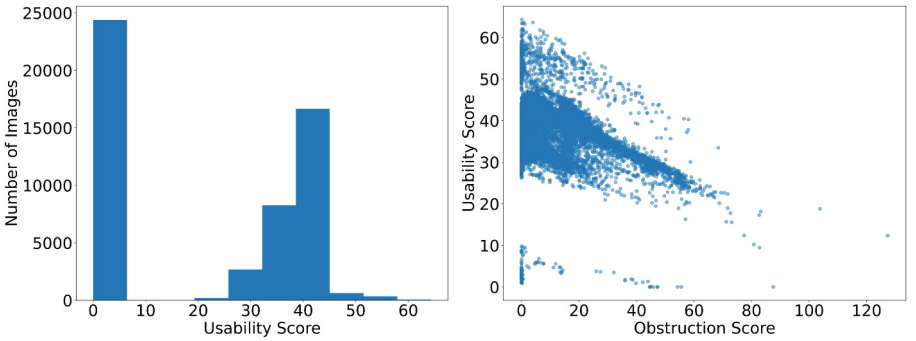


Fig. 8. SLI content based distribution of (a) usability score (b) obstruction on usability.

pedestrian presence shows minimal influence, indicating that usability is more dependent on spatial composition than human activity density.

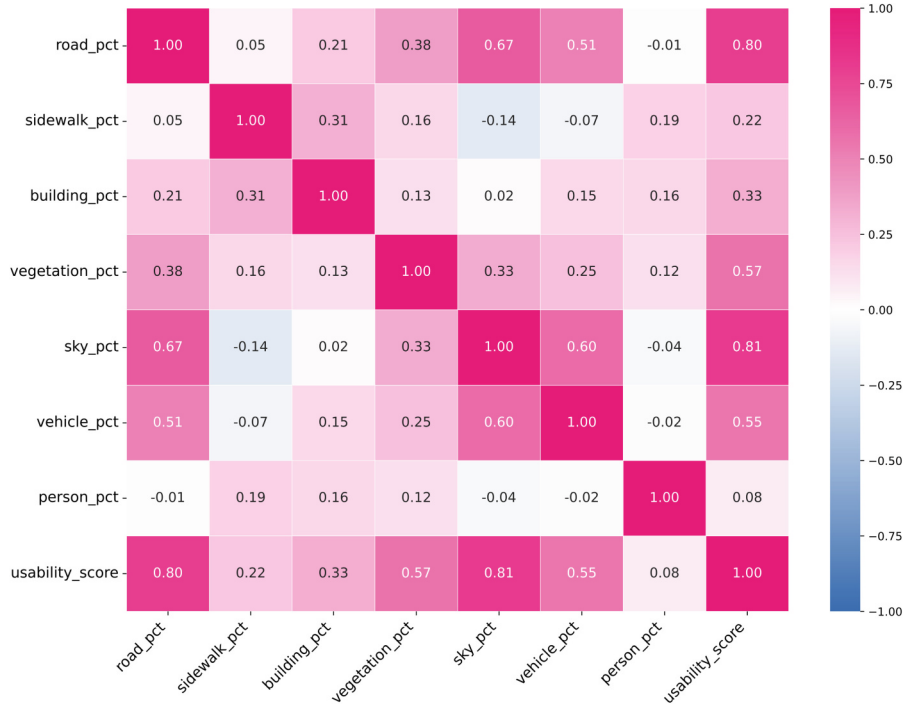


Fig. 9. Correlation between object coverage and usability.

4 Discussion and Conclusion

This study explores the adequacy of SLI-based data for urban perception mapping through a series of exploratory analyses. Districts of Ankara characterized by high urban population density are examined in terms of data availability within Mapillary, a crowdsourced SLI platform. As one of the first studies in Türkiye to assess SLI data quality, the findings indicate that data availability is largely concentrated along primary arterial roads, while street-level or point-based data is mainly observed in areas that can be considered part of the urban core.

From a temporal perspective, the dataset exhibits significant variability, with certain years showing peak levels of data production while others contain little to no data. In addition, data production is highly uneven in terms of participation, with approximately 20% of users contributing the majority of the dataset. These findings highlight notable temporal and participation-based biases in the data.

Within the scope of thematic assessment, the visual content of the images is analyzed by quantifying the area occupied by different objects, enabling the derivation of usability scores. Furthermore, an obstruction score is introduced to evaluate the extent to which dominant elements within the images may hinder meaningful interpretation.

Overall, the analysis of approximately 200,000 images for Ankara suggests that, from a spatial perspective, the dataset does not adequately represent a large portion of the urban environment. The data is also characterized by temporal and participation-related biases, and a substantial proportion of the images exhibit limited suitability for urban perception studies.

Nevertheless, the presence of repeated observations in central urban areas and relatively high usability scores in certain high-density zones indicate that crowdsourced SLI data retains potential for targeted analyses. Despite limitations in data quality, biases, and content-related constraints, openly available SLI datasets can still serve as valuable resources for localized studies. Prior to their application, data filtering, weighting, integration, and enrichment techniques can be employed to enhance their usability and analytical value.

In future studies, defining the usability score through an explicit formulation and weighting scheme, and validating it using human-based evaluations and established urban perception models, is considered an important direction for improving methodological robustness.

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Improving Communication Procedures to Foster Rail Cross-Border Accessibility: A Survey on Connections Between Italy and Slovenia

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Abstract. Border regions often introduce accessibility asymmetries that limit citizens' ability to access work and education opportunities. In this context, improving cross-border connections is not merely a logistical need, but a fundamental prerequisite for ensuring equality and inclusivity.

The study analyses cross-border accessibility through a survey conducted in Italy, with reference to its border with Slovenia. The survey explored two complementary dimensions. First, the perceived quality of local public transport, both via road and rail, in relation to daily commuting. Second, the perception of accessibility to cross-border connections with Slovenia.

The results reveal an overall satisfactory perception of local public transport services but, at the same time, cross-border connections with Slovenia are perceived as poorly accessible. Also, even in the event of service improvements, the propensity of respondents to use such connections remains moderate. This may suggest the presence of barriers beyond the mere characteristics of the offer, including limited familiarity with existing connections and consolidated mobility habits.

The study falls into the impact evaluation of a digital translation tool considered in the European project T4Rail (Translate for Rail) IT-SI, which aims at fostering cross-border railway services by facilitating communication procedures at the border between Italy and Slovenia. Notably, the importance attributed by respondents to travel time reduction as a driver to shift towards railway cross-border connections reinforces the relevance of the T4Rail tool. Future developments of the study consider the employment of econometric analyses to capture the relationship among the examined variables, in support of the elaboration of incentive policies.

Keywords: Cross-border connections · Accessibility survey · Digital communication tool

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1 Introduction

Cross-border transport connectivity is essential for territorial integration and equal access to opportunities for proximity territories. However, many border regions in the European Union (EU) still have fragmented and poorly coordinated transport systems (Medeiros, 2019). Instead of functioning as integrated mobility corridors, borders often act as barriers, exacerbating spatial inequalities and hindering the realisation of European integration objectives (Decoville and Durand, 2018; Wiesböck et al., 2016).

Yet infrastructure provision alone cannot guarantee effective mobility. Even where physical connections exist, cross-border transport remains underutilised when services are infrequent, poorly integrated, or simply unknown to potential users, leaving the mobility potential inherent in geographical proximity largely untapped (Medeiros et al., 2021; Svensson and Balogh, 2018). Moreover, especially for railway transport, additional barriers to seamless cross-border transport systems can be related to a lack of interoperability according to different aspects, which range from organizational and technological disparities to normative and language constraints (Walker et al., 2009). The consequences of all these issues extend beyond mere inconvenience. Indeed, limited cross-border accessibility restricts residents' ability to pursue educational and professional opportunities available across the border, thereby constraining individual development and reinforcing spatial inequalities (Edzes et al., 2022).

Addressing this gap is particularly urgent within the EU, where seamless cross-border mobility is a core objective of both transport and cohesion policy, most notably embodied in the Trans-European Transport Network (TEN-T) (Christodoulou and Christidis, 2019; Medeiros, 2019). Bridging the gap between infrastructure availability and actual accessibility is therefore not merely a logistical challenge, but a fundamental prerequisite for territorial equality and inclusive regional development.

The Friuli-Venezia Giulia (FVG) region in north-eastern Italy offers a compelling case study of these dynamics. Strategically positioned at the intersection of three TEN-T corridors and bordering both Austria to the north and Slovenia to the east, FVG is a frontier region where the integration of national transport systems for both freight and passenger mobility remains an open challenge.

Building on these considerations, the present study was developed. Through a survey administered to a sample living within the FVG region ($n = 397$), the study explores two complementary dimensions. Firstly, it examines the perceived quality of local public transport by road and rail in relation to daily commuting patterns. Secondly, it examines the perceived accessibility of cross-border connections with Slovenia.

This study was conducted as part of the activities considered in the European project called T4Rail (Translate for Rail) IT-SI. The project aims to promote cross-border rail services by streamlining communication procedures at the Italy–Slovenia border using a dedicated digital translation tool. This latter consists of an application to automatically translate a set of predefined messages related to railway operations, contributing to reduce the duration of train stops at the border station and thus to increase the attractiveness of the rail mode. Indeed, shorter idle times at the Italian-Slovenian border would potentially improve railway service quality, enhancing accessibility and thus fostering territorial cohesion between the two countries. A discussion on the challenges and opportunities arising from technological improvements in cross-border rail transport is provided in

(Sinatra et al., 2026), with respect to operational, economic, environmental, employment and territorial aspects. In such a context, the performed study focuses on evaluating the broader societal impact of the T4Rail project, complementing the analysis carried out at the mentioned levels of investigation. To the best of author's knowledge, no comparable study has been previously conducted in the region.

The study therefore aims to provide a comprehensive picture of transport accessibility in the FVG region, with a particular focus on local public transport mobility and on cross-border rail connections between Italy and Slovenia.

The paper is organized as follows. Section 2 describes the methodology adopted for data collection and the characteristics of the sample. Section 3 presents and discusses the results. Section 4 offers concluding remarks and policy implications.

2 Methodology

As mentioned, the FVG region is located in north-eastern Italy, in a strategic position for freight and passengers flows towards both central-eastern Europe and the Mediterranean basin, thanks to the major ports situated within its territory. FVG is also located at the intersection of three TEN-T Corridors, i.e., the Baltic-Adriatic Corridor, the Mediterranean Corridor, and the newly introduced Western Balkans-Eastern Mediterranean Corridor (Fig. 1). In this context, the railway sector plays a key role by supporting cross-border freight and passenger transport – particularly with Austria and Slovenia – while also representing a significant source of regional employment.

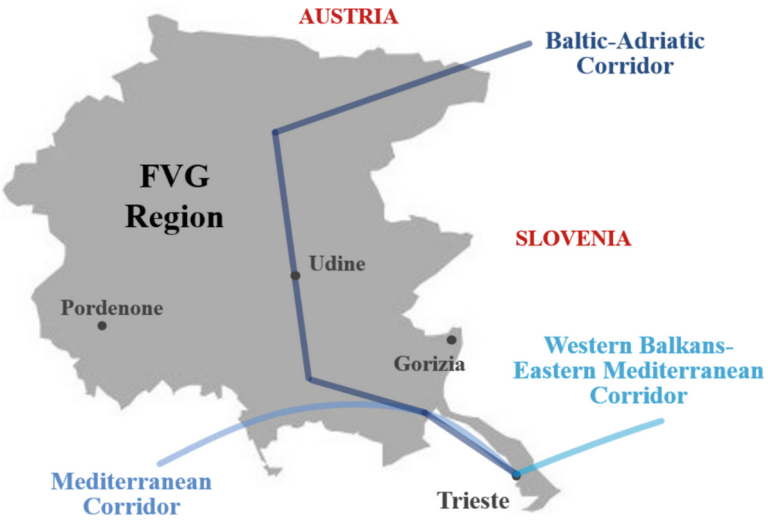

Fig. 1. Friuli Venezia Giulia Region and related TEN-T Corridors. Source: Authors' elaboration

To collect data aimed at assessing accessibility to local public transport and the propensity to use cross-border rail connections to Slovenia, a questionnaire was administered targeting dwellers in the FVG region. Data collection took place between December 2025 and February 2026, both in person and online (i.e., Computer-Aided Web Interviewing).

Prior to official administration, a pre-test was carried out with approximately ten respondents to verify that the questions were clearly formulated and that the branching logic had been implemented correctly.

The questionnaire consisted of three sections. The first section collected respondents' demographic data, including gender, age, and education level. The question on the net monthly income of interviewees was made optional – this was the only exception in the questionnaire – given its sensitive nature. Nonetheless, such a question was functional to the subsequent branching question, which investigated the monthly income share allocated to transport expenses.

The second section gathered data on accessibility to public transport services using two five-point Likert scale rating questions (1 = very poor; 5 = very good). The first question asked respondents to rate the accessibility of different categories of destinations in or near their municipality of residence using public transport (e.g. urban buses, regional buses or trains). The second question asked respondents to evaluate the characteristics of the urban public transport service in terms of the number of available lines, service frequency and stop proximity. For this question, the same Likert scale was used as for the first question, with the addition of a "I don't know" option for respondents who felt they did not have enough information to answer.

The third section explored accessibility concerning cross-border mobility between Italy and Slovenia through two rating questions. The first question investigated how respondents evaluate the accessibility of cross-border connections on a five-point Likert scale (1 = very poor; 5 = very good). Then, the second question examined their willingness to use cross-border rail connections should improvements be made, i.e., either in terms of reduced travel times or increased service frequency, also measured on a five-point Likert scale (1 = not at all willing; 5 = very willing).

2.1 The Sample

The initial sample consisted of 397 respondents residing in the FVG region, specifically across the provinces of a few main cities, i.e., Trieste, Udine, and Gorizia. The province of Pordenone, which is another main regional city, was excluded from the survey, because its geographical distance from the Slovenian border makes it fall outside the scope of the research (Fig. 1). On the contrary, among the cities involved in the survey, Trieste and Gorizia are the ones lying the closest to Slovenia, although many villages belonging to the province of Udine are not far from it. As far as the demographic composition of the sample, attention was paid to the active layer of the population, i.e., from 15 years and over, in line with the objective of the survey of evaluating local and cross-border transport service accessibility for work and study purposes. In this sense, the survey also targeted students attending regional high schools and universities, who represent a suitable sample for the mentioned goal.

Given the fact that, to the best of authors' knowledge, no comparable study has been previously conducted in the FVG region, the sample characteristics were benchmarked against regional-level figures provided by the Italian National Institute of Statistics (ISTAT) to provide contextual reference.

The sample showed a slight female majority (53%), which is broadly consistent with the regional figure of 51.1%.[1] The sample was also relatively young, with the 15–18 age group being the most represented (25%), followed by the 25–34 age group (14%) and the 18–24 age group (11%). Additionally, over half of the sample (53%) held an upper secondary school diploma, which is above the regional proportion of 40.1%. Furthermore, 39% of the sample held a bachelor's or master's degree, or a higher qualification such as a postgraduate master's or PhD, compared to a regional proportion of 15.4%.[2] The residence of the sample was concentrated mostly in the provinces of Trieste (45%) and Udine (33%).

With respect to income, 36% of respondents reported no monthly earnings, consistently with the large student component of the sample. Among those with an income, approximately 37% earned between €1,200 and €2,400 per month, while 7% earned between €2,400 and €3,000.

The monthly transport expenditure is relatively modest for most respondents: 27% spent up to €50, 29% spent between €51 and €100, and 18% spent between 101 and €150.

The predominant mode of transport of respondents was private cars (50%), followed by public transport, encompassing urban and regional buses and trains, which was used by 43% of respondents. Commuting patterns further highlighted the mobility intensity of the sample: 32% of respondents travelled outside their municipality of residence on a daily basis, and an additional 20% did so several times a week.

Table 1 presents the full socio-economic profile of the sample.

Table 1. Socio-economic profile of the sample (n = 397). Source: Authors' elaboration.

	No.	%
Total sample	397	100
Gender		
Female	209	53%
Male	184	46%
I prefer not to answer	4	1%
Age groups		
15–18	100	25%
18–24	43	11%
25–34	56	14%
35–44	53	13%

(*continued*)

[1] https://www.istat.it/wp-content/uploads/2025/04/Censimento-permanente-popolazione_Anno-2023_FVG.pdf

Table 1. (*continued*)

	No.	%
45–54	52	13%
55–64	46	12%
65+	47	12%
Province of residence		
Gorizia	83	21%
Trieste	181	45,5%
Udine	133	33,5%
Level of education		
Bachelor's or Master's degree or higher university qualification (e.g. Master's/PhD)	156	39%
Primary level (primary school/lower secondary school)	31	8%
Upper secondary school (e.g. sixth form college, vocational college)	210	53%
Occupation		
Housewife	9	2%
Employee	153	38%
Unemployed	19	5%
Self-employed	23	6%
Retired	36	9%
Student	157	40%
Net monthly income		
Up to 1,200€	44	11%
From 1,200€ to 1,800€	86	22%
From 1,800€ to 2,400€	62	16%
From 2,400€ to 3,000€	26	7%
Over 3,000€	13	3%
I do not receive any monthly income	142	36%
Missing data (those who preferred not to answer the question)	24	6%
Monthly transport budget		
Up to 50€	109	27%
From 51€ to 100€	117	29%
From 101€ to 150€	71	18%
From 151€ to 200€	28	7%
Over 200€	14	4%
I would not know how to quantify it	58	15%

(*continued*)

Table 1. (*continued*)

	No.	%
Means of transport to which the largest share of the monthly budget is allocated		
Private car	199	50%
Bicycle	1	0.3%
Car sharing	1	0.3%
Bike sharing	1	0.3%
Public transport (city buses, regional buses, trains, …)	173	43.5%
Scooter or motorbike	17	4.3%
Taxi	5	1.3%
Journeys outside one's municipality of residence		
Daily	126	32%
Several times a week	81	20%
Once a week	60	15%
Several times a month	48	12%
Once a month	33	9%
Rarely	49	12%

3 Results

The data analysis yielded a nuanced picture of transport accessibility, examined through descriptive statistics across three areas: local public transport accessibility, the assessment of urban public transport services and cross-border connections between Italy and Slovenia. At this phase of the study, the analysis has been intentionally limited to descriptive statistics to capture the main insights of the survey, in line with the most common approach used in the majority of previous contributions on the topic, as reported in the literature review performed by (Tsiopa et al., 2024). However, additional detailed results could be derived in the future using more articulated econometric techniques.

3.1 Local Public Transport Accessibility

The assessment of local public transport accessibility – by urban buses, regional buses, or trains – revealed a differentiated picture depending on the considered destination. Regarding accessibility to the workplace, 35% of respondents expressed a positive judgement (ratings 4 and 5), while 31% a negative one (ratings 1 and 2). 34% of interviewees took a neutral position. This broadly balanced distribution suggests that a significant portion of the sample reaches their workplace by other means of transport, consistent with the finding that 50% of respondents primarily use a private car for their own trips.

The accessibility of educational institutions was perceived more positively, with 52% of respondents expressing a positive opinion, compared to 19% who expressed a negative opinion. The remaining 29% were neutral. This finding is consistent with the high proportion of students in the sample, reflecting the widespread coverage of public transport networks serving schools and universities.

Regarding access to shops and commercial services, 46% of respondents gave a positive assessment, 30% a neutral one and 24% a negative one. Access to recreational activities was viewed somewhat more critically, with 37% of respondents giving a positive response, 33% a neutral response and 29% a negative response. In this regard, a study concerning students' leisure transfers is reported in (Caramuta et al., 2025), which describes the planning of a bus demand responsive transport service implemented in the main city of the FVG region to address the mobility needs of such users. A similar pattern emerged for healthcare services, where 39% of respondents gave a positive rating, 35% a neutral rating and 25% a negative rating.

Table 2 provides a detailed overview of responses concerning accessibility to activities and services through local public transport.

Table 2. Judgements on accessibility to activities and services through local public transport. Source: Authors' elaboration.

	1 = Very poor	2 = Poor	3 = Neutral	4 = Good	5 = Very good
Work activity	15%	16%	34%	26%	10%
Education (school, university)	8%	11%	29%	38%	14%
Shops/commercial services	10%	14%	30%	34%	12%
Recreational activities/leisure	12%	18%	33%	30%	8%
Health services	10%	15%	35%	29%	10%

Educational institutions were perceived as the most accessible destination by public transport, while uncertainty was greatest regarding the workplace, with responses distributed almost equally across the three positions. Leisure destinations and healthcare services occupy an intermediate position, with a comparatively higher proportion of neutral responses, which may reflect more sporadic and less organized mobility patterns compared to regular commuting.

3.2 Assessment of Urban Public Transport Services

With regard to the characteristics of urban public transport services, the sample expressed an overall favourable judgement across all three examined aspects. The number of available lines received positive ratings from 55% of respondents, compared to 24% of negative ones. Service frequency also achieved a predominantly positive rating (48%), albeit with 28% and 22% of negative and neutral responses, respectively. The best-rated aspect

was the distance of stops from places of residence, with 60% of respondents giving a positive rating and only 14% giving a negative rating. A marginal 2% of interviewed people were unable to express a judgement. These results indicate a generally satisfactory perception of the urban public transport provision, with stop proximity being perceived as a key strength, while service frequency was attributed to the greatest dissatisfaction. This could discourage people from using public transport.

Table 3 illustrates the judgements expressed by respondents with respect to the characteristics of urban public transport services, for each level of the rating scale.

Table 3. Judgements on the characteristics of urban public transport services. Source: Authors' elaboration.

	1 = Very poor	2 = Poor	3 = Neutral	4 = Good	5 = Very good	I don't know
Number of available lines	10%	14%	20%	33%	22%	2%
Frequency of services	12%	16%	22%	32%	16%	2%
Distance between stops	7%	7%	24%	38%	22%	2%

In terms of the proximity of their house from the nearest railway station, the survey proved that 32% of respondents lived more than 2 km away but had a good local public transport connection. On the contrary, 19% of interviewed people lived at the same distance, but without adequate transport services. Besides, it turned out that 15% of respondents lived within a walking distance of up to 400 m from the nearest railway station and another 13% of them lived within a reasonable walking or cycling distance (400 m to 2 km) from it, under good pedestrian and cycling infrastructure conditions.

As for the nearest regional bus stop, 23% of interviewees lived within the same walking distance from it, whereas 21% lived more than 2 km away, although with a good local public transport connection. In contrast, the survey also revealed that 16% of respondents lived more than 2 km away from such a stop without a proper public transport connection and 13% of them lived within walking or cycling distance under good infrastructure conditions. Accordingly, the majority of the sample could reach transport nodes relatively easily, although approximately one fifth of respondents face limited accessibility to the rail network.

3.3 Accessibility to Cross-Border Connections

With reference to mobility generated by work or study purposes, the findings on the existing cross-border connections between Italy and Slovenia revealed an overall critical perception of accessibility. Regarding rail connections, 44% of respondents rated them as poor (scale points 1 and 2) and only 17% attributed a positive judgement (scale points

4 and 5). A noteworthy finding is the 39% of interviewees having neutral position, which is a result likely attributable to limited familiarity with the existing offer.

A similar picture emerged for cross-border accessibility by regional buses, where the largest share of respondents (44%) expressed a neutral position and 35% provided a negative assessment (scale points 1 and 2), with an even smaller positive share.

Table 4 contains a precise indication of judgements collected on the use of the existing cross-border connections between Italy and Slovenia for work or study purposes.

Table 4. Judgements on accessibility to existing cross-border connections between Italy and Slovenia for work or study purposes. Source: Authors' elaboration.

	1 = Very poor	2 = Poor	3 = Neutral	4 = Good	5 = Very good
Via train	19%	25%	39%	15%	2%
Via regional bus	13%	22%	44%	18%	3%

In terms of willingness to use cross-border rail connections following service improvements, the results showed a balanced distribution. Regarding reduced travel times, 37% of respondents said they would use such connections, while 30% said they would not. The results for the scenario of increased service frequency were similar, with 36% of people willing to use rail cross-border connections and 29% unwilling to do so. These findings suggest that even when faced with the prospect of potential service improvements, a significant proportion of respondents remain sceptical about using cross-border rail connections. This may reflect additional barriers, such as ticketing fragmentation, limited awareness of available services or deep-rooted mobility habits, which extend beyond the characteristics of the service itself.

Table 5 includes the exact data gathered on the willingness of using cross-border rail connections between Italy and Slovenia, in case of the realization of service improvements.

Table 5. Judgements on the willingness of using cross-border rail connections between Italy and Slovenia after service improvements. Source: Authors' elaboration.

	1 = Not at all willing	2 = Not very willing	3 = Neutral	4 = Quite willing	5 = Very willing
Reduction of travel time	14%	17%	33%	28%	9%
Increase of service frequency	13%	16%	35%	26%	11%

4 Discussion

As highlighted in (Tsiopa et al., 2024), even if most papers on cross-border mobility have been developed according to a transport perspective, heterogeneity can be observed in a variety of investigation features, like employed techniques, variables, data types, and application scope. Moreover, given the greater stress posed on specificities rather than on commonalities, comparability among research studies on the topic considered is difficult to fulfill. Based on those findings, the present contribution differs from previous scientific papers at least for one of the following reasons: the approach used to collect mobility data, the examined geographical area, the transport modes considered, and the investigation goal. Regarding this latter aspect, of course, differences in the objective of the analysis partially motivate methodological discrepancies with respect to existing contributions.

For instance, considering papers which take into account both rail and road modes, public transport accessibility of cross-border commuters has been analyzed in (Cavallaro and Dianin, 2020) referring to Central Europe, more specifically to the boundary between Hungary and Austria. The analysis consisted in estimating cross-border commuting public transport accessibility through a network efficiency indicator along the main connections, comparing the resulting values with those related to domestic commuting public transport accessibility. The study proved a quite significant difference between the cross-border and domestic public transport attractiveness, mainly because of long travel times, fragmentation of multimodal solutions and uncompetitive fares. Besides, the investigation pointed out a more limited cross-border accessibility in rural areas, advocating a stronger collaboration among transport companies operating in different territories. Another effort to evaluate cross-border accessibility using a quantitative approach has been made in (Bertram et al., 2024), which proposes a cartographic visualization of spatial accessibility while focusing on German borders. Nevertheless, in this case, attention was paid only to public transfers by rail, other than to private car connections, thus overlooking possible bus services. The "space-time-line" maps provided in such a study showed once again relevant differences between cross-border and domestic connections when using either the road or rail mode, with the latter one being generally slower than the former one in most connections. In addition, rural border areas demonstrated poor mobility conditions in both the considered modes and cross-border links with border regions turned out slower than cross-border links between major cities.

The only contributions sharing a similar geographical context with the present paper are (Gabrovec, 2013; Gabrovec et al., 2021), which deal with cross-border mobility between Slovenia and, respectively, Italy and Austria. However, in the former study, the analysis was limited to two border provinces (i.e., Gorizia/Gorica and Muggia/Mulje) and to road mode, since no railway connections were available at the time in which the investigation was conducted. In addition, based on statistical data, field observations and interviews, such a paper examines the daily travel needs of the greatest share of public transport users in the considered area, which is constituted mainly by students and pensioners. Consequently, cross-border commuting for work purposes was overlooked by that analysis, which still enabled to formulate proposals for joint public transport planning on the Italian and Slovenian sides. Regarding the latter study, mobility between Slovenia and neighboring countries was investigated throughout three decades (from

1991 to 2019), in order to assess the effects of political changes on cross-border public transport. Then, attention was concentrated specifically on transfers between Slovenia and Austria in the Carinthia region, referring to rail mode, which was the only available option for cross-border public transport. In this case, mobility derived by both work and education reasons were examined, using questionnaires to assess users' trip frequency and satisfaction with the service provision.

Against these two contributions, other than focusing on an unexplored area, the study reported in the present paper examines a more comprehensive transport offer, the related perception of passengers and even their willingness to change mobility habits in face of service improvements. In this sense, the article exceeds the mere analysis of traffic data concerning cross-border flows with reference to the users' characteristics, suggesting recommendations for policy makers.

5 Conclusion

This study aimed to provide a comprehensive overview of transport accessibility in the FVG region, with a particular focus on local mobility within the region and on cross-border rail connections between Italy and Slovenia. To that end, a survey was administered in the context of the European project T4Rail, whose objective is to enhance border operations by improving communication procedures thanks to a digital translation tool. Such technological innovation is thus meant to enhance the attractiveness of rail cross-border transfer, positively impacting at economic, social, environmental and territorial level.

Regarding cross-border connections, the data reveal untapped potential. The majority of respondents rated the accessibility to Slovenia as poor, both by rail and regional buses. A significant proportion of neutral responses indicate widespread unfamiliarity with the existing services. Furthermore, willingness to use these connections in case of service improvements remains moderate.

The findings regarding local public transport suggest that this latter is generally considered satisfactory in terms of network coverage and the proximity of stops. However, there are significant issues regarding service frequency and accessibility to workplaces. The fact that many people still rely on private cars indicates that public transport remains an uncompetitive alternative for many people when dealing with work-related journeys.

In terms of policy implications, these findings highlight important considerations. Firstly, operational interventions on the supply side, such as reducing travel times and increasing service frequency, may not be sufficient to change deep-rooted mobility habits. Complementary demand-side measures are therefore necessary. These measures could include targeted communication and awareness campaigns to reduce limited familiarity with cross-border connections.

Secondly, increasing the frequency of local public transport appears to be a priority, particularly on routes with higher commuter demand, in order to make public transport a more competitive alternative to private cars. This is a necessary step, given that half of the sample still relies predominantly on such mobility alternative.

Finally, reducing travel times on cross-border connections between Italy and Slovenia is the most effective way to increase users' willingness to adopt those services. In

this respect, the digital tool proposed in the T4Rail project, which was developed to specifically facilitate communication procedures between Italian and Slovenian railway operators, aims to reduce the time spent at borders due to language barriers. This may stimulate demand for cross-border transport.

Future research could extend the analysis to the Slovenian side of the border, so as to obtain a broader framework of cross-border mobility patterns and attitudes. Incorporating the perspective of Slovenian residents and commuters would allow for a more systematic comparison of accessibility perceptions across the two national contexts, potentially revealing asymmetries in service quality, awareness, and travel behaviour. Furthermore, longitudinal data collection following the implementation of service improvements for cross-border connections would provide valuable evidence on the extent to which supply-side interventions are capable of translating into actual behavioural change. Finally, regression models are meant to be employed to capture the relationship among the examined variables and thus support the elaboration of incentive policies.

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From Ephemeral to Permanent: Street Experiments and the Evolution of Historical Urban Landscapes

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Abstract. From the 2005 San Francisco experiments by Rebar to the post-pandemic urban responses, temporary interventions, known as Street Experiments, are a consolidated trend in tactical urbanism. Public spaces, streets and squares have become key places for testing innovative, accessible, and landscape-sensitive urban models, integrating social interaction, recreation, and commerce. These, generally characterised by a bottom-up and reversible approach, link spatial alterations to urgent contemporary issues such as quality of life, energy transition, and active mobility.

The study proposed here is part of broader research on street experiments aimed to investigate their transitional potential and propose design methodologies to bridge the gap between ephemeral trials and permanent urban improvements.

In particular, this contribution proposes a reflection about how street experiments can act as a bridge to lasting structural changes in complex historical contexts. This study views the historic city as a place of long-term change where temporary experiments act as catalysts for permanent transformation. These approaches in stratified urban contexts, examining both the underlying processes and the physical alteration of urban fabrics, have been analysed. Through a selection of European case studies and international best practices, the study proposes a critical reflection on urban design within historical settings.

Keywords: Tactical Urbanism · Street Experiments · Historic City · Urban Transition · Public Space · Sustainable Mobility

1 Introduction

The transformation of urban public space is a pivotal issue in the current international debate on urban policies and contemporary city design strategies [1–4]. Specifically, new intervention modes have been defined, integrating design experimentation, sustainable reconfiguration strategies, and urban participation processes, and they have been fostered by the progressive redefinition of the role of the street. This has evolved from an infrastructure primarily dedicated to vehicular mobility to a multifunctional hub for sociality and urban life [5–9].

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In this context, in the recent years, the temporary space transformation practices have spread widely, and they have been often categorised as interventions of tactical urbanism [10, 11]. Among these, the street experiments are one of the most significant forms of contemporary urban experimentation. They introduce temporary configurations of street space aimed at testing new relationships between mobility, public space, and urban quality [7, 12–15].

Within the European landscape, issues linked to the ecological transition, carbon emission reduction, and the promotion of sustainable mobility have repositioned urban infrastructures at the center of the planning and design debate, emphasising the need to reinterpret the street not merely as mobility infrastructure, but as a fundamental component of public space and a central tool in constructing urban quality.

From this perspective, the street experiments are intentional, temporary interventions that modify the use, regulation, or spatial configuration of a street. Their goal, as the scholar Luca Bertolini states, is to explore new modes of organising mobility and public space, facilitating the shift from a "streets for traffic" conception to a "streets for people" vision [16].

Furthermore, during the pandemic, there was a significantly accelerated adoption of the street experiments [17–21]. Numerous European and North American cities introduced temporary interventions to ensure safety in public spaces and encourage active mobility, such as walking and cycling [22–25]

It is interesting to put in evidence how the operational efficacy of the street experiments is in the relationship between time and urban design. Temporary practices demonstrate that permanence is not an original condition, but the result of selection, adaptation, and consolidation, as modern tradition often thought of city transformation as the establishment of stable, finished layouts. Time is not an external variable, but rather a structural component of the project that tests, refines, and gradually stabilises spatial configurations. The scientific community increasingly views these practices not just as operational temporary fixes, but as tools for knowledge and urban innovation. Indeed, these experiments allow us for the observation of user behaviour, the collection of data on public space usage, and the assessment of impacts under real-world conditions, thereby building an empirical foundation to inform design decisions and urban policies [26–29].

Starting from these considerations, the study proposed is part of ongoing research, and aims to interprete the street experiments as design transition devices through which urban projects can evolve from experimental spatial configurations into permanent urban assets [7, 30, 31]. In this view, temporality is not merely a preliminary phase but an operational tool capable of mediating between experimentation, learning, and the consolidation of public space transformations, specially in a consolidated urban fabrics. This issue is particularly relevant in historic cities, where morphological stratification and conservation constraints require an approach that balances innovation with preservation. Here, temporary experiments serve as effective tools for introducing innovation in sensitive contexts, allowing for the testing of new models of use without producing immediately irreversible changes.

Thus, this contribution aims to understand how can temporary and reversible interventions contribute to lasting urban change without compromising the morphological and heritage balance of historical urban fabrics.

Based on this framework, the paper addresses two research questions:

1. Which design and operational characteristics enable a street experiment to evolve from a temporary configuration into a permanent transformation of public space?
2. How are these conditions reconfigured when experiments are applied to historic contexts, characterised by established spatial layouts and a high density of cultural and identity values?

To achieve this aim, the paper's organisation is articulated as follows: After the Introduction (1), the contribution highlights the role of temporary experimentation as a tool for urban learning and an incremental component of urban design through a comparative analysis of significant European case studies (Paris, Barcelona, and Milan), (2), then, it proposes a reflection on the street experiments are applied to historic contexts, and their relationships (3). The Conclusion (4) discusses the results obtained from the literature evaluation, as well as the main findings of the study, and the research agenda.

2 Street Experiments and Urban Design

The role of the street experiments in the transformation of urban space is analysed through a comparative approach based on the examination of several significant European case studies. The selection, Paris, Barcelona, and Milan, was made in relation to the relevance of the urban policies adopted in recent years and the widespread use of temporary experimentation in public spaces.

This analysis focuses on the strictly design-oriented aspects of these transformations: it observes how temporary interventions affect spatial configuration, the redistribution of surfaces among different uses, and the redefinition of the street as a place for social interaction and urban life. By comparing these diverse contexts, the main aim is to identify the operational conditions and design logics that allow temporary experiments to evolve into permanent urban transformations.

In this perspective, the street experiments redefine the role of urban design. Temporary experimentation introduces a design mode based on incremental, reversible, and adaptive processes, which is contrary to how planning has traditionally operated through the definition of stable and definitive layouts. The project is no longer designed as a final act, but rather as an evolving process that develops through successive phases of testing, verification, and consolidation.

Within this framework, the street-space assumes a new centrality as a privileged field of design intervention. Traditionally conceived as a space intended primarily for vehicular circulation, the street is now reinterpreted as a complex and multifunctional public space capable of hosting diverse forms of use, lingering, and social relations.This shift implies a revision of the design logics governing the configuration of the street section and the relationship between public space and the urban fabric.

Temporality in this context is not just a temporary condition but an operational tool that enables the introduction of progressive transformations and verification of their effects before stabilisation. Through light interventions, provisional signage, mobile furniture, temporary platforms, and tactical painting, it is possible to quickly modify surface distribution, redefining the balance between traffic, active mobility, and collective use.

Fig. 1. Paris, Réinventons nos places, Place du Panthéon. (A. Manca).

The case-studies of Paris, Barcelona, and Milan are particularly relevant because they allow for the observation of three distinct modes of integrating temporary experimentation into urban transformation processes.

These three cases are not treated as simple applications but as comparative devices. Paris demonstrates the integration of the temporary phase into a regulated governance process; Barcelona highlights experimentation's ability to impact the spatial structure of the existing city; Milan emphasises a more performative and anticipatory dimension, where the temporary tends to coincide with a rapid prefiguration of permanence.

The complexity of the contexts and the experiments required a cognitive process based on an analytical-critical approach. This process was aimed at investigating the dimensional, morphological, and typological aspects of the interventions, as well as the fundamental connections between form and use. The methodology was carried out by analysing the spatial and formal characteristics of the contexts and their modifications, before and after the experiments, across three distinct scales: urban, proximity, and site-specific.

The in-depth analysis of the threes cases aimed to illustrate the methods and processes by which public space transformations were initiated and maintained, enabling the evolution of temporary practices into permanent interventions. Furthermore, the research puts in evidence the connections between the various stakeholders involved and identifies the planning and design tools suitable for this transition, with a specific focus on safety and accessibility.

Fig. 2. Barcelona, Superilla di Sant Antoni. (S.Rossetti).

The comparison allows for a clarification of the operational potential of the street experiments, as well as the limits and ambiguities emerging in their relationship with the construction of urban form.

In Paris (Fig. 1), specifically the *Réinventons nos places!* (2016–2021) project, temporality is embedded from the outset within a structured governance framework. The distinction between a techno-administrative branch and one dedicated to *in situ* experimentation articulated in successive phases: observation, co-design, temporary activation, evaluation. Here, interventions modify the relationship between vehicular flows, pedestrian paths, and social spaces. However, these are not open-ended formal explorations, but regulated tools for verification aimed at stabilising strategically oriented layouts [32, 33].

In Barcelona (Fig. 2), the *Superilles* (Superblocks) project (est. 2016) introduces a model where temporality operates as a spatial reorganisation device capable of affecting the structure of the existing city. Intervening in the Cerdà grid without structural transformations, the project acts on the street section and hierarchy, redistributing surfaces between traffic and proximity uses. Through reversible devices, the street is reinterpreted as a "habitable space." However, the progressive extension of the model has produced heterogeneous results, highlighting the difficulty of translating a change of use into a coherent and recognisable urban form [34, 35].

In Milan (Fig. 3), the *Piazze Aperte* (Open Squares) program (est. 2018) introduces a third mode, where temporality takes on a predominantly performative and anticipatory character. Interventions act directly on the street surface, producing an immediate redistribution of space. While generating new practices of appropriation, the experimentation

often coincides with a prefiguration already oriented toward stabilisation, sometimes leaving the transition to a more structured morphological definition unresolved [36, 37].

3 The Historic City as a Laboratory: Temporary Experiments and Urban Evolution

This research highlights how specific urban contexts, characterised by unique territorial and socio-cultural features, can serve as ideal "laboratories" for testing high-quality transformations of public and street spaces [38, 39]. The historic urban landscape, and in particular the stratified and multifunctional urban context, which embodies historical and cultural values and meanings, is one of the privileged contexts for the temporary experimentation of effective and quality public and street spaces. In this framework, the historic city is not merely a past heritage but a dynamic environment where temporary interventions can trigger a transition toward permanent, sustainable modifications. Drawing from case studies in Barcelona, Paris, and Milan, the research allowed to explore the historic city's role as a fundamental catalyst for successful urban experimentation. The stratified urban fabric is characterised by a complex mosaic of historical signs, cultural values, and identity-forming elements and it provides a fertile ground for street experiments that aim to redefine the relationship between heritage and contemporary life.

The research seeks to clarify how temporary transformations can effectively address the modern crises facing historic centres, such as physical decay, social abandonment, and the pressures of gentrification and over tourism. These strategies can be used as tools to safeguard both material and immaterial heritage while simultaneously promoting social interaction and introducing new identity markers. At the same time, the study seeks to understand if the historic city can determinate the success of these experiments, facilitating the shift from ephemeral interventions to lasting urban features.

The historic centres represent significant documents of urban culture, even regardless of their intrinsic artistic or formal merit or their particular environmental appearance, which may further enrich or enhance their value, since not only architecture but also the urban structure possesses, in itself, meaning and value [40]. Therefore, interventions within these fabrics are aimed not only at ensuring the conservation of individual buildings, but also at preserving and passing on to future generations the values and collective specificities that characterise the historic center itself [41]. These include, for example, those defined by Article 2 of the Washington Charter (International Charter for the Conservation of Historic Towns and Urban Areas, 1987), such as: the urban form; the relationships between different urban spaces (built-up, open, and green spaces); the form and appearance of buildings; the relationships of the city with its natural or man-made environment; and, finally, the various functions and roles acquired by the city throughout its history [42].

Therefore, a "bell jar" approach to preservation is to be avoided: Safeguarding a historic center should not mean freezing it in time, but it means to adapt harmoniously to contemporary life [42]. In this perspective, the concept of city is to continue and to evolve by adding new layers of meaning. This is particularly essential in the current European

Fig. 3. Milan, Piazze Aperte (Open Squares), Piazza Via Val Lagarina. (A. Manca).

context: where the historic centres are often sites of conflict due to sustainability challenges, lack of accessibility, and rigid regulatory constraints, temporary experimentation emerges as a viable middle ground between administrative immobility, and unregulated speculation.

As the above cases demonstrate, temporary experiments are adeguate measures able to respond to the specificities of a place, meeting modern demands for safety, well-being, and inclusivity. These interventions improve the overall quality of urban life through the introduction of light mobility (reducing or eliminating vehicular traffic) and the creation of new green areas or social hubs.

The reversibility of such projects represents a key advantage. These approaches allow planners to monitor effects in real-time and correct flaws before any permanent changes are made. This process fosters a renewed sense of belonging among residents, as they witness the regeneration of their landscape in a way that is consistent with historical values but responsive to 21st-century needs.

Thus, as Salvatore Settis, the Italian scholar, states the historic city can be framed as a theatre of democracy [43], that is, considered as part of the historical landscapes that represent a map that reflects the relationship between society and its territory, then every intervention must be guided by the spirit of social justice [43].

In the same times, also the street experiments are inherently democratic; they use limited resources to generate significant improvements in public health, safety, and accessibility. Most importantly, as many research affirm, these experiments are most successful when they involve the community in the planning and design phases: Active public participation ensures that the projects are calibrated to the actual needs of the

diverse populations inhabiting the city. By transforming the "space of the street" into a "place for the people," these experiments strengthen the social fabric and ensure that the evolution of the historic city results in inclusive and accessible places.

4 Conclusions

In conclusion, the research, here proposed, is focused on application of temporary experimentation in the historic city, on their relationships, and the transition from ephemeral to permanent. The study introduces questions that go beyond reversibility, directly involving the nature of design in contexts of high morphological, symbolic, and relational density, such as the historical ones.

Indeed, European historic centres are stratified spatial systems where urban form is the result of long-term processes, that took in place over the centuries. Furthermore, these are places characterised by regulatory and strategic constraints for their protection and conservation. Public space here is not just a support for contemporary practices but a structural component of heritage. Intervening in these spaces requires the ability to operate within complex morphological structures, ensuring that transformation does not become a simple replacement of use or a superficial overlap of new devices.

In this framework, temporality plays a crucial role in testing the compatibility between new uses and consolidated spatial layouts. The street experiments intervene on spatial hierarchies, thresholds, and the relationships between solids and voids. In historic contexts, the public space is never configured neutrally; the street section and the proportion of open surfaces are elements through which it establishes the historic city recognisability. Therefore, material reversibility is not the only component able to guarantee compatibility: experimentation must be evaluated by its ability to respect or critically rework the morphological logic of the context.

Thus, the temporary experimentation establishes a knowledge-based dimension that exceeds functional verification, in order to observe how the historic space reacts to change, putting in evidence resistances and latent potentials. This is particularly relevant in "traffic evaporation" processes, where reorganisation affects fragile equilibrium between different users, accessibility, economic activity, and social practices.

However, a major limitation remains: the risk of a separation between use and structure, where the temporary reconfiguration of space does not find a full morphological translation in permanent layouts. This highlights the difficulty of governing the transition from temporary transformation to the construction of durable urban forms consistent with the historic context.

As the analysis shows, the street experiments are now main tools for reformulating public space. They allow for the initiation of flexible transformation processes, replacing deterministic logics with modes based on adaptation and progressive decision-making.

Furthermore, one of the most relevant aspects of the street experiments is capacity to function as collective and design learning devices. Temporary configurations allow the direct observation of usage patterns and the collection of empirical data, reducing uncertainty and guiding design choices with greater precision.

The comparison between the different case-studies shows that the transition from temporary to permanent is neither linear nor guaranteed, and it depends on diverse aspect such as:

- Urban Design Quality: Temporary experiments affect both use and spatial configuration, and they show greater consolidation potential.
- Strategic Framework: Integrating experiments into a broader vision to avoid isolated episodes.
- Community Engagement: Building legitimacy and stability for permanent solutions.

In the historic city, these conditions are even more vital. The temporal dimension is an integral part of the design process, where the form of public space is defined through successive cycles of testing and re-elaboration.

The central disciplinary knot lies in the relationship between use and form. It is not enough for experimentation to produce new uses; these must find a coherent translation within the spatial structure. Temporality does not replace the project; it redefines its operational conditions. Responsibility shifts to the "moment of translation where the temporary experience is transformed into a permanent urban asset.

Ultimately, the street experiments are not an alternative to urban design but a redefinition of it, acting as a transition device capable of transforming lived experience into urban form.

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User-Centric Routing Based on Residents' Needs and Preferences

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Abstract. Walkability indices are widely used to support sustainable urban planning and pedestrian routing, but most existing approaches adopt a one-size-fits-all approach that fails to capture the preferences of different subpopulations within the city. This paper proposes a user-centric walkability framework with user-specific weighting that supports personalised route choice. Based on a comprehensive literature review, the framework examines micro-scale elements of the built environment used to compute max-reward routes through the city of Sofia. To ensure the interoperability of the reviewed scoring frameworks, macro-feature weights are translated and normalised using a multi-criteria decision analysis approach based on a correspondence matrix. The results highlight a systematic mismatch between conventionally suggested routes and optimal routes for underrepresented populations. The proposed framework provides a transferable basis for more inclusive, data-driven navigation services and city planning.

Keywords: Walkability Score · User-Centric Routing · Pedestrian Comfort · Pedestrian-friendly Urban Environment

1 Introduction

Walkability, defined as the extent to which an area supports walking, has become a crucial consideration in sustainable urban planning. Cities around the globe recognise the multifaceted benefits of good walkability, including improved public health, social cohesion, lower carbon emissions and more efficient land use [1, 2]. Researchers have accordingly developed various walkability indices as decision-support and urban-planning evaluation tools. Some of these indices have been developed for general purposes, while others aim to address the walkability preferences of specific population groups, such as women, children, the elderly, tourists, or people with disabilities. Neglecting the perspectives of these groups can lead to a measurable mismatch between official walkability scores and individuals' actual walking experiences [3]. For example, studies have shown that women perceive urban spaces differently from men due to concerns about personal safety and harassment [4]. Similarly, the senior population and the elderly face age-related constraints that are not captured by typical indices, such as poor lighting, steep

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hills, or poorly paved roads, which can be minor nuisances for younger people. When walkability indices ignore these factors, they overestimate the walking friendliness for the different population

groups affected by them. The same issue persists for people with mobility impairments because they constitute a small percentage of the population, and walkability indices are often not tailored to their needs. This overlooks crucial elements that might discourage, or even physically prevent, people in wheelchairs from taking a certain path. Features such as continuous curb ramps, smooth ground surfaces and unobstructed sidewalks are crucial for wheelchair users [5]. Children also have unique needs, since they value wide sidewalks on which they can safely run, safe crossings and slow traffic speeds [6]. Tourists also represent a special category of pedestrians, often neglected in walkability research. Past research shows that, in many ways, tourist walkability overlaps with that of the general population [7]. However, places a much higher importance on cultural and historical monuments, ambient areas with traditional architecture, and the availability of stores and restaurants.

Recent research on composite walkability indices has demonstrated robust approaches to capturing the multidimensional nature of walkable environments. For example, the study by Appolloni et al. developed a so-called walking suitability index of the territory (T-WSI), which assesses neighbourhood-scale walkability through 12 micro-indicators spanning the macro-categories of practicability, safety, urbanity, and appeal [8]. However, this method relies on street-level audits and is better suited to area-wide evaluation than to single-path analysis. Similarly, Ruiz-Padillo et al. proposed a weighted index utilising a multi-criteria Fuzzy Analytic Hierarchy Process (Fuzzy AHP) to derive meaningful scores for street segments, even when they do not fully fall within a single predefined category [9]. Their case study of Porto Alegre, Brazil, demonstrated the universal importance of factors such as public security, traffic safety, and pavement quality in influencing walkability.

Beyond individual indices, recent reviews have synthesised common patterns and gaps in walkability metrics [10]. Fonseca et al. reviewed 132 studies and observed that most composite indices emphasise macro-scale attributes such as residential density, land-use mix, and intersection density. The study found that small-scale streetscape design and security features are underrepresented in conventional walkability assessments. Similarly, Akinci et al. conducted a systematic review of 146 studies, 24 on the elderly and 122 on the general population, to analyse trends in walkability scores for the two population groups [11]. Their study revealed discrepancies in the examined features between elderly people and the general population, such as mismatches in the importance placed on safety, path quality, steepness, and the abundance of greenery. Such results suggest that a one-size-fits-all index often marginalises or completely excludes underrepresented groups.

This study aims to evaluate and combine existing approaches to estimate the walkability index, thereby developing a set of metrics that account for the needs and preferences of different population groups. It also provides a means to measure the difference in routes proposed by those metrics.

The rest of the paper is structured as follows. Section 2 describes the walkability scoring methodology. Section 3 presents the results from its application, including optimal route finding for different population groups. Section 4 concludes the paper and outlines future work.

2 Walkability Scoring Methodology

The complete study workflow is shown in Fig. 1. Its subsequent steps are explained in detail in the following sections.

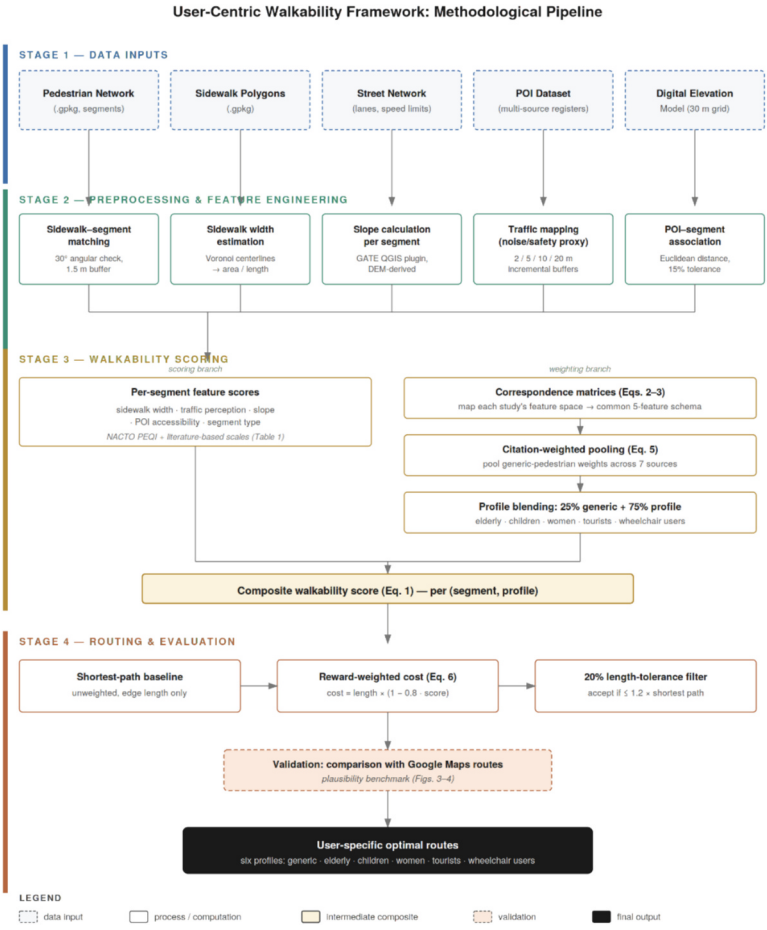


Fig. 1. Methodology Workflow

2.1 Study Area and Datasets

The framework is developed and evaluated on the municipality of Sofia's street network, the capital and largest urban centre of Bulgaria, with a population of approximately 1.2 million. Sofia lies in the Sofia Valley and is bounded to the south by the Vitosha massif, which produces significant topological variation (Fig. 6). Street gradients vary widely, even within central districts, enabling slope to be used as a discriminative feature in the proposed methodology. Additionally, Sofia is a useful test location because of its heterogeneous urban layout. The historic core, organised around pre-socialist boulevards and squares, hosts most of the city's heritage sites, museums, cafes, restaurants and stores. These features result in a tourist profile that is substantially distinct from the generic pedestrian. Surrounding the core are socialist-era residential districts marked by panel-block housing with variable sidewalk quality and widths. Beyond the ring road, post-1990 urban development has produced car-centric suburbs with weaker pedestrian infrastructure [12]. This range of built environment features spans the full range of conditions the framework is designed to differentiate and supports meaningful comparisons across user groups.

The pedestrian network is stored as a vector layer and provided in .gpkg format. Each segment of the network represents a walkable path with several attributes such as name, type and length in meters. Sidewalks, streets, parking areas, bike lanes and parks are represented as polygons in .gpkg format. They are characterised by attributes like area and perimeter. A Points of Interest (POIs) dataset is collected from multiple sources, including open data platforms, national, regional, and local registers. It includes urban facilities that citizens frequently use, grouped by primary function and further divided into subgroups based on specific functions, with consideration of their significance to citizens' well-being [1]. The street network is stored as a vector layer in .gpkg format. The network segments are characterised by attributes such as vehicle speed limits and the number of lanes.

2.2 Data Preprocessing

Before evaluating the quality of pedestrian network segments and computing composite walkability scores, several preprocessing steps are taken. This included various data enrichment procedures to add attributes via spatial indexing, including calculating sidewalk widths and the slopes of street segments.

The pedestrian network segments and sidewalk polygons do not originate from the same dataset, and therefore, a matching procedure is developed. First, the network segments representing sidewalks are split at bends with angles greater than 30°. This ensures that no segments fall within multiple streets [13]. After that, a spatial buffer is added to the polygons because, in many cases, the segments do not overlap them directly. While Brezina et al. use a 5-m buffer to associate street centerlines with sidewalk polygons, this study uses a 1.5-m buffer to associate pedestrian network sidewalk segments with sidewalk polygons. This decision is based on the fact that along a single street, there are often two sidewalk polygons and two sidewalk segments, representing the sidewalks on the two opposing banks. After buffering, a final check is conducted to examine if the angular alignment of the polygon and segment differs by more than 30°. If this is true,

the segment is assumed to be a "rogue" one, not representing the same sidewalk as the polygon [13].

The sidewalk polygons are enriched with a width attribute, derived from the polygon's area and length. The area is an inherent polygon attribute, but the length requires additional calculation. Voronoi tessellations are used to draw close-to-optimal centerlines [14]. After that, the average width of each polygon is calculated using the standard formula for a rectangle [13]. Considering that a street's sidewalk is represented by multiple polygons, and therefore multiple measurements are taken for each street, this calculation provides an estimation of where sidewalks of insufficient widths might be encountered. The slope of pedestrian network segments is obtained using the GATE QGIS plugin, which utilises segment-wise slope calculation with a Digital Elevation Model (DEM). The DEM contains height measurements taken at 30-m intervals, making calculations more precise for long street/network segments.

Pedestrian network segments are analysed with respect to traffic noise, a key source of pedestrian discomfort. An algorithm is developed to associate pedestrian network segments with corresponding street segments. Traffic-related discomfort is estimated using the number of traffic lanes and the maximum permitted vehicle speed. For each pedestrian segment, the algorithm computes its directional angle (alignment) and generates a spatial buffer. Street segments whose angular alignment differs by no more than 30° from that of the pedestrian segment are considered candidates and are mapped accordingly. If no matching street segment is identified, the buffer distance is incrementally expanded. Buffer distances of 2, 5, 10, and 20 m are applied, as empirical inspection indicates that larger buffers frequently result in incorrect mappings to streets separated by vegetation or located on the opposite side of buildings. Such barriers substantially reduce perceived or actual noise levels [15, 16].

An important criterion for evaluating the quality of a pedestrian network is its accessibility to various POIs. To determine which POIs are accessible from which network segments, an algorithm is developed, iterating through all POIs and calculating the Euclidean distance from each POI to the surrounding lines [17]. The ten closest segments are identified, and the POI is marked as accessible from the closest segment as well as from any other segment that is no more than 15% farther than the top candidate. This is useful for mapping POIs in dense parts of the network, such as fountains, monuments, and statues in public parks and squares, where a POI is effectively accessible from multiple pedestrian segments. At the same time, this approach is precise enough to avoid associating stores, restaurants, cafés, pharmacies, schools, and other POIs located in a building with pedestrian network segments on the opposite side of the building.

2.3 Walkability Scoring

To find the most comfortable route from point A to B, a max-reward path-finding algorithm is developed with a different reward function value for each population group. The first step is to assign reward values to each segment of the pedestrian network. The reward function is calculated according to Eq. 1 as follows:

$$\sum_{i=1}^{n} w_i \times s_i(e) \tag{1}$$

where w is the weight of this scoring category, and s is the quality score of the feature for the corresponding segment.

Table 1 compares different methods for scoring the quality of the micro-attributes of street segments. The "Score" column includes the scoring approaches used in the studies examined in this paper's literature review. The "Pedestrian Quality Index" column contains the relevant scoring method used by the National Association of City Transportation Officials (NACTO) [18].

Sidewalk Width. Sidewalk width scores are calculated from the sidewalk's width attribute. After examining two width-scoring approaches [1, 19]. The approach proposed by the San Francisco Department of Public Health was chosen for its greater relevance and better data separation. While Shaaban's methodology [19] is easier to use and has been developed for sidewalks measured in metric distances, the metric does not account for the specifics of Doha's cityscape, which differs from Sofia's pedestrian infrastructure and walking habits, as well as those of San Francisco. Moreover, NACTO's scoring system [18] led to a more meaningful distinction between sidewalks, as the mean sidewalk width in Sofia was approximately 2.5 m. Sidewalk width scores are only assigned to pedestrian network segments of the sidewalk subtype and are considered only when available. This means that when choosing between two edges of type "sidewalk", the algorithm selects the one with the larger width. Such a choice is most useful in urban neighbourhoods, where selecting adjacent streets or sidewalks does not drastically affect travel time but can substantially affect perceived walking comfort.

Traffic Perception. This score is a composite evaluation of the noise and safety effects of heavy traffic in the built environment. Traffic volume, the number of lanes and speed limits all correlate with the perceived pedestrian safety of walking areas [10]. These features also contribute to noise pollution, which reduces the appeal of adjacent pedestrian areas [16]. Here, NACTO's scoring system is chosen again, as it splits segment scoring into two independent parts: one for the number of lanes and another for the speed limit. In the case of the provided data, this proves useful because there are different types of streets and boulevards that share one of these two features but never both. This methodology enables greater granularity in the types of streets examined. Only pedestrian segments within a 20-m Euclidean distance of a traffic street are evaluated. Segments beyond that receive the maximum possible score for traffic perception, as in most cases, there is either a building or another physical obstruction between the pedestrian segment and the street [16].

Slope. As NACTO [18] does not have a comprehensive steepness scoring system, the slope is evaluated based on current literature, which suggests that an incline of 8% is critical for most pedestrians [8]. Although this metric has long been debated, as hilly areas often have many streets with higher inclines, in this study, it is assumed that pedestrians are generally willing to take a detour when the incline exceeds 8%. On the other hand, any slope below 2% is still considered usable, even by physically challenged users. The rest of the range (2–5% and 5–8%) is split to ensure data granularity.

POI Accessibility. POI accessibility measures how close the street segment is to mobility infrastructure, green infrastructure, schools and educational facilities, child social infrastructure, health facilities, sports infrastructure, cultural infrastructure and retail

Table 1. Scoring metrics.

Category	Score	Pedestrian Quality Index
Width	0–1 m = 0.1 1–1.5 m = 0.3 1.5–2.5 m = 0.6 >2.5 m = 1 [19]	0 = 4 0–1.52 m = 7 1.52–2.41 m = 13 2.41–3.63 m = 19 More than 3.63 m = 22
Noise disturbance / Traffic perception	No adjacent street = 1 Adjacent street with 1 lane = 0.7 Adjacent street with two lanes and speed limit = < 50 = 0.5 Adjacent street with two lanes and speed limit >50 && = < 80 = 0.2 Adjacent street with more than two lanes or speed limit >80 = 0 [10].	Lanes: 0 = 24 1 = 22 2 = 19 3 = 9 4+ = 4 Speed Limit: < 32.2 km/h = 27 Not posted (0) = 22 32.2–40.2 km/h = 22 41.8–56.3 km/h = 12 > = 56.3 km/h = 2
Slope	0–2% = 1 2–5% = 0.70 5–8% = 0.35 >8% = 0 [8]	
POI accessibility	0–1, [1]	Retail Use: 0 = 9 1–2 = 11 3+ = 19
Type	Sidewalk = 1 Crossing with a traffic light = 0.7 Zebra crossing = 0.6 Parking = 0.2 Unregulated crossing = 0 Paved parkway = 0.9 Unpaved parkway = 0.8 Parkway = 0.8 Underpass = 0.3 Overpass = 0.3 Road surface (all other types) = 0	

and services. This metric builds on previous work using the same POI dataset [1]. However, here, each POI is only associated with the street segments it is accessible from, rather than having an area of effect that encompasses all segments surrounding it. The scoring of this feature follows NACTO's "Retail Use" score [18]where more than 3 accessible POIs indicate that the segment is well connected. The reason for capping the score at three POIs is that pedestrian segments are relatively short (often only one

city block). Moreover, not capping the score favoured shopping malls and other retail clusters, unlike the pathfinding algorithm.

Type. This score is designed to place greater emphasis on more pedestrian-friendly aspects of the network. Since this feature is highly dataset-dependent and the segment types are not standardised, a custom scoring methodology is used. Specifically, traffic lights and other regulated crossings are given a higher score than unregulated crossings. Likewise, sidewalks are given a slightly higher score than parkways, as walking through a park should be discouraged under certain conditions, such as at night or when the unpaved areas are wet. Finally, underpasses and overpasses receive a low score, as pedestrians often view them as natural barriers and would rather take a path around them than use them [20]. Additionally, navigating public parking lots or walking on streets used by cars is highly discouraged.

2.4 Weights

This section describes the procedure and justification for selecting the specific weights. It begins with a description of the default pedestrian type and its weights, then proceeds to details on how the weights are adjusted to suit the other population groups.

The weights for each population group are calculated based on current literature. Since different studies have used varying features to assess walkability, these features have to be mapped to the available data. This is why an approach from Multi-Criteria Decision Analysis, known as a correspondence matrix (also called a concordance or crosswalk), is used. Conceptually, this matrix specifies the fraction of each source feature to be reassigned to each target feature, allowing one-to-many and many-to-one mappings while maintaining overall importance. When the matrix is applied to a study's weight vector, its "weight mass" is redistributed from the study's native feature-space into the common schema, yielding a directly comparable set of weights. When multiple papers are used, papers are reweighed by the count of their citations. An example application of the correspondence matrix algorithm is given here. Note that in this study, all cells in the mapping matrix have a value of either 0 or 1 to avoid distributing weights in an uninformed or random way:

1. Collect all of the scoring weights used in the paper in a 1xN matrix.

$w^{(p)}$: [Pedestrian infrastructure = 0.2, Maximum speed = 0.1, Crossing availability = 0.25, Noise level = 0.05, Gradient = 0.3, Greenness = 0.1]

2. Create a mapping matrix M where each row corresponds to one of our scoring features and each column to one of the features used in the paper.

$$M^{(p)} \in R^{n \times K_p} \tag{2}$$

where M is an $m \times p$ matrix, p is the number of features in the examined paper, n is the number of features (5 in the current study), K_p is the length of the list of features (weights) in the examined paper.

Table 2 presents an example matrix with the values mapped.

Table 2. Sample correspondence matrix.

	Pedestrian infrastructure	Maximum speed	Crossing availability	Noise level	Gradient	Greenness
Sidewalk width	0.8	0	0	0	0	0
Traffic perception	0	1	0	0.8	0	0
Slope	0	0	0	0	1	0
POI accessibility	0	0	0	0.1	0	0.1
Type	0.2	0	1	0.1	0	0.2

3. Translate the matrix into features by multiplying the matrix by the matrix of the paper's scoring weights.

$$\hat{W}^{(p)} = M^{(p)} \times w^{(p)} = [0.160, 0.140, 0.300, 0.015, 0.315] \tag{3}$$

4. Renormalise the weights so that they sum to 1.

$$W = \frac{\hat{W}^{(p)}}{\sum \hat{W}^{(p)}} = [0.172043, 0.150538, 0.322581, 0.016129, 0.338710] \tag{4}$$

5. Combine the scores of all papers. Pool all of the scores and weight them differently based on the number of citations each paper has received.

$$W_{pool} = \frac{\sum_{p=1}^{p} \alpha_p W^{(p)}}{\sum_{p=1}^{p} \alpha_p} \tag{5}$$

6. For each user type, reweigh the scoring weights with the generic pedestrian weights contributing 25% and the weights derived from the user type paper contributing 75% of the final weight.

Generic Pedestrian. This is a primary pedestrian group whose weights are calculated based on the literature [8–11]. All subsequent weight profiles utilise the generic pedestrian's weights, reweighed according to their specific requirements. The employed studies propose weighing based on surveys of pedestrians, surveys of experts in the field, direct data collection from phone walking habits, and a literature review of previous studies on the topic. Therefore, when computing the composite weights, the studies are reweighted by their number of citations.

Elderly. The weights for the elderly population are based on the study by Ye [21], with a contribution of 75% compared to 25% from the generic pedestrian weights. The elderly's walkability perception centres on functional accessibility, comfort, and safety

from crime, rather than traffic safety. High-density, mixed-use areas enhance perceived walkability, while well-maintained, properly paved paths ensure walking safety. After translating the weights via a correspondence matrix, metrics such as sidewalk width and traffic perception become less important, while slope, the number of accessible POIs, and street type become more important. The employed metrics are the "Land use mix – access" mapped to POI Accessibility, and "Street connectivity", mapped to Type.

Children. The weights for the children population are based on the study by Zuo [6]. The employed metrics from the study are the "Effective street width" mapped to Sidewalk with, "Interfacial diversity" mapped to POI Accessibility, "Street flatness" mapped to Slope, "Green looking ratio" mapped to Type, and "Sound Decibels" mapped to Traffic perception. According to the survey, the children prioritise flat, clean and sufficiently wide streets and therefore would prefer paved walking paths. High-traffic streets also seem to be unpopular among children due to noise, vehicle encroachment, and deficiencies such as potholes and obstructions. Quantified, these findings indicate a rise in the importance of slope, POI Accessibility, and Type weights, and a decrease in Traffic perception.

Women. The weights for the female population are based on the study by Golan et al. [4]. Women rank crime, homelessness and physical safety as the most important factors when selecting a walking path. Moreover, they described avoiding streets with encampments, large groups of men or poor sanitation. Secondary factors included vehicular traffic, parks and open spaces and types of nearby businesses. Streets with many amenities were ranked high, but only when they were perceived as safe and maintained. The negative correlation between a general, ungendered Walk Score and the proposed Walkability Index for Women is examined. Often, areas with a high Walk Score were the least desirable for women due to concerns about safety or cleanliness. The employed metrics are the "Sidewalk Quality" mapped to Sidewalk width, and "Presence of Parks", mapped to Type, "Vehicular Traffic Volume", mapped to Traffic perception, "Types of Businesses", mapped to POI accessibility, and "Slope", mapped to Slope.

Tourists. The weights for the tourists are based on the study by Hassanshahi et al. [22]. Tourists favour streets that are connected to cultural and heritage sites, mixed-use tourism-compatible POIs such as cafes, shops, and restaurants, and streets with high security metrics. Additionally, tourists favour highly connected, integrated streets that facilitate natural pedestrian movement. It is suggested that urban planners should prioritise heritage visibility and route connectivity, enhance safety and ensure public transit access while maintaining comforts such as access to food and beverages. The employed metrics from the study are the "Imageability and heritage assets" mapped to POI accessibility, and "Land use and activity", mapped to Type, "Traffic safety", mapped to Traffic perception, "Accessibility", mapped to POI accessibility, and **"**Comfort and convenience**"**, mapped to Sidewalk width.

Disabled People. The wheelchair-user weights are based on the study by Jehle et al. [3]. The study finds that barrier-free sidewalks and sidewalk width are the most important features for wheelchair users, as they enable them to traverse a given sidewalk. Additionally, the discomfort caused by sloped streets scales faster for wheelchair users, and their tolerance for slopes is lower. Wheelchair users also prefer smooth, paved streets

and parkways, and unpaved streets affect them more than pedestrians. Therefore, traffic perception and POI density are less important to them. The employed metrics from the study are the "Sidewalk width" mapped to Sidewalk width, and "Slope", mapped to Slope, "Number of car lanes", mapped to Traffic perception, "Max speed", mapped to Traffic perception, "Safe street crossings", mapped to Type, "Underpasses", mapped to Type, and "Number of POIs", mapped to POI accessibility.

Table 3 summarises the weight for the different population groups.

Table 3. Metric weights.

	Generic pedestrian	Elderly	Children	Women	Tourists	Wheelchair users
Sidewalk width	0.136395	0.175347	0.205741	0.127074	0.143616	0.302828
Traffic perception	0.279145	0.225661	0.191677	0.249538	0.199838	0.130861
Slope	0.125414	0.159484	0.156975	0.188378	0.031353	0.182819
POI accessibility	0.220057	0.221011	0.206756	0.203775	0.405080	0.094102
Type	0.238988	0.218496	0.238851	0.231235	0.220112	0.289389

2.5 Routing

Computing the paths includes calculation of the fastest path and all lowest-cost paths with a cost reduction of 0.8, using the following equation:

$$\text{cost}_{\text{edge}} = \text{length}_{\text{edge}} \times \left(1 - \text{cost}_{\textit{reduction factor}} \times \text{score}_{\text{walkability}}\right) \tag{6}$$

The candidate for the lowest-cost path was accepted only if its total length was within 20% of the shortest path's length. Since walkability scores are precomputed offline, the routing query reduces to a shortest-path search, making it computationally feasible to integrate with navigation services.

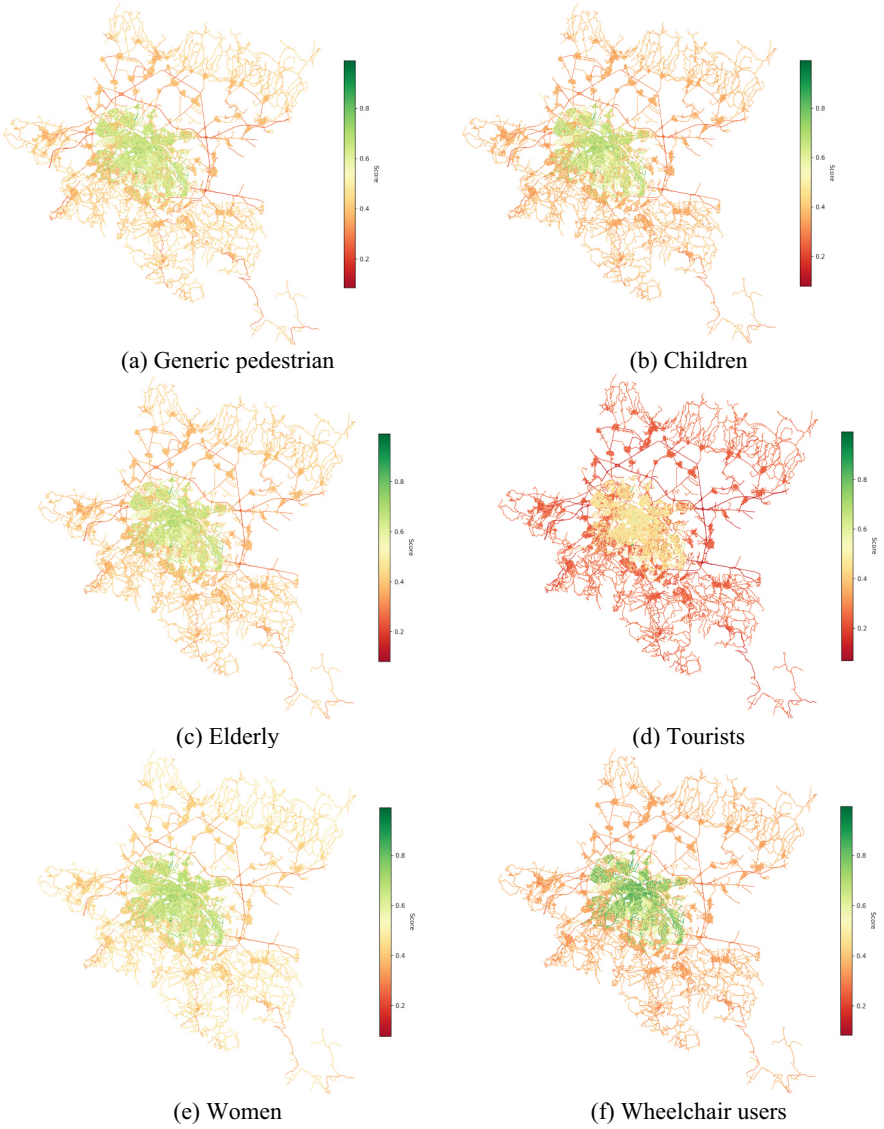
3 Results

3.1 Walkability Scores and Coefficient of Variation

Examining walkability scores across all population groups, it is clear that walkable areas of the city are located within urban neighbourhoods. Pedestrian network segments outside the ring road, where most roads are used only by cars or have poorly maintained sidewalks, score significantly lower than those within the city.

Fig. 2 summarises the city-wide segment scores for each of the six user profiles. The highest scores are concentrated in the inner-city neighbourhoods within Sofia's ring

road. In contrast, remote neighbourhoods with more car-centric design and walking paths along busy roads and heavy-traffic boulevards score lower across all user groups. This is explained by infrastructure quality, wide sidewalks, alleys within parks, regulated sidewalks, and a higher POI concentration. The framework's POI, traffic, and type features are the main drivers of this difference between inner-city and outer-city scores.



(a) Generic pedestrian (b) Children

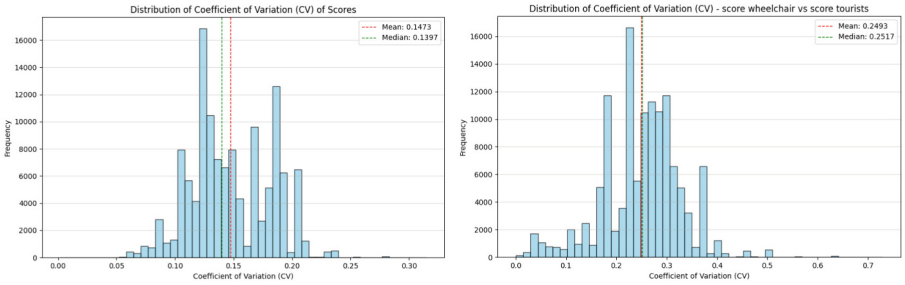
(c) Elderly (d) Tourists

(e) Women (f) Wheelchair users

Fig. 2. Walkability scores of the generic pedestrian group (a), the children group (b), the elderly group (c), the tourist group (d), the woman group (e) and the wheelchair user group (f).

The generic pedestrian, children, elderly, and women categories produce similar patterns (Fig. 4a-c, Fig. 2e). This indicates that, despite some weights differing, the shared or similar weights (POIs, traffic, type) are significant enough to drive the results in the same direction. The difference in scores becomes clearer with the more specialised profiles. The wheelchair user profile (Fig. 2f) shows a more pronounced difference between its highest- and lowest-scoring paths. This profile assigns an extremely high score to a selected set of pedestrian segments within the city centre, with apparently high scores in the sidewalk width and segment type categories. Another outlier is the tourist profile (Fig. 2d), which focuses mainly on POI accessibility. As a result, it assigns a lower overall score to the city network. However, more informative than the overall score is the difference between different areas within the city. It is apparent that this type of user prefers inner-city areas with nearby POIs, such as historical sites, cultural venues, restaurants, and entertainment venues.

Analysing the Coefficient of Variation (CV) scores reveals that there is generally little variation between different user groups (see Fig. 3). This is to be expected, as most population groups consider the same attributes of the pedestrian network to be the most important. However, the difference between groups with little in common increases sharply. For example, the CV between wheelchair users and tourists is nearly double that of all other indices. This supports the findings of the literature review and suggests that user groups with divergent requirements may assign different scores to the same edges of the network.



(a) All scores (b) Generic pedestrian and wheelchair user

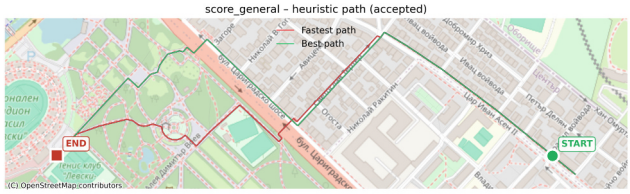
Fig. 3. Coefficient of Variation between the scores of all population groups (a) and between generic pedestrian and wheelchair user groups.

3.2 Optimal Route Finding

To evaluate the path-finding capabilities of the proposed methodology, a routing algorithm was developed. The paths were evaluated against a commonly used pedestrian navigation application. After the shortest paths were calculated, they were visualised alongside the shortest path. Also, a visualisation of the best paths for all user groups was created to examine how they differ. The results aligned with those from the previous section. Most subpopulations followed paths very similar to the best option. However, the groups with more specific requirements, such as tourists, wheelchair users, and, to a lesser extent, women, sometimes preferred different paths than the other groups (see Fig. 5), which aligns with the CV scores. Additionally, there was a high overlap between the paths suggested by Google Maps (see Fig. 4) and the fastest paths found by the path-finding algorithm (see Fig. 5). Moreover, the alternative paths suggested by Google Maps often overlapped with one or more user groups' preferences.

Fig. 4. Routing paths suggested by Google Maps.

(e) All user-groups compared



(a) Generic pedestrian

(b) Tourists

(c) Women

(d) Wheelchair users

(e) All user-groups compared

Fig. 5. Optimal routing paths, calculated for each population group.

4 Discussion

The study was motivated by a recurrent observation in the current literature. Composite indices designed for the general population tend to underrepresent groups whose needs diverge from the average. The results empirically address this concern, clarify where such divergences occur, and measure them on a shared network.

4.1 Findings in Relation to Prior Work

The walkability score maps for the different user profiles (Fig. 2a-c, e) show broadly similar spatial patterns. This is consistent with the central finding of Fonseca et al. [10], indicating that macro attributes like residential density, land-use mix, etc., dominate composite indices. In the proposed framework, these attributes are presented as weights, including POI accessibility, traffic perception, and segment type. Although the weights of these features differ across user groups, they are sufficient to roughly align the scores within each user group across different areas of the city.

The point where the framework departs from a one-size-fits-all index is the divergence between profiles with distinct infrastructural requirements. This is best exemplified by the CV metric, which is nearly double when measuring wheelchair users versus the general population compared to the average value between all user groups (Fig. 3). This, in addition to the routing experiments (Fig. 5), confirms that specific user profiles often select paths different from the general population. This pattern aligns with the review of Akinci et al. [11], who found measurable discrepancies between walkability operationalisations that focus on the elderly and those that target the general population. Their paper also concludes that a one-size-fits-all framework marginalises groups with special needs. The present framework extends this beyond the elderly-versus-general comparison, suggesting that marginalisation is not uniform but is largest for tourists [22] and wheelchair users [3], and smaller for women, the elderly, and children.

4.2 Methodological Contribution

Among the multi-criteria approaches reviewed, the closest methodological precedent is Ruiz-Padillo et al. [9], who apply a Fuzzy Analytic Hierarchy Process to derive walkability weights for the Porto Alegre region. Their approach is similar to that of Campisi et al. [20]. It derives weights from a single expert or stakeholder and applies them to a specific area. The correspondence matrix introduced differs from the approaches they used. It pools weights across a set of studies, each with its own distinct feature schema, by mapping every study's feature space onto a shared five-feature representation. The practical advantages come in the form of transferability, as the framework enables easier addition of new user groups or reevaluating current groups, as these actions require only the mapping of a relevant study.

4.3 Limitations

Two limitations should be made explicit. First, POI accessibility is operationalised through Euclidean distance with a 15% tolerance threshold for segment association. While this is a viable simplification of the association task as POIs are accessed from the nearest network segment, it does not capture distance-weighted accessibility throughout the graph. Second, validation is currently limited only to a benchmark with existing navigation applications, which does not directly establish user preferences.

5 Conclusion

This paper presents a user-centric framework for assessing walkability and pedestrian route planning, which accounts for the varying preferences of different population groups. Using Sofia's pedestrian network and supporting datasets, the study operationalises five metrics on the segment level (sidewalk width, traffic perception, slope, POI accessibility and segment type). The results indicate that even with common, readily available data, walkability patterns can show meaningful differences. Although walkability scores remain broadly consistent across user groups, meaningful mismatches are observed between populations with divergent requirements, namely tourists and wheelchair users. Routing experiments show that user-specific scoring can yield paths different from those generated by standard navigation tools. This illustrates the need for user-specific routing and evaluation options.

Future work should (i) implement a more sophisticated method for POI to network segment mapping (ii) further validate the framework through replication using data from different cities; (iii) use different underlying studies to test the scope to which the framework can be applied; (iv) incorporate additional user-groups and new micro-scale features (where possible) to increase the relevance of the suggested paths; (v) update weights using population-specific surveys to decrease the reliance on priors based only on past literature.

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Vehicular Speed Profiles on Raised Pedestrian Crossing to Inform 30 Km/h Zone Implementation

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Abstract. High vehicular speeds are likely to cause fatal crashes when a car hits a pedestrian. To reduce this probability, risk mitigation measures are required. A traffic calming device is a measure implemented to alter driver behavior and reduce speeds, thereby improving safety conditions for all vulnerable users. In this paper, a simplified methodology to evaluate vehicular speed profiles, according to vehicle type, is proposed. This is a crucial step in evaluating the effectiveness of the traffic calming measures for different types of road users and understanding their behaviours. The models show good prediction accuracy in terms of Pearson coefficient ($P \approx 0.7$). The results of this study demonstrate how the use of Raised Pedestrian Crossing (RPC) reduces speeds near its installation, but this reduction is lower for Sport Utility Vehicles compared to other vehicle types. Furthermore, the development of speed profiles for different vehicle types may be a new contribution to the implementation of speed models within traffic microsimulation models, thus studying the impact of using these measures on proper traffic flow. The application that could follow is to implement these measures to effectively create reduced speed zones (Zone 30), without the use of external enforcement for speed control.

Keywords: Sustainable Mobility · Road Safety · Pedestrian Safety

1 Introduction

Improving the safety conditions for vulnerable users and reducing the risks associated with interactions with motorized flows is an essential step in promoting and strengthening sustainable and smart mobility. As shown in the current literature [1], higher vehicular speeds are more likely to cause fatal crashes when a car hits a pedestrian. To reduce this probability, risk mitigation measures are required [2]. The most used devices are defined as Traffic Calming Devices, which aim to reduce speeds by applying some psycho-physical discomforts to drivers in the vicinity. In general, a traffic calming device is a measure implemented to alter driver behavior and reduce speeds, thereby improving safety conditions for all vulnerable users [3].

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A first classification of the most common traffic calming measures could be based on vertical and horizontal devices [4]. Among the first category, it is possible to find all devices that induce speed reduction by a vertical displacement that leads to discomfort, such as speed humps and raised platforms. To the second category, for instance, belong all the devices that induce speed reduction by causing a horizontal displacement of the vehicle: it is possible to find chicanes and carriageway narrowing (which also lead to a psycho-physical discomfort) [5].

Among the vertical devices that cause vertical deflections, there are Raised Pedestrian Crossings (RPC). RPCs are often used to allow pedestrians to cross streets safely and modify driver behaviours by reducing their travel speeds in urban areas. Traffic calming configuration, height or width, and finally materials, are strongly related not only to vehicle speed reduction, but also to measurement effectiveness [6]. In this context, evaluating crossing speeds and speed reduction efficiency and effectiveness are key to improving vulnerable road user safety [7].

According to Barbosa et al. [8], after RPC installation, the speed of the 85% percentile is reduced by 10%, and the number of crashes could be reduced by less by 10%. As shown by the study of Distefano [9], after analyzing crash data five years before and five years after the installation of an RPC, the authors found that after the installation of the device, the number of fatal crashes was reduced by 100%, while the number of injuries decreased by 50%. In another study conducted in the city of Burgos, Northern Spain [10], the author found, after analyzing several traffic calming devices, that both pedestrian RPC and Lane Narrowing lead to the greatest speed reduction. In particular, after evaluating the speed of the 85% percentile, the RPC led to a speed reduction of 20 km/h.

It is worth noting that the installation of such type of devices, in addition to speed reduction, could lead to a worsening of vehicular traffic conditions, by reducing road capacity and increasing traffic delays. As already shown by Garcia et al. [11], after the calibration of a microsimulation software with real data collected with GPS devices, the authors found that if the speed table has a more inclined entry ramp, the higher the speed reduction registered. In addition, the spacing between traffic calming devices is not only linked to a reduced speed but also to a reduced capacity. Another aspect to bear in mind is that, although traffic calming measures are useful to influence driver behaviours, they may not always be so effective in reducing speeds. According to Majer and Sołowczuk [12], poor speed table design could lead to unpredictable driver behaviours, or the presence of short length roads could be relevant.

From the analysis of the literature, two main gaps emerge that need to be addressed for future research. The first one regards the development of models that take into account the different vehicle typologies that cross the traffic calming devices. Previous studies have shown that there may be differences between crossing speeds, but without much strong evidence, and only with the use of statistical analyses and without the development of ad hoc models. Furthermore, no models emerge from the literature that allow for evaluating the mean and variance taking into account the different categories of vehicles, nor values of accelerations and speeds that have a low probability of being exceeded.

In this paper, a simplified methodology to evaluate vehicular speed profiles, according to vehicle type, is proposed. This is a crucial step in evaluating the effectiveness of

the traffic calming measures for different types of road users and understanding their behaviours. The innovative aspect that is proposed in this paper is to analyse this vehicular speed profile by considering different types of vehicles. In this perspective, the proposed modelling approach provides a quantitative support for the design of 30 km/h Zones, allowing practitioners to calibrate traffic calming measures according to different vehicle classes and to ensure that target speeds are consistently achieved under real operating conditions. Since this research is based on a single specific site alone, without replication across multiple sites, the entire work can be configured as a methodological case study rather than a generally transferable design paper.

The whole paper will be structured in this way: after the introductory Section with evidence from literature, a Sect. 2 on the methodological aspect will be proposed, and then the case study in Sect. 3; then the results in Sect. 4 will be shown, and in the following Sect. 5, a brief discussion will be reported; finally, a Sect. 6 with overall conclusions.

2 Methodology

This paper aims, as already stated, at vehicular speed profile evaluation in the vicinity of a raised pedestrian crossing (RPC). Evaluating the speed profile is essential for traffic microsimulation analysis and for traffic calming effectiveness assessment in reducing speeds. The methodology (see Fig. 1) involves using cameras on the edge of the road, near the raised pedestrian crossing, to collect speed data. Video data collection can be carried out using various devices equipped with video cameras. The necessary video quality must be quite high, as time measures must be taken at each milestone marked at the PRC to assess the travel speed at that milestone. Knowing the instants of time at which the vehicle passes the marked milestones, given the distance fixed a priori between them, it is possible to derive the speed. The optimal site of analysis should be selected, bearing in mind accessibility to camera positioning and relevance in terms of traffic considerations.

After the video editing phase, consisting of data collection and pre-processing, the video from the cameras has been analyzed. For each milestone, speed assessment in the vicinity of Traffic Calming Measures (TCM) had been carried out, and data have been labelled according to vehicle category, and only isolated vehicles have been considered eligible. The assumption of an isolated vehicle is important as the objective of reconstructing speed profiles is closely linked to the study of vehicle and user behavior in relation to RPC. Studying the isolated vehicle means reducing to zero any possible interactions with other users (other drivers and crossing pods), to isolate the real behavior assumed by the user. Based on average speed, all observations involving two different vehicles crossing the same finish line within 15 s were discarded. Above this 15-s time gap, isolated vehicle/ free-flow conditions were deemed met [13, 14].

Subsequently, for each vehicle, the speed profile for each vehicle was plotted using linear (Eq. 1) and parabolic (Eq. 2) mathematical functions in the access and exit branches of the RPC:

$$v_{deceleration,k} = \mathrm{m}_k \times s + q_k \tag{1}$$

Where:

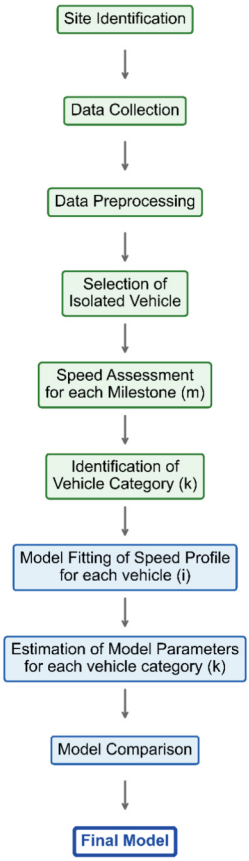


Fig. 1. Flow chart of the proposed methodology to reconstruct vehicular speed profile in the nearby of an RPC.

- $v_{deceleration,\,k}$ is the vehicle speed in the deceleration phase approaching the RPC;
- s is the abscissa;
- m_k and q_k are the model calibration coefficients;
- k is the vehicle category.

$$v_{acceleration,k} = a_k \times s^2 + b_k \times s + c \tag{2}$$

Where:

- $v_{acceleration,\,k}$ is the vehicle speed in the acceleration phase after crossing the RPC;
- s is the abscissa;
- a_k, b_k, and c_k are the model calibration coefficients;
- k is the vehicle category.

Given the actual speed values, the model was calibrated, and the estimates were evaluated for each vehicle that passed through. Once this was done, average parameters

were evaluated for each vehicle category, allowing for a single model per category. For each traffic calming approach branch and for each vehicle category, different models have been evaluated, and the best of these was chosen by comparing their performance in terms of Pearson Coefficient. Other types of functions (such as the exponential one, based on the real mechanics of locomotion) have been calibrated: only those with the best fit are reported in this article.

3 Case Study

The RPC under analysis is located in the city of Cassino, Lazio, Italy, in front of the Department of Civil and Mechanical Engineering (see Fig. 2). The RPC allows pedestrians to cross the road and so link directly to the multilevel parking located in the opposite direction to the entrance of the Department. The road on which is installed (Gaetano di Biasio Street) is characterized by elevated traffic flows. Additionally, the RPC is not only used by university students, but also by other school students and pedestrians. As it is possible to observe in Fig. 3, the RPC has a length of 6.00 m and a width of 3.75 m.

Fig. 2. Location of the RPC under study in the City of Cassino (red dot). The two directions of Analysis have also been reported (black arrows). Source; Open Street Map [15].

Video camera equipment had been installed on the rooftop of the Department's main building to have a clear overview of the RPC and the approaching vehicles, and also to avoid problems related to the privacy of road users. In addition, 8 milestones have been defined, and for each of them, speed values have been collected. The distance between milestones has been selected according to the camera acquisition frequency of 20 frames per second. An ad hoc software has been implemented in Python to analyze video recordings and collect vehicular speed values.

The data collection campaign, carried out on different days, in different lighting conditions, and during off-peak hours (to avoid excessive vehicle and pedestrian traffic

volumes and therefore minimize interactions between road users), led to the collection of 19,840 discrete speed measurements for 2,480 different vehicles and users. The forward collection has been differentiated by the two different directions of travel that are recorded near the RPC. This is mainly because RPC is not perfectly positioned on a zero-slope road, but there is a 1% slope.

Fig. 3. Detail of the RPC under study in the City of Cassino.

4 Results

After the video editing phase, data on predefined milestones have been collected for each vehicle category k. Five class vehicles have been defined: City Car (n = 1123), Sedan (n = 393), Station Wagon (n = 117), Sport Utility Vehicle (n = 627), and Heavy-Duty Vehicle (214). Other vehicle classes have not been analyzed (for instance, two-wheeler vehicles) due to the limited number of observations in the dataset. Before the models were created, the normality of the speed data at the RPC was taken into consideration. As can be seen from Figs. 4 and 5, the QQ plots show a normal pattern of the data.

For each vehicle class, the best model for speed profile is a combined model consisting of a linear model in the deceleration phase, while a parabolic model in the acceleration phase after crossing the RPC. Model description is provided in the "Methodology" section, while the estimated parameters are reported in Tables 1 and 2 for the incoming and outgoing direction, respectively. As already stated, the analysis has been made for the two travel directions due to the road slope (see Fig. 2).

In addition, from Fig. 6, 7, 8, 9, 10, the graphical output of the combined model is shown for each vehicle category. The vehicular speed profiles in grey represent the measured speed profile, while the red one is the estimated model.

As it emerges from all graphs, in the incoming direction (a), with a negative slope, vehicular speed at 20 m from the RPC is higher than the speed after 15 m from the RPC. While there is a reduction in speed in the entry branch, after crossing the RPC, the

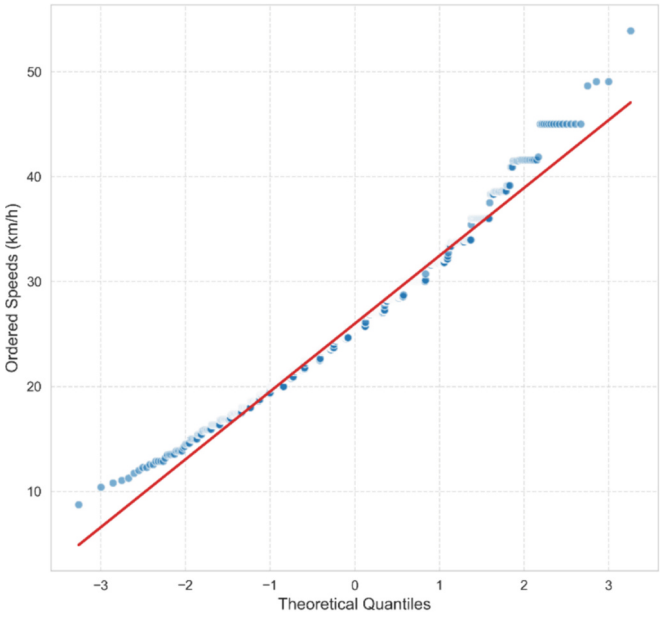


Fig. 4. Q-Q plot for crossing speeds in the outgoing direction.

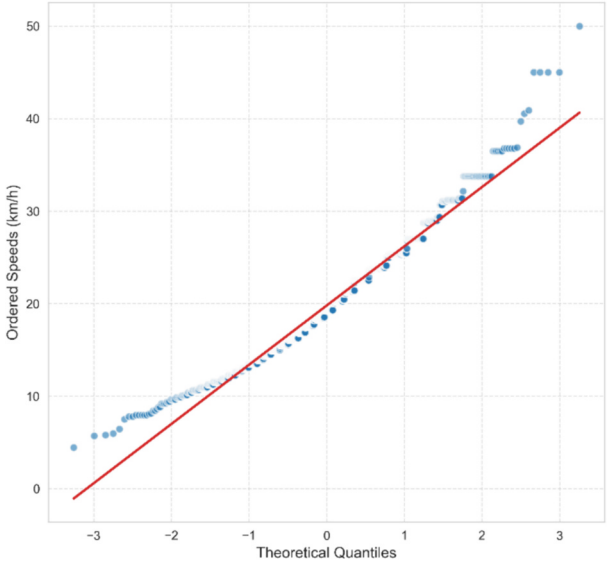
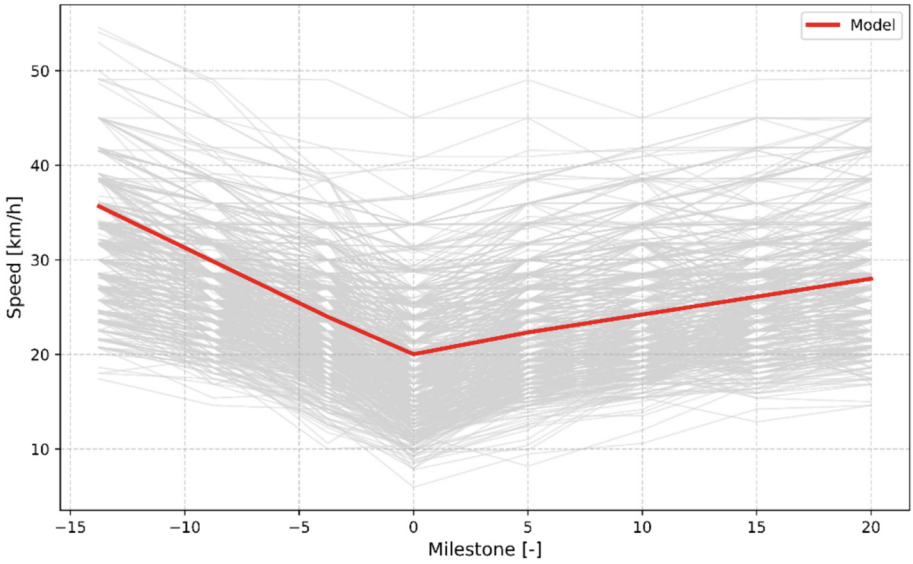
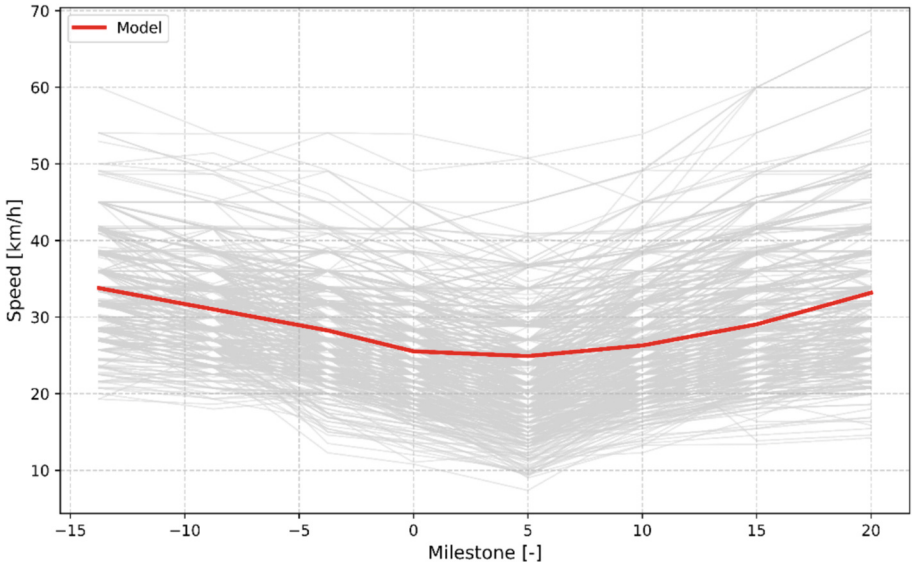


Fig. 5. Q-Q plot for crossing speeds in the incoming direction.

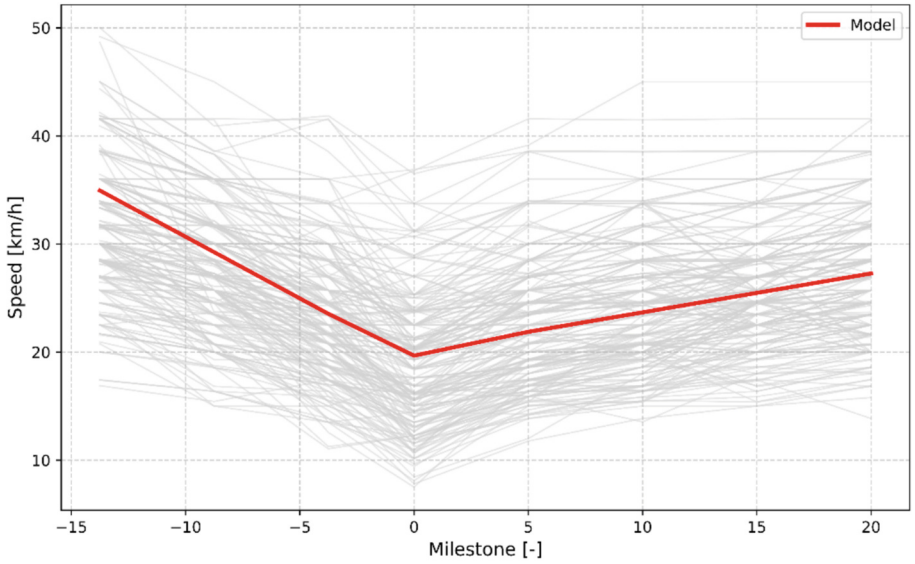


a)



b)

Fig. 6. Graphical representation of the vehicular speed model for the city car: a) the speed profile in the incoming direction; b) speed profile of the city car in the outgoing direction.



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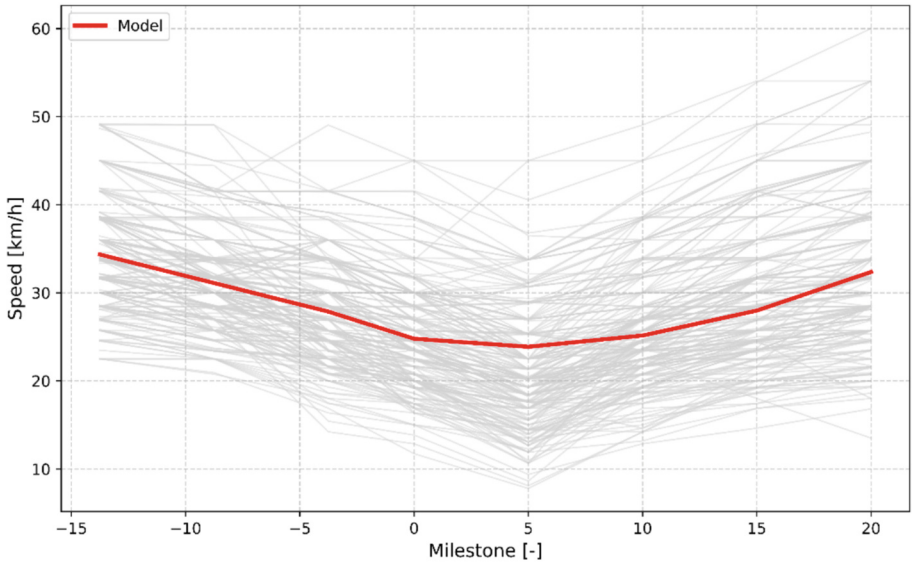
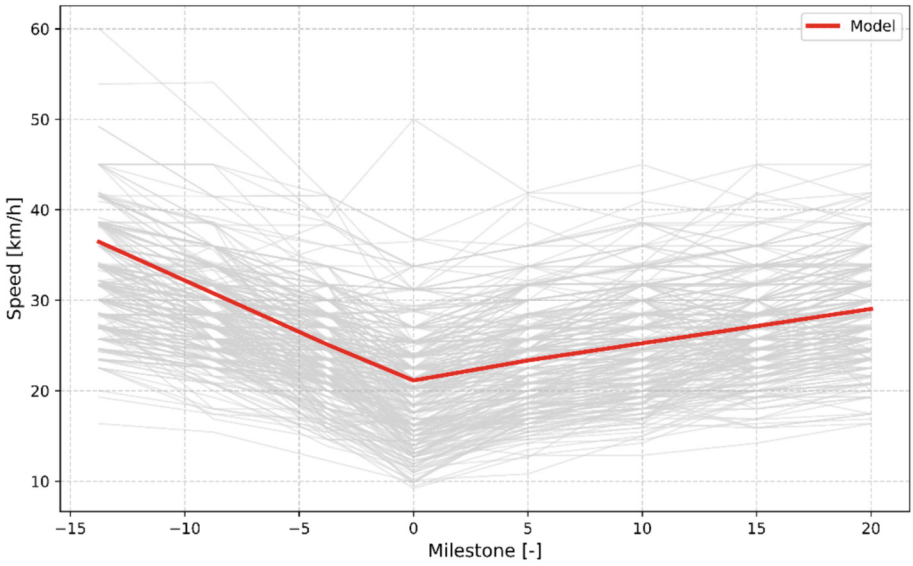
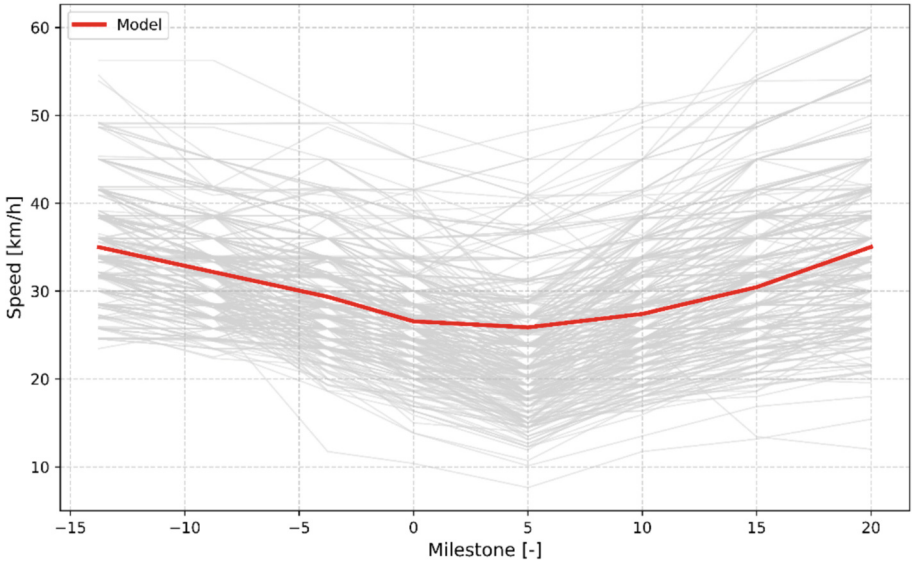


b)

Fig. 7. Graphical representation of the vehicular speed model for the sedan: a) the speed profile in the incoming direction; b) speed profile in the outgoing direction.

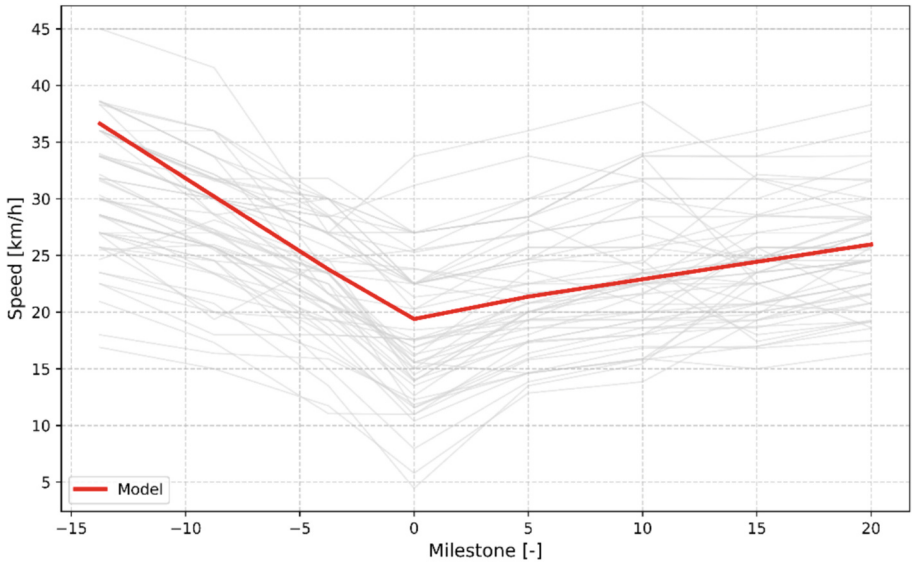


a)

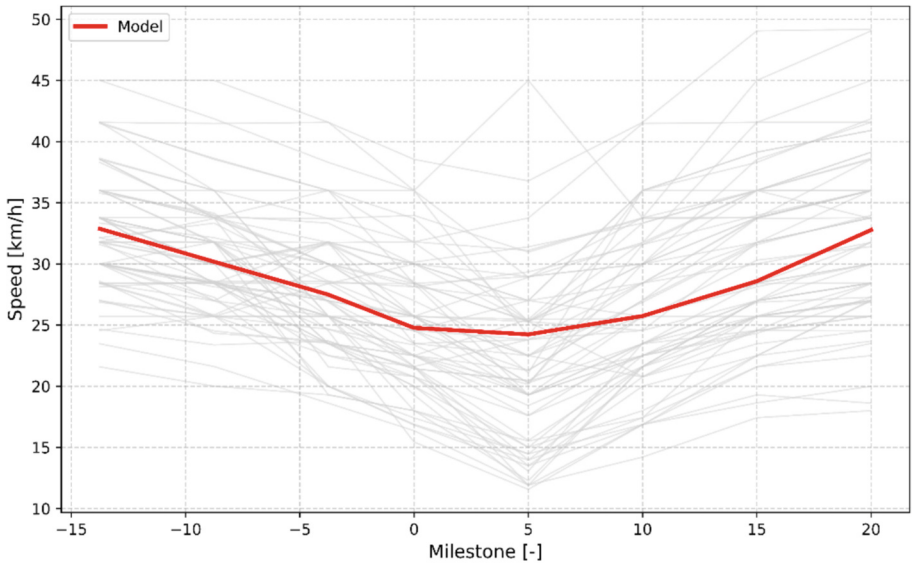


b)

Fig. 8. Graphical representation of the vehicular speed model for the SUV: a) the speed profile in the incoming direction; b) speed profile in the outgoing direction.

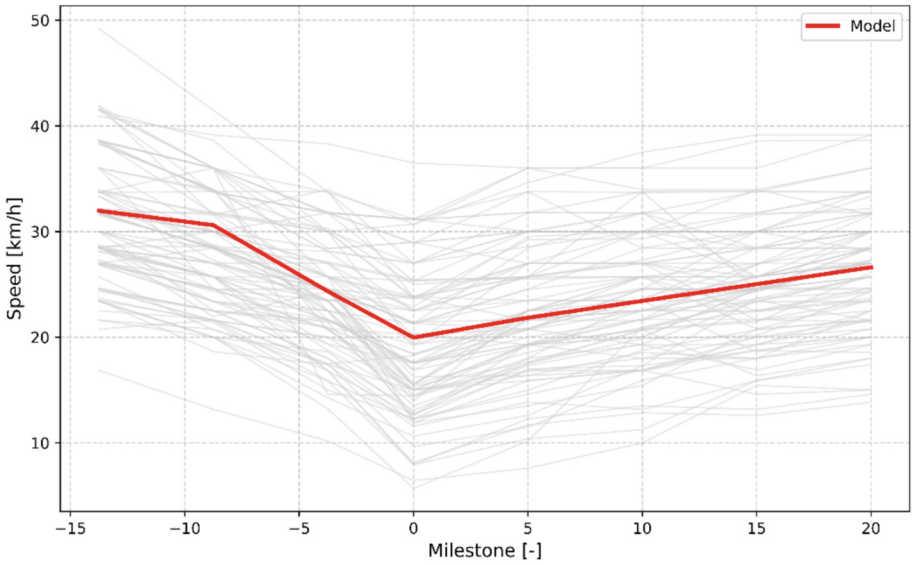


a)

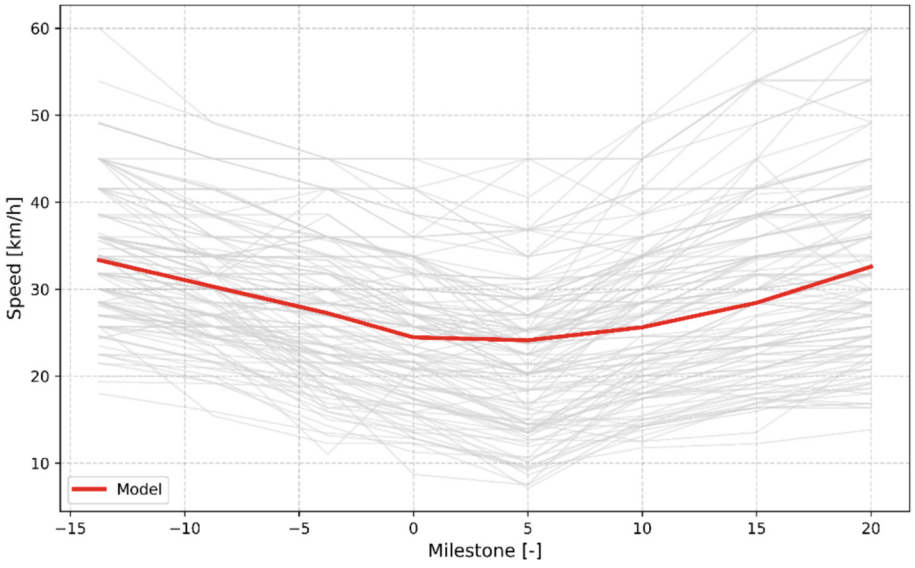


b)

Fig. 9. Graphical representation of the vehicular speed model for the Station Wagon: a) the speed profile in the incoming direction; b) speed profile in the outgoing direction.



a)



b)

Fig. 10. Graphical representation of the vehicular speed model for the Heavy-Duty Vehicle: a) the speed profile in the incoming direction; b) speed profile in the outgoing direction.

gradient with which the speed increases is higher than in the entry section. This shows that drivers tend to accelerate and reach high speeds after crossing the RPC, but this could be due to a widening of both the lane and the roadway.

In the opposite outgoing direction, with a positive slope (b), it is possible to observe in all graphs that the speed 15 m before and 20 m after the RPC is almost the same. In addition, in this direction, in the acceleration phase, it is possible to observe a more parabolic speed profile than the opposite direction (a) with a negative gradient.

Going to Tables 1 and 2, and specifically on the estimates of the linear model in the Deceleration Phase, it is worth noting, looking at the known term of the linear relationship (in particular q_k), that SUVs compared to other vehicle types, tend to cross PRC with a higher average velocity than other vehicle categories (the difference is more marked in the outgoing direction, described in Table 2). This could be due to the different stiffness of the suspension systems or the reduced visual perception of the structure from a raised driving position. It emerges that the negative slopes (Table 1) are beneficial in reducing crossing speeds that are lower than those in the opposite direction (b), with a positive slope. In Table 3 and 4, the Mean Absolute Error (MAE) for the linear and parabolic model in both directions have been reported.

Table 1. Estimation of the calibration coefficient of the linear and parabolic models to describe vehicular speed profile in the incoming direction.

Variable	Linear Model (Deceleration Phase)		Parabolic Model (Acceleration Phase)			
	m_k	q_k	a_k	b_k	c_k	Pearson (P)
City Car	0.378557	20.42865	-0.02175	-1.12472	19.6006	0.717159
Sedan	0.359991	20.07026	-0.01796	-1.10462	19.26042	0.736754
SUV	0.379507	21.44814	-0.01914	-1.09882	20.818	0.720141
Station Wagon	0.317725	20.25318	-0.02728	-1.19568	19.65861	0.717473
Heavy Duty Vehicle	0.307414	19.82455	-0.02667	-1.23205	18.95272	0.740551

Table 2. Estimation of the calibration coefficient of the linear and parabolic models to describe vehicular speed profile in the outgoing direction.

Variable	Linear Model (Deceleration Phase)		Parabolic Model (Acceleration Phase)			
	m_k	q_k	a_k	b_k	c_k	Pearson (P)
City Car	−-0.55261	26.18206	0.027296	-0.13103	24.8738	0.640476
Sedan	-0.64885	25.42485	0.031097	-0.21106	24.14558	0.69267
SUV	-0.56432	27.23512	0.030517	-0.15311	25.87957	0.646925
Station Wagon	-0.61014	24.95177	0.026642	-0.10177	23.97185	0.660369
Heavy Duty Vehicle	-0.5382	25.46817	0.026827	-0.1015	24.07225	0.671542

Table 3. Mean Absolute Error (MAE) for the linear and parabolic model in the incoming direction.

Variable	Linear Model (Deceleration Phase)	Parabolic Model (Acceleration Phase)
	MAE	MAE
City Car	5.32	4.68
Sedan	5.18	4.81
SUV	5.22	4.56
Station Wagon	4.92	4.64
Heavy Duty Vehicle	5.25	4.86

Table 4. Mean Absolute Error (MAE) for the linear and parabolic model in the outgoing direction.

Variable	Linear Model (Deceleration Phase)	Parabolic Model (Acceleration Phase)
	MAE	MAE
City Car	4.76	6.07
Sedan	4.71	5.95
SUV	4.52	5.89
Station Wagon	4.07	5.36
Heavy Duty Vehicle	6.16	7.54

5 Conclusions

From the literature analysis carried out, high vehicle speed values represent one of the main risk factors associated with fatal crashes, especially for pedestrians. Reducing road user speeds across all contexts is a strategy to reduce risk and increase safety for all vulnerable road users. Recently, traffic-calming measures have been implemented worldwide as a strategy to reduce the risk of road crashes. Among those that play an important role in pedestrian safety in urban areas, it is possible to find raised pedestrian crossings. These devices aim to induce a state of discomfort in the driver when crossing and to adapt the driving behaviour by reducing crossing speeds. The use of several RPCs, together with other traffic calming measures, could, in fact, control and reduce travel speeds in particular areas of the urban context. The application that could follow is to implement these measures to effectively create reduced speed zones (Zone 30), without the use of external equipment for speed control, but only by inserting devices that modify the driving behavior. Therefore, understanding how road users behave in the vicinity of a PRC is essential to understanding the extent of speed reduction. Obviously, a user's driving behavior is influenced by several very different factors, such as road width, road type, and vehicle type. To minimize the interference of external variables on behavior,

video camera data were collected in this study on a PRC located in the city of Cassino. The collected data were processed using appropriately developed software. Only some observations were considered suitable for the development of the analysis, namely, all those in which the condition of an isolated vehicle and no crossing pedestrians on the PRC occurred. All this was necessary to ensure that driving behavior was not conditioned by external factors.

Following the data collection and preprocessing phase, the data were analyzed with the aim of obtaining speed profiles, i.e., how the vehicles behave when approaching and exiting the PRC. This analysis was conducted for different vehicle types (small car, sedan, station wagon, SUV, and heavy vehicles), and then for each vehicle type, two speed profiles (in both directions) were evaluated. The best model in terms of Pearson coefficient (P) was found to be a mixed model consisting of two submodels: a linear one in deceleration and a parabolic one in the acceleration phase. What emerges from the analyses is that crossing speeds are strongly influenced by the type of vehicle: SUVs tend to cross the PRC in both directions at higher speeds than the other types analyzed. Furthermore, it can be noted that the speed of approach to the RPC is also influenced by the width of the road section.

The results of this study demonstrate how the use of RPCs reduces speeds near their installation. In addition to that, by analyzing acceleration and deceleration speed profiles, to guarantee 30 km/h, spacing between RPC should be 40/50 m (in line with previous studies [16]), but further analyses are needed to validate this spacing. Furthermore, the development of speed profiles for different vehicle types may be a new contribution to the implementation of speed models within traffic microsimulation models, thus studying the impact of using these measures on proper traffic flow. Furthermore, by knowing the velocity profiles and deriving the respective accelerations or decelerations, it is possible to understand how to space different RPCs so as to effectively create a zone in which the velocities do not exceed a certain value, as in Zone 30.

Author Contributions

Conceptualization, C.G. and N.S.; **methodology**, C.G. and N.S.; **software**, C.G. and N.S.; **validation**, C.G. and N.S.; **formal analysis**, C.G. and N.S.; **investigation**, C.G. and N.S.; **resources**, C.G. and N.S.; **data curation**, C.G. and N.S.; **writing—original draft preparation**, C.G. and N.S.; **writing—review and editing**, C.G. and N.S.; **visualization**, C.G. and N.S..; **supervision**, D.A.M. and N.V.; **project administration**, D.A.M. and N.V.; **funding acquisition**, D.A.M. and N.V. All authors have read and agreed to the published version of the manuscript.

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Gender Differences in Injury Severity in Pedestrian–E-Scooter Collisions: A Simulation Study Using Multi-body Tools

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Abstract. The adoption of electric micromobility, encouraged by the sustainability goals of the Agenda 2030, has revolutionized urban transportation, although it often preceded the development of appropriate regulations and infrastructure. In Italy, ISTAT data show a concerning increase in accidents involving electric scooters, many of which include pedestrians. This study fills a gap in scientific research: the lack of biomechanical analyses that consider gender differences. Using a multibody simulation environment, 120 impact scenarios involving e-scooters and pedestrians are investigated, with variations in mass, impact angles, and speed. The outcomes are assessed through the HIC (Head Injury Criterion) index to determine the severity of head injuries. The study highlights that initial speed is the main factor determining injury severity, and that anthropometric differences between men and women significantly influence the dynamics of falls and the extent of impact with the ground.

Keywords: E-scooter · Pedestrian · HIC · Multi-body · Gender Differences · Micromobility

1 Introduction

In recent years, environmental impact has become a significant issue. To combat this problem, the United Nations Organization has adopted a global legislative framework, the Agenda 2030 [1], which defines 17 Sustainable Development Goals (SDGs) to be pursued by 2030.

Among the various objectives, this legislative framework certainly aims to encourage reducing pollution, given the use of private vehicles such as cars, to the detriment of a mobility defined as sustainable.

A transport system is considered sustainable when it provides easy access to places, goods, and services that cater to different societal groups and future generations, while

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ensuring the health and safety of the population. The key element is awareness, with citizen engagement through alternative suggestions to encourage lifestyle changes. Sustainable mobility has developed from this foundation, promoting travel by micro-mobility devices such as e-scooters and electric bikes, as well as walking and shared vehicles like car and bike sharing. In this context, urban micromobility has become a transformative approach in both developed and developing cities [2]. Electric scooters, in particular, symbolize this shift. These modes of transport are especially suited to short journeys, thanks to their convenience, versatility, and ease of use. However, the increase in micromobility has not kept pace with the development of adequate regulations and infrastructure suitable and safe for such vehicles. Many cities introduced electric scooters before establishing policies on their use in circulation zones, maximum speeds, and the required protective gear. Studies indicate that most e-scooter users do not wear helmets, even at moderate or high speeds [3].

However, this increases the risks users face on their journeys and raises the likelihood of collisions with other road users. E-scooters, compared to other micromobility modes, expose drivers to greater risk due to their intrinsic characteristics, such as smaller wheels, a higher center of gravity, and limited braking stability [4]. An additional factor increasing the risk of injury for scooter riders is the low helmet use rate; studies from various regions show helmet use below 10% among e-scooter riders [5–7]. The low rate of helmet use confirms the high incidence of head injuries, as documented by emergency services.

Furthermore, the use of such modes of transport has increased interactions with pedestrians, especially in shared areas. Numerous studies show that, recently, there has been a significant increase in pedestrian injuries following impacts with micromobility devices [8–10].

Data on accidents involving these road users underscore the importance of ensuring their safety.

In Italy, ISTAT data from 2023 [11] report a total of 3,365 accidents involving electric scooter drivers, with 3,195 injuries and 21 deaths. These figures are higher than in 2022, which recorded 2,929 accidents, 2,787 injuries, and 16 fatalities. Many of these accidents involve collisions with pedestrians, including 182 injured, one pedestrian hit, and one pedestrian killed. Of the 3,173 accidents recorded in 2023, approximately 1,573 involved vulnerable road users, with more men than women affected. Despite increasing safety concerns, scientific insights into the dynamics of micromobility and pedestrian collisions remain limited, with most data originating from injury reports rather than biomechanical or simulation research.

Unlike motor vehicles, electric scooters often come into contact with a pedestrian's limbs or torso before they start to fall. This contact leads to the development of a rotary moment that generates unusual falls, different from those generated by the auto-pedestrian contact.

Furthermore, the handlebars and frame of these vehicles have rigid surfaces that could hit parts of the pedestrian's body before the e-scooter even falls, increasing the risk of injury.

Once established, it is crucial to thoroughly analyze the body's kinematics and the relative impact velocities that pedestrians experience in accidents involving mobility

vehicles. While conventional empirical data are available, the development of simulation-based methods to better understand injury mechanisms is highlighted. As a result, details like the direction of impact, the gender of the scooter rider, the pedestrian's gender, and the passenger's posture are often overlooked.

While some studies examine how impact direction affects user injuries, there is a lack of analysis of how anthropometric parameters such as body mass, height, center of gravity position, and segmental mass distribution influence outcomes.

Most standardized simulations and crash tests use male anthropometric models (50^{th} percentile), often ignoring important biomechanical differences between men and women, like body mass distribution, neck muscle endurance, and height. These factors directly influence head movement and injury results [12, 13]. These limitations underscore the need for research that systematically examines micromobility collision mechanisms and assesses injury severity in controlled settings.

This study seeks to address this gap by examining how the HIC (Head Injury Criterion) index varies in scooter-pedestrian impacts using the Virtual Crash multibody simulation environment [14]. It aims to quantify how gender-based anthropometric differences affect TBI severity, offering new insights to help create more inclusive safety standards.

2 Materials and Methods

The present research, therefore, aims to investigate whether and what differences exist in the severity of injuries sustained by vulnerable users following impact. In particular, the investigation focuses on potential differences in injury severity between men and women. The type of impact investigated is a collision between an e-scooter driver and a pedestrian, based on the need highlighted by recent years' accident data.

Therefore, it was decided to investigate the dynamics of collisions between these two vulnerable road users. In the technical literature, the most relevant parameter for assessing the pedestrian's injury is the HIC (Head Injury Criterion) [15–18].

This criterion, to assess head injuries, which are the most serious injuries to the body following an accident, is based on the measurement of the actual head deceleration after impact (see Eq. 1).

$$HIC = \max\left[(t_2 - t_1) \bullet \left(\frac{\int_{t1}^{t2} a(t)dt}{t_2 - t_1}\right)^{2.5}\right] \tag{1}$$

Where:

-a represents the acceleration over the time interval;

-t_2 and t_1 represent the time interval that maximizes the average deceleration.

The equation proposed above can be simplified as a mass-spring model (see Eq. 2) [19]:

$$HIC = K * V^{2.5} \tag{2}$$

Where:

-K is a constant of proportionality equal to 33.93;

-V is the maximum velocity of impact (m/s);

Using the AIS scale, HIC values (dimensionless) can be converted to assess the likelihood of serious injury [20]. This probability can be evaluated through the following relationship for AIS4 (see Eq. 3).

$$Probability\ of\ injury = \frac{1}{\left[1 + \exp\left(\left(\frac{4{,}9+200}{HIC}\right) - 0,00351 \bullet HIC\right)\right]} \tag{3}$$

This relationship uses the maximum head-to-ground impact velocity from crash test simulations to estimate HIC values. The HIC values are then used to assess the likelihood of severe TBI (Traumatic Brain Injury) using the AIS (Abbreviated Injury Scale; see Fig. 1). This establishes a relationship between the vehicle's collision speed and the likelihood of severe head injuries.

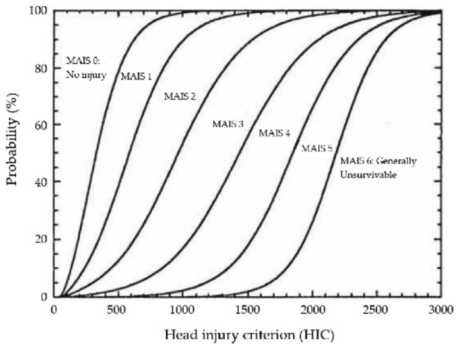

Fig. 1. Prasad–Mertz probability curves for a specific injury at a given HIC value [21].

Therefore, to estimate the HIC sustained by users involved in an accident, it is necessary to know the head's speed at impact.

To know this magnitude, a multi-body simulation software, such as Virtual Crash, was used in the present research [14].

Virtual Crash is a well-known, moment-based crash reconstruction software widely used in car accident research and by law enforcement agencies in Europe and America. The software is based on Kudlich–Slibar rigid-body impulse models [22] and uses a mixed Euler-Runge-Kutta numerical integration method [23]. Importing diverse models, such as CAD models of vehicles, pedestrians, terrain, and obstacles, enables the most accurate reconstruction of the working environment.

The software uses 13 ellipsoidal objects connected by joints to create a ragdoll model of cyclists and pedestrians, with shape, size, and weight adjustable. Changes in mechanical properties, such as joint stiffness, damping, and posture, can create a realistic human model. The models have been adapted to replicate the postures of e-scooter riders and pedestrians.

This software enables the development of a sensitivity analysis with a low computational burden; for this reason, it was used in the present research.

However, since Virtual Crash is a software based on rigid models, it is necessary to validate its outputs against those from more sophisticated finite element software.

D'Apuzzo et al. [24] investigated the impact between a scooter driver and an SUV, developing the simulation using Virtual Crash. They then compared the HIC results with those presented by Ptak et al. [25], obtained by implementing the same simulations in Madymo. Madymo is a finite element software that goes beyond the rigid model simplification provided by Virtual Crash. A comparison of the HIC values showed a strong correlation, leading to the identification of a more critical case history involving a frontal impact in which deformations play a fundamental role. In this case, the HIC value from the Virtual Crash software, despite being notably different from Madymo's, is very high. This suggests an inherent criticality of the Greater scenario that exceeds the more accurately reconstructed one.

Therefore, in any case, the HIC values obtained would allow for safety considerations.

Despite these limitations, Virtual CRASH offers significant advantages for studying collisions in the micromobility field. It enables systematic variation of parameters such as velocity, mass, angle, and anthropometry, thereby isolating the effects of each factor on injury severity. In addition, it provides kinematic outputs, such as head velocity, impact time, and center of mass motion, which are essential for calculating injury metrics, such as the criterion for head injury.

The methodology is first and foremost based on the definition of the influential variables to be considered.

It was decided to analyze the influence of the following characteristics:

- Type of e-scooter with different masses;
- Speed of the scooter driver;
- Type of pedestrian hit, distinguished in terms of gender;
- Type of scooter driver, distinguished in terms of gender;
- Types of impact angles.

The choice of electric scooter type fell on the typical micromobility vehicle used in urban areas. The substantial difference among the types chosen in the simulations concerns mass. From the analysis of the literature [26–28] and from the mobility reports shared, also by sharing companies, it was possible to identify characteristic masses of these vehicles: 12, 15, and 20 kg, which respectively indicate different types of material, i.e., carbon fiber, aluminum, and steel.

As for the height and orientation of the handlebars, they are adjusted in the Virtual Crash software (see Fig. 2) to accommodate typical riding postures, ensuring that both male and female riders adopt realistic positions.

As regards permitted speed limits, the Highway Code D.L. 2021 [29] provides a maximum of 20 km/h, while in pedestrian areas it drops to 6 km/h.

Particular attention should be paid if you use a sharing scooter. These vehicles are equipped with a GPS tracking system that connects to the company's network via the application installed on the user's mobile phone. These applications automatically limit vehicle speed to 6 km/h when users enter an area marked on the GPS as a pedestrian area, as required by Legislative Decree 2021.

Fig. 2. Model of e-scooters in Virtual Crash software.

The technical data sheets for the scooters showed that the maximum speed ranges from 25 to 30 km/h.

As for the angles of impact selected for the simulations, they correspond to:

-0° = frontal impact;

-0° off-center = off-center frontal impact;

-90° = side impact;

-180° = rear impact;

-180° off-center = off-center rear impact.

These directions were chosen because they represent real, standard, and observed collision configurations in shared spaces between pedestrians and micromobility.

Frontal impacts typically occur when a scooter rider approaches a pedestrian head-on, while offset impacts occur when a pedestrian tries to avoid an approaching scooter rider. Side impacts often happen at intersections or when pedestrians are in the path of an approaching e-scooter.

As defined in the Introduction, a specific gap in the current research concerns the analysis of any differences, in terms of harmfulness, between users involved in accidents based on gender.

This aspect appears essential, as differences in mass, height, and the position of the center of gravity can influence the outcomes of collisions. Generally, women have lower mass and stature than men, which could alter the extent of rotation during impact and, consequently, influence the timing and severity of head impacts with the ground.

As for the Virtual Crash software, it uses 13 ellipsoidal objects connected by joints to create a ragdoll model of cyclists and pedestrians, with adjustable shape, size, and weight. Mechanical properties, such as joint stiffness, damping, and postures, can be modified to obtain a more realistic human model. The models have been adapted to replicate the postures of scooter drivers and pedestrians.

To evaluate the anthropometric proportions, referring to the male and female dummies to be considered, the type of "adult" dummy was examined, and, based on literature analysis, the proportions were deduced.

For male models, the height is about 1.75 m, and the mass is about 75 kg. The women's models were configured with a height of 1.62 m and a mass of 62 kg [30–34].

Once these variables were defined, 120 simulations were performed in the Virtual Crash software (see Table 1).

Table 1. Parameters and variables considered for the impact scenarios.

E-scooter weight (kg)	E-scooter speed (km/h)	Impact Angle (°)	Pedestrian Gender	Rider Gender
12 15 30	6 15 20 30	0 180 90 0 off 180 off	Male Female	Male Female

From the simulations, the time history of the head speed experienced by the subjects involved in the accident (see Fig. 3) was obtained, which, when applied to the Head Injury Criterion, enabled the HIC to be evaluated.

Fig. 3. Head speed time history experienced by the e-scooter rider and the pedestrian in the Virtual Crash.

3 Analysis of Results

From the simulations, it was possible to analyze the impact mechanism on the users' heads. As far as pedestrians are concerned, there is an impact mechanism that includes two phases:

– Primary impact with the electric scooter: in this type of impact, the effect on the pedestrian's lower limbs first occurs. However, depending on the scooter model, the first contact may also affect the pelvis and/or torso. This impact then determines the trajectory of the pedestrian's torso as it is rotated and translated, shifting the center of mass relative to the feet.
– Secondary impact with the ground: following the first impact, the head touches the ground, and it is precisely this impact that determines the most severe HIC values.

The kinematics of the scooter rider's head follow a similar principle. When the rider is destabilized, the body can be thrown over the handlebars or to the side, resulting in a secondary impact with the ground.

As previously mentioned, the focus of the present research is to investigate whether and how gender difference affects the severity of injuries sustained as a result of impact. For this purpose, the HIC values, respectively for pedestrians and riders, obtained from the combinations of simulations described above, were correlated. In particular, for the pedestrian, the HIC correlation is shown in Fig. 4.

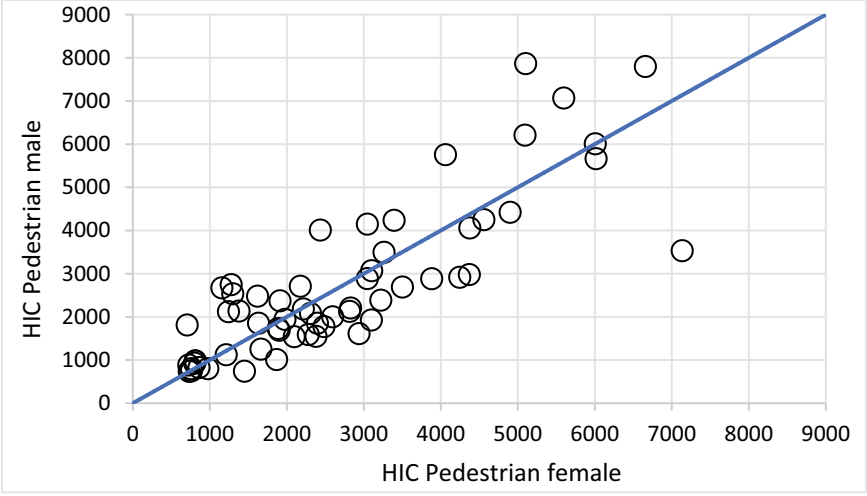

Fig. 4. HIC comparison between male and female pedestrians for electric scooter impacts.

The data show a general positive correlation, although there are substantial differences. There is significant dispersion around the bisector, indicating that the biomechanical response to impact differs substantially between the two genera.

The trend shows that, under the same accident conditions, male pedestrians have higher HIC values than women. This evidence could depend on the height and center of mass; even among pedestrians, the man is taller. This condition could, in the event of a fall, expose the head to impacts with the ground of greater kinetic energy.

Having ascertained this, we intend to investigate how the initial impact variables, set as simulation conditions, can influence the pedestrian's injury, differentiated by gender.

To investigate this, a correlation matrix (see Fig. 5) is presented that, using Pearson coefficients, allows examination of the relationships between the input variables and the Head Injury Criterion (HIC) injury index, calculated separately for male and female subjects.

The results show that the initial speed is the parameter most strongly correlated with HIC for both subjects, with Pearson correlation coefficients of 0.61 and 0.54 for the male and female pedestrians, respectively. Therefore, this highlights a slightly greater sensitivity of male pedestrians to changes in speed.

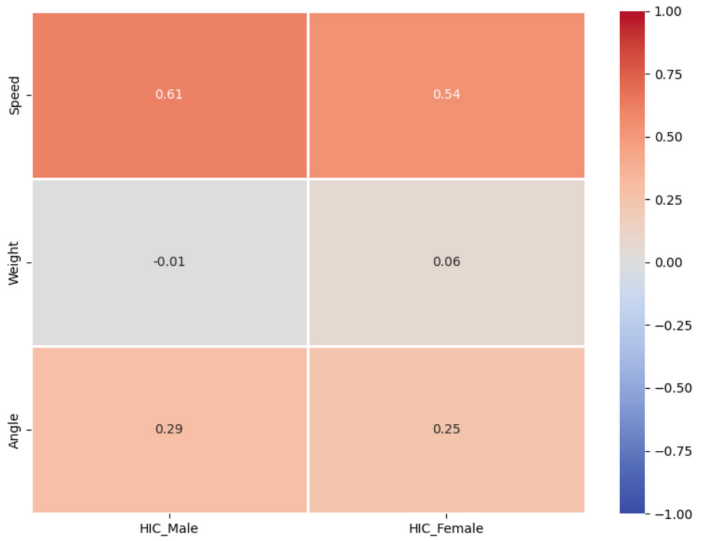

Fig. 5. Correlation matrix between impact parameters (speed, weight, and angle) and Head Injury Criterion (HIC) for male and female models.

As for the weight of the vehicle (in this case, an e-scooter), there is little correlation for both male and female pedestrians, with Pearson coefficients of −0.01 and 0.06, respectively.

The angle of impact, on the other hand, shows a modest correlation, similar for both sexes, suggesting a secondary effect.

Therefore, differences can be observed between male and female pedestrians, but for both, the vehicle's initial speed is a significant factor in the injuries sustained.

From the results obtained, it was therefore decided to investigate in greater depth the link between vehicle speed and the outcomes of injuries suffered by pedestrians, men and women (see Fig. 6).

What can be seen is that, in general, as speed increases, HIC values also increase markedly, confirming the strong relationship between speed and the severity of injuries sustained by pedestrians in impact events, as shown in the literature.

More specifically, at low speeds (5–15 km/h), there is an overlap between men and women. At higher speeds between 20 and 30 km/h, however, women begin to record higher HIC values than men.

It is therefore emphasized that this parameter should be investigated to understand the intrinsic variability it can generate across different simulation scenarios.

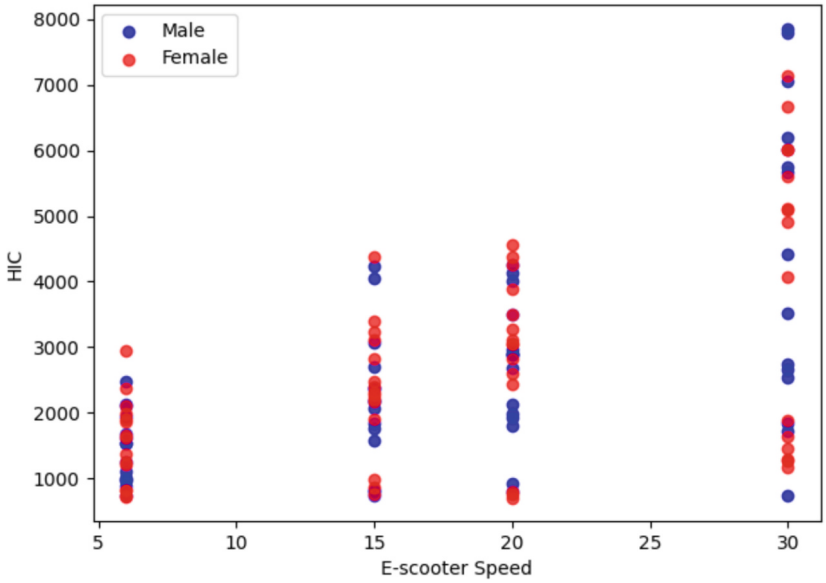

Fig. 6. Correlation between Speed and Head Injury Criterion (HIC) for male and female models.

4 Conclusion

The present work aims to investigate the influence of gender differences on the harm subjects suffer as a result of an impact. ISTAT data show that accidents involving micro-mobility vehicles are growing and, above all, that among the various vehicles, electric scooters account for a significant share. In addition, there are worrying data on collisions between drivers of these vehicles and pedestrians. This has led to a focus on this type of accident.

To determine the severity of the injury sustained by the subjects as a result of the impact, the Head Injury Criterion was used, which is expressed as the HIC. This criterion bases the severity of the recorded injury on the speed of the impact sustained by the subjects involved. To determine this magnitude, 120 simulations were conducted using the Virtual Crash accident reconstruction software. The simulations vary according to different boundary conditions: the gender of the subjects involved, the vehicle's initial speed and weight, and the angles of impact.

The analysis focused on the pedestrian figure. First of all, it was clear that the gender difference influences the outcome of the clash, with men recording greater injuries than women. This probably happens because men are taller, which exposes their heads to a greater fall with higher kinetic energy. Therefore, biomechanical gender differences influence the injuries sustained.

Having ascertained this, it was decided to investigate how the various input conditions could, or could not, influence the severity of the injury.

It was found that vehicle speed is the parameter most strongly correlated with HIC for both genders, with Pearson correlation coefficients of 0.61 for males and 0.54 for females. However, a significant fact that emerges, for higher speeds, is that the trend is reversed: women suffer greater injuries than men. This underlines a particular intrinsic criticality in some impact scenarios.

In contrast, the vehicle's mass (12, 15, or 20 kg) has almost no effect on injury severity.

This research, therefore, not only underlines the need to consider gender differences for these types of studies but also supports the effectiveness of speed restrictions, such as the 6 km/h limit, in pedestrian areas, to drastically reduce the risk of permanent or fatal trauma.

The gender differences considered in this study are limited to anthropometric parameters (mass and height), since Virtual Crash employs rigid-body multibody models that do not allow detailed biomechanical characterization of tissue properties or neck stiffness.

Future developments include investigating the influence of gender differences on injuries sustained by scooter drivers and implementing new simulations that include other modes of micromobility.

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Determinants of Micromobility Adoption in University Campuses: Preliminary Findings from a Small-Scale City in Italy

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Abstract. University campuses are ideal environments for promoting sustainable urban mobility. However, the adoption of active and electric micromobility faces socio-demographic and behavioral barriers. This study investigates and compares the propensity of a university community to adopt e-bikes, e-scooters, and traditional bicycles as alternatives to private cars. Based on a travel survey conducted at the University of Cassino (Italy), three Ordered Logit models have been calibrated, characterized by a McFadden/Pseudo R^2 of 0.0947, 0.1118, 0.1039. Explanatory variables include socio-demographics, university status, attendance, and current travel habits. Results show that off-campus students exhibit the highest propensity to adopt all three modes, whereas habitual car drivers reveal some resistances. A significant gender gap emerges, with females less likely to adopt micromobility, particularly traditional bicycles. Comparing the transport modes, e-bikes prove to be the most inclusive option: they overcome the physical fatigue barrier for extra-urban commuters and the age barrier (>45 years) that significantly limits e-scooter and traditional bike usage. Conversely, e-scooters show strong potential for last-mile connectivity among combined public transit users.

Keywords: Sustainable Mobility · Smart Mobility · Safety

1 Introduction

The recent growth of micromobility transport mode solutions in cities (such as bike, e-scooter, and e-bike) has raised some safety concerns among all road users. Study users preferences and propensity towards micromobility could be a fundamental step to promote and address policies to foster sustainable mobility, but at the same ensure adequate safety levels for these users [1–4].

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Micromobility users make their trip for different reasons, but it is essential to determine the contributing factors to understand how to change and pursue the modal split towards these sustainable transport modes. An emerging trend in literature it is expressed by the study of micromobility of university students [5, 6], that are one of the main category to use such type of transport mode. From an online survey conducted in Sweden [7], it emerges that high income, held a driving license, car and e-bike ownership, and public transit subscription are the main determinants toward the use of e-scooters. Users with inclination towards more sustainable transport mode, registered an higher e-scooter propensity than others. Although micromobility transport mode belongs to the same category, scholars have found conflict between bike and e-scooter share: for instance Yang et al. [8] have shown that the use of bike decrease in e-scooter sharing areas by 10.2%. Regarding the crash frequency of e-scooters, the number of crashes increase in area shared with pedestrian and cyclists, near to schools facilities and in areas with larger Black, Asian and Minority Ethnic population [9]. Regarding e-bike, some studies in Netherland found that women use more e-bike than men, but differences are narrow for elderly [10], while e-bike ownership decrease the adoption of muscular bike, and then, marginally, the use of car and public transit. It has also been found that built environment at destination work location rathern than the residential location play a crucial role: for instance the presence of road with bike lanes, major trunk road, and the presence in the neighborhoods are associated with increased levels of e-bike use [11]. In another work conducted in China [12], it has been highlighted that e-bike adoption in Henan Province is influenced mainly by socio-demographic factors (such as family size and occupation) and economic savings, the main motivation for use. Unexpectedly, environmental concerns show a negative impact on utilization. Furthermore, the presence of adequate infrastructure (cycle lane and charging stations) is crucial to promoting a more widespread and sustainable use of e-bikes. However, these spatial interactions and infrastructural gaps fundamentally shape the safety landscape, as the competition for urban space and the lack of dedicated paths directly correlate with specific crash dynamics and increased risk levels.

As it emerges from recent study [13] safety may exert positive influence on micromobility choices. In a comparative study on e-scooters users and non users [14], it has been found that non users of e-scooter tend to assume more safe behaviours than systematic users, and to perceive safety in a different manner than the e-scooter users. Among micromobility transport mode, it is worth mentioning e-bike. According to Guo et al. [15], the main determinants related to e-bike crash severity are age, gender, e-bike behavior, license plate, bicycle type, location, and speed limits. Some other authors found that, for e-bike commuting, the main factor related to the choice is weather conditions [16].

As shown in a study conducted in UK [17], the authors discuss the benefits of cycling for individuals and society but also highlight the disproportionately high rates of road traffic injuries and fatalities sustained by cyclists. According to Meuleners et al. [18], 93% of all cyclist crashes occurred on local government-controlled roads, rather than state roads. According to the authors, this is expected since cyclists tend to prefer traveling on smaller roads with less traffic. Other scholars [19] identify the characteristics of older cyclists and explore which of these characteristics are associated with self-reported cycling crashes. More than 800 cyclists aged over 65 completed a questionnaire that

covered demographics, bicycle specifications, and personal characteristics. Firstly, with every passing year, the chance of falling increased by 7.3%. Secondly, if cyclists had mental impairments, the chance of falling increased by a factor of 2.5. Thirdly, if cyclists were less than entirely confident, the likelihood of falling increased by a factor of 1.8. Finally, older cyclists living in rural areas were 2.1 times more likely to fall than those residing in urban areas. The study concludes that demographic, cy-cling, and personal factors contribute to an increased risk of self-reported falls among older cyclists. It was also observed that male cyclists, with an average age of 49, were most frequently involved in fractures [20]. High-energy fractures were most common in the acetabulum (100%), pelvis (84.2%), vertebra (75%), and tibia (70.3%) among cyclists. Finally, it was found that single bicycle crashes and collisions with other bicycles were significantly less likely to result in high-energy fractures compared to collisions with a car. A database of 2269 geo-located crashes in Madrid (involving at least one bike) was used to link each crash to a set of infrastructure and traffic variables [21]. This allowed the researchers to compare bike road safety between different districts in Madrid and model the severity of bike crashes using binary logit regression. The study also found that most serious crashes occurred at intersections between avenues and roads with a level of protection 1. It is important to note that, according to the authors, at intersections, cycling infrastructure is no longer protected (even if it is level 1), and the risk of a serious crash is higher.

In this paper, three Ordered Logit Models have been proposed to highlight the most important determinant related to university student propensity towards micromobility mode of transport. The innovative aspect that is proposed in this paper is to analyse university student propensity in campuses in a small city located in Italy, with the aim of highlighting the most important contributing factors to micromobility propensity and safety perceptions. Investigating a medium-small urban context is essential to fill a gap in the literature, which traditionally focuses on metropolitan areas [21] characterized by extensive mass transit networks. In smaller realities, the ‘last-mile’ problem often encompasses the entire commute, and the high dependency on private cars is exacerbated by the lack of public transport. Furthermore, in these contexts, the interaction between micromobility and traditional traffic occurs on high-speed arterial roads rather than protected urban roads, making the study of propensity factors crucial for local policy-making.

The whole paper will be structured in this way: after the introductory Section with evidence from literature, a Sect. 2 on the methodological aspect will be proposed, and then the case study in Sect. 3; then the results in Sect. 4 will be shown, and in the following Sect. 5, a brief discussion will be reported; finally, a Sect. 6 with overall conclusions.

2 Methodology

The response variable that needs to be predicted is the propensity of a user to move with a specific transport mode. Since this variable in the survey follows an ordered nature, an Ordered Logit Model has been calibrated to evaluate propensity toward sustainable transport micro mobility models. The simplest Discrete Choice Model is the Logit Model (Eq. 1):

$$p(X) = \frac{e^{\beta_0 + \sum \beta_i X_i}}{1 + e^{\beta_0 + \sum \beta_i X_i}} \quad (1)$$

Where:

- p(X) is the predicted probability;
- xi are the independent variable or features;
- β0…βi are the regression coefficients of the model.

Ordered Logit Models, such as Logit Models, belong to the family of Discrete Choice Models. For each user j, the propensity Y_i can be expressed as (Eq.2):

$$Y_i^* = x_i'\beta + \varepsilon_i \quad (2)$$

Where:
$Y_i^*$is the propensity;
x_i is the vector of independent variables;
β is the vector of coefficients;
ε_i is the error term.
If the number of outcomes is *j*, the model selects *j-1* thresholds $\tau_1 \ldots \tau_{J-1}$ (Eq. 3):

$$Y_i = j \quad \text{se} \quad \tau_{j-1} < Y_i^* \leq \tau_j \quad (3)$$

The probability that a user *i* chooses the category *j* is described by Eq. 4:

$$P(Y_i = j) = F\left(\tau_j - x_i'\beta\right) - F\left(\tau_{j-1} - x_i'\beta\right) \quad (4)$$

3 Case Study

The research was conducted in the city of Cassino, an Italian municipality situated in the southern area of Lazio, within the province of Frosinone. It is the second most populous city in the province (as of 01/01/2022 it recorded approximately 35,235 residents, compared to 43,830 in the city of Frosinone), with a population density of 422 inhabitants per square kilometer [22]. The municipal territory covers 83.42 km^2 and lies at an average elevation of 40 m above sea level, excluding the mountainous areas included within its administrative boundaries, below which the main urban settlement is located. The present-day urban structure is the outcome of historical transformations, particularly the complete reconstruction undertaken after World War II due to the extensive damage caused by wartime bombings. The central urban area hosts key administrative and public services, including the courthouse, city hall, university facilities, schools of various levels, the hospital, cultural institutions, and numerous commercial establishments, especially along Corso della Repubblica, Viale Dante, and Via Enrico De Nicola.

The concentration of such diverse services and activity hubs generates significant vehicular traffic throughout different times of the day, leading to issues associated with the sustainability of the local transportation system. The University of Cassino and Southern Lazio is one of the Universities located in Central Italy, with several academic centres in the cities of Frosinone, Atina, Gaeta, and Cassino. The main Campuses are located in the Municipality of Cassino, and in particular the Faculties of Economics, Law, Literature, Social Sciences and Health in the Folcara Area, and in the City Centre the Departments of Engineering (see Fig. 1). In Table 1 the main questions in the survey have been reported.

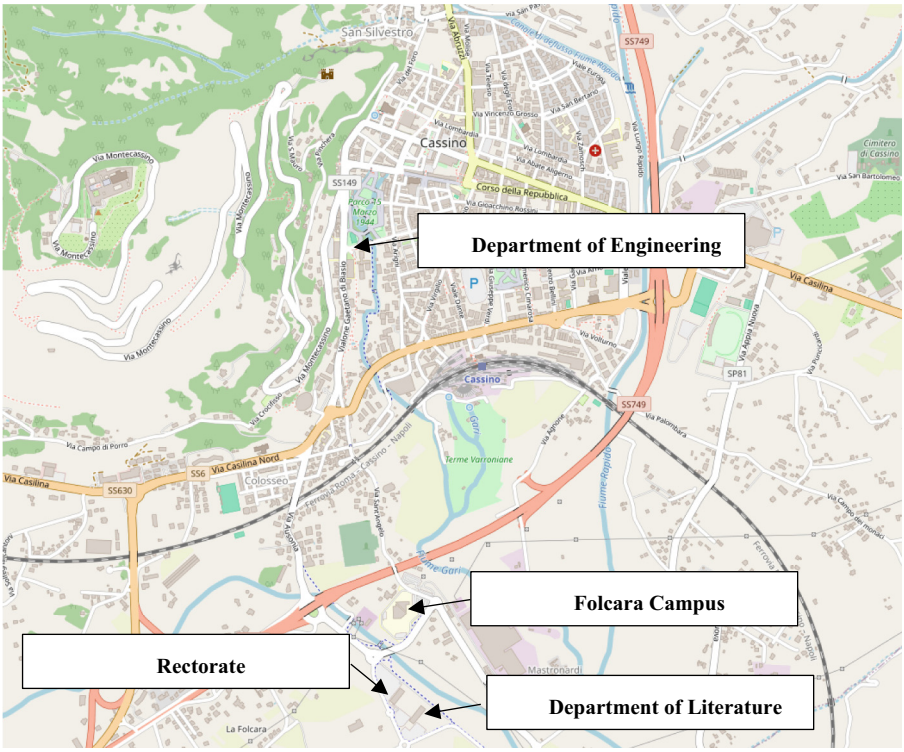

Fig. 1. Location of the Main Campuses in the City of Cassino. Source: Open Street Map [23].

Table 1. Structure of the survey.

Survey Questions
General Information
• Campus where you attend classes
• Gender
• Enrollment status
• Working student
• Type of course you are attending
• Type of class attendance
• During the periods in which you attend the university, do you rent accommodation in Cassino or in nearby municipalities? (Non-resident student)
• Age
• Frequency of attendance at university campuses (in-person activities)
Usual mode of transport to get to the university:
• By car (as a passenger)
• By car (as a passenger)
• By car/motorbike + train + bus
• By bus + electric scooter
• By bus + train
• By suburban bus
• By urban bus
• By bicycle + bus
• By bicycle + train
• By e-bike / regular bicycle / electric scooter or similar vehicles
• By metro
• By motorbike/scooter
• By carpooling system (BlaBlaCar or similar)
• By train
• By train + bus
• By train + electric scooter
• Using multiple modes of transport different from those listed above
• On foot (select this option only if the entire journey is made on foot)
• Usual ARRIVAL time from the university during the week. Please answer based on a “typical” week during the current semester teaching period
• Usual DEPARTURE time from the university during the week. Please answer based on a “typical” week during the current semester teaching period
Would you be willing to use, as an alternative to private car/motorbike:
• Shared electric scooters?
• Carpooling (shared travel with other colleagues in one of their cars)?
• Car sharing (using a vehicle provided by a third party, paying for the service)?
• Scooter sharing?
• Public transport?
• E-bike?
• Regular bicycle?
• Campus where you attend classes
• Gender
• Enrollment status
• Working student
• Type of course you are attending
• Type of class attendance

4 Results

4.1 Descriptive Statistical Analysis

The data collection was carried out through an online survey distributed between January and May 2025. The survey link was disseminated via official university student website. A total of 10,990 raw entries were initially recorded. However, a significant attrition rate has been observed: 4,280 participants (38.9% of the total) have been classified as 'non-responders' as they abandoned the questionnaire after the initial socio-demographic section. To ensure the statistical robustness and integrity of the Ordered Logit Models, these incomplete records have been excluded. The final valid sample consisted of 6,710 respondents who completed all mandatory sections. Considering an university population of 10,990 (equal to the number of participant because the survey has been administered to the whole student population) students and staff, the survey achieved a high response rate of 61.1%, providing a solid and representative database for the estimation of the behavioral determinants of micromobility.

As first step to have an overview of transportation habits and propensity in the University Campuses, a descriptive statistical analysis has been conducted. The results show that there is a great proportion of in-site students. It is worth noting that there is a great number of not responding students to the survey, as it is possible to see in Table 1. More than 50% of students is over 30, while there is a constant distribution among other class age. It also emerges that 56% of students are women and the 50% are correctly enrolled at the University. A great proportion of students is also a full-time worker (42%) and is following a Bachelor Degree. Students that use car to make their trip are the 23.66%, with a high level of attendance (27.21%). The minority of responders is willing to use micro mobility transport mode, as it possible to see from Table 2.

By investigating current habitual usage of micro mobility among Italian and Foreign Students (see Fig. 2), the 44.80% of foreign students use e-scoters, while Italians 10.48%. The same patter is also registered for bike and e-bike (45.57 for foreign students, 10.63 for Italian students). Regarding the propensity, it is worth highlighting those foreign students are more willing to use micromobility mode of transport compared to Italian students (see Fig. 3).

Table 2. Results of Statistical Analysis.

Variable	Response	Number [–-]	Frequency [%]
Off-site Students	Yes	1843	16.77
	No	6680	60.79
	Not Responding	2467	22.45
Age	< 19 years	242	2,2
	19-21 years	1593	14,49
	22-25 years	1676	15,25
	25-30 years	1580	14,38

(*continued*)

Table 2. (*continued*)

Variable	Response	Number [−-]	Frequency [%]
	30-35 years	1341	12,2
	35-45 years	2430	22,11
	> 45 years	1790	16,29
	Not Responding	338	3,08
Gender	Female	6254	56,91
	Male	4512	41,06
	Not Responding	224	2.04
Career	Not completed all exams	1272	11,57
	Current Student	5581	50,78
	Only final exam left	645	5,87
	Not Responding	3492	31,77
Working Status	Full Time Working Student	4713	42,88
	Part Time Working Student	2049	18,64
	Only Student	3508	31,92
	Not Responding	720	6,55
Course	Master	2824	25,7
	Bachelor	3119	28,38
	Single Cycle Degree	866	7,88
	Not Responding	4181	38,04
Department	Folcara Campus	5619	51,13
	Department of Engineering	1556	14,16
	Departement of Literature	692	6,3
	Frosinone Campus	458	4,17
	Not Responding	2665	24,25
Attendance	High (3-5 days)	2990	27,21
	Medium (1-2 days)	1799	16,37
	Low (< 1day)	2308	21
	Not Responding	3893	35,42
Transport Mode	Car Driver	2600	23,66
	Car Passenger	244	2,22
	Bus	1137	10,35
	Train	1804	16,41
	Micromobility	110	1,00
	Pedestrian	406	3,69

(*continued*)

Table 2. (*continued*)

Variable	Response	Number [−-]	Frequency [%]
	Powerd-.two Wheeler	130	1,18
	Not Responding	4559	41,48
E-scooter Propensity	Definitely no	3064	27,88
	Unsure	1182	10,76
	Probably no	897	8,16
	Probably yes	800	7,28
	Definitely yes	582	5,3
	Not Responding	4465	40,63
E-bike Propensity	Definitely no	2774	25,24
	Unsure	1105	10,05
	Probably no	1029	9,36
	Probably yes	913	8,31
	Definitely yes	809	7,36
	Not Responding	4360	39,67
Bike Propensity	Definitely no	2928	26,64
	Unsure	1144	10,41
	Probably no	1038	9,44
	Probably yes	841	7,65
	Definitely yes	659	6
	Not Responding	4380	39,85

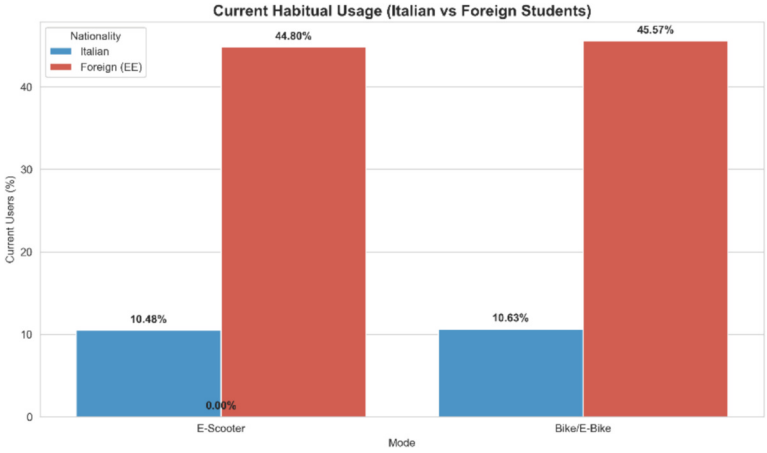

Fig. 2. Current Habitual Usage of micromobility among students.

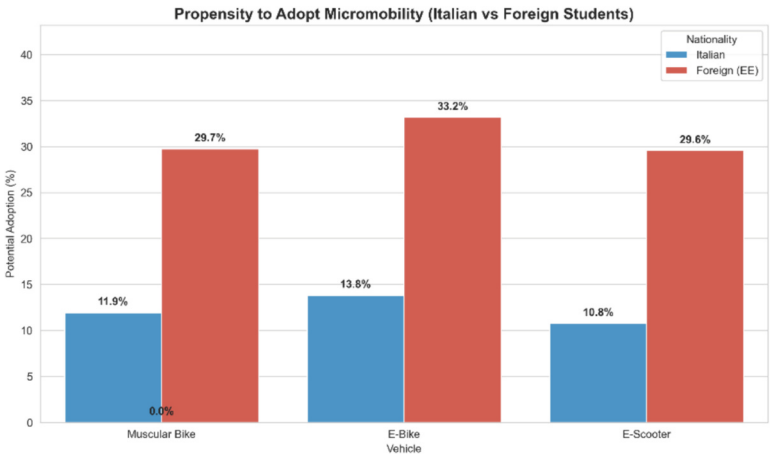

Fig. 3. Micromobility Propensity among students.

4.2 Model Results

In Table 3, Table 4, and Table 5 the main results have been reported for the three OLM, respectively. All the analyses have been performed with R software. It is worth noting that all missing data have been deleted for the analysis. As it emerges from Table 3, students over 45 years are more likely to adopt a Muscular Bike to make their home-to-study trips, while female students are more adverse than male student to use this transport mode. From the analysis of contributing factors, on site students that live in the city are more willing to use bike to reach the campuses and different department. From the analysis of actual transport habits, it clearly emerges that student that drive car to reach the university or use an intercity bus, are less likely to use muscular bikes. On the contrary, students that complete their trips with other micro mobility modes of transport, or with powered two-wheeler, or on foot, are more prone to switch to muscular bike. A great propensity toward bike has also been shown by high attendance students involved in Master Degree courses that reach the Department of Engineering.

Regarding the e-bike propensity (Table 4), there are factors in common with those previously recorded. Off-site students, who use other micromobility devices, or scooters, who can also move on foot, or who regularly attend engineering school and master's courses, are more likely to use e-bikes, while female students or those who drive to attend classes are less likely (as also shown for bike). Other factors emerge that differ from those previously identified. For example, student workers are much more likely to use e-bikes, or they use trains as the primary mode of transportation (factors different from those governing the propensity to travel for bicycles).

Analyzing the results of the e-scooter models (Table 5), what emerges is that, as in the case of bicycles, the propensity factors are those of being out-of-town students, users who use micromobility vehicles, or two-wheeled vehicles, and who regularly attend university. Aversion factors are gender, age, car use.

A notable finding is the significant propensity of Full-time working students towards e-bikes (Estimates = 0.168, $p < 0.05$), a trend that remains non-significant for both e-scooters and muscular bikes. This preference can be attributed to practical determinants related to time-efficiency and physical effort management.

Working students often face tighter schedules, necessitating a reliable and fast mode of transport that minimizes travel time between the workplace and the University. Unlike muscular bikes, e-bikes allow for higher average speeds and the ability to cover longer distances or inclines without the physical exertion. Furthermore, while e-scooters are effective for 'last-mile' distances, the e-bike offers a more robust solution for home-study commuting, providing a level of reliability and speed that aligns with the needs of students.

A resume and a comparison of the most important variable related to each micromobility transport mode are reported in Table 5.

Table 3. OLM Results for Muscular Bike (McFadden Pseudo $R^2 = 0.1039$). Variable: the predictor or factor being analyzed. Baseline is the reference category used for comparison; Estimates are the estimated effect (coefficient) of the variable; Std. Error is the standard error of the estimate (measure of uncertainty); P > |z| is p-value testing the statistical significance of the estimate.

Variable	Baseline	Estimates	Std. Error	P > |z|
Age_19_21_years	Age_Under_19_years	0,031383591	0,198592358	0,874433
Age_22_25_years	"	0,255784208	0,201093928	0,203385962
Age_25_30_years	"	0,253081824	0,211737732	0,231985126
Age_30_35_years	"	0,284338496	0,223969074	0,204247263
Age_35_45_years	"	0,084688935	0,224365765	0,705832336
Age_Over_45_years	"	−0,466955098	0,233805471	0,045804013
Gender_Female	Gender_Male	-0,443335634	0,069725138	2,03955E-10
Off-site_Student	On-site_Student	0,987911356	0,081330814	5,96351E-34
Part_time_working_Student	Full_time_Student	0,093119011	0,084084251	0,268099896
Full_time_working_Student	"	0,137822469	0,084462775	0,102731323
Transport_Mode_Car_Passenger	Others	-0,003758258	0,074961489	0,960014134
Transport_Mode_Car_Driver	"	-0,287828675	0,073035456	8,11614E-05
Transport_Mode_Intercity_Bus	"	-0,268879482	0,090822067	0,003071319
Transport_Mode_Urban_Bus	"	0,091635465	0,095811699	0,338864088
Transport_Mode_Micromobility	"	0,356941676	0,133395218	0,007454653
Transport_Mode_Powered_Two_wheeler	"	0,493355377	0,135002292	0,000257762
Transport_Mode_Train	"	0,105672411	0,092400246	0,25277389
Transport_Mode_Pedestrian	"	0,266424925	0,081928327	0,001146255
Low_attendance_1/2_days	Not_attending	-0,0468	0,0899	0,6028
High_attendance_3/5_days	"	0,3140	0,0865	0,0003
Departement_of_Engineering	Campus	0,2181	0,0834	0,0089
Departement_of_Literature	"	0,2019	0,1102	0,0669
Master	Bachelor	0,2568	0,0833	0,0020
Single_Cycle_Degree	"	-0,0837	0,1129	0,4584

Table 4. OLM Results for e-bike (McFadden Pseudo $R^2 = 0.0947$).

Variable	Baseline	Estimates	Std. Error	P > |z|
Age_19_21_years	Age_Under_19_years	0,006258254	0,190237621	0,973756694
Age_22_25_years	“	0,249902547	0,192779905	0,194868653
Age_25_30_years	“	0,295202327	0,20286118	0,145615623
Age_30_35_years	“	0,291608175	0,215720573	0,1764436
Age_35_45_years	“	0,062184598	0,215175458	0,772585322
Age_Over_45_years	“	−0,408323123	0,223861099	0,068151749
Gender_Female	Gender_Male	-0,385634306	0,067675686	1,2103E-08
Off-site_Student	On-site_Student	0,934963519	0,080468445	3,29945E-31
Part_time_working_Student	Full_time_Student	0,134052577	0,081797968	0,101249655
Full_time_working_Student	“	0,168628041	0,082712589	0,0414777
Transport_Mode_Car_Passenger	Others	-0,012114786	0,072850286	0,867923204
Transport_Mode_Car_Driver	“	-0,328037146	0,071093969	3,94736E-06
Transport_Mode_Intercity_Bus	“	-0,162847774	0,086984116	0,061185121
Transport_Mode_Urban_Bus	“	0,050229311	0,093067311	0,589397394
Transport_Mode_Micromobility	“	0,518308175	0,133117488	9,87616E-05
Transport_Mode_Powered_Two_wheeler	“	0,441095012	0,132839456	0,000898525
Transport_Mode_Train	“	0,217032118	0,090031332	0,015925049
Transport_Mode_Pedestrian	“	0,209629792	0,080280999	0,009022496
Low_attendance_1/2_days	Not_attending	-0,076978775	0,087196063	0,377331386
High_attendance_3/5_days	“	0,311772402	0,084067908	0,000208426
Departement_of_Engineering	Campus	0,247145438	0,081861208	0,002535446
Departement_of_Literature	“	0,181543326	0,10742598	0,091039673
Master	Bachelor	0,231195587	0,081090233	0,004356958
Single_Cycle_Degree	“	-0,099968235	0,108972278	0,358947171

Table 5. OLM Results for e-scooter (McFadden Pseudo $R^2 = 0.1118$).

Variable	Baseline	Estimates	Std. Error	P > |z|
Age_19_21_years	Age_Under_19_years	0,001460066	0,195324784	0,994035815
Age_22_25_years	“	0,199589912	0,198392179	0,314397676
Age_25_30_years	“	0,241600595	0,209134924	0,247993009
Age_30_35_years	“	0,265890305	0,222456349	0,231990502
Age_35_45_years	“	−0,036280097	0,222033841	0,870204327
Age_Over_45_years	“	-0,47683254	0,232852622	0,040580889
Gender_Female	Gender_Male	-0,354326513	0,071244689	6,57974E-07
Off-site_Student	On-site_Student	0,930954809	0,083177423	4,44255E-29
Part_time_working_Student	Full_time_Student	0,231255537	0,085404162	0,006773525
Full_time_working_Student	“	0,149349125	0,086183238	0,083108924
Transport_Mode_Car_Passenger	Others	0,020650618	0,076982498	0,788506261
Transport_Mode_Car_Driver	“	-0,391149783	0,074896458	1,76485E-07
Transport_Mode_Intercity_Bus	“	-0,160821572	0,091816993	0,079852119

(*continued*)

Table 5. (*continued*)

Variable	Baseline	Estimates	Std. Error	P > |z|
Transport_Mode_Urban_Bus	“	-0,069795874	0,099851111	0,484552359
Transport_Mode_Micromobility	“	0,575417015	0,13740722	2,81825E-05
Transport_Mode_Powered_Two_wheeler	“	0,440444815	0,13637626	0,001239507
Transport_Mode_Train	“	-0,045474091	0,096128886	0,636175121
Transport_Mode_Pedestrian	“	0,065124012	0,085074402	0,443976966
Low_attendance_1/2_days	Not_attending	-0,056377455	0,091986662	0,539950871
High_attendance_3/5_days	“	0,288457745	0,088276028	0,001084332
Departement_of_Engineering	Campus	0,11242313	0,085600013	0,189063652
Departement_of_Literature	“	-0,05373288	0,116093406	0,643477774
Master	Bachelor	0,166653728	0,085630595	0,051631471
Single_Cycle_Degree	“	-0,093765963	0,116340361	0,420264501

Table 6. Resume of the significant Variables from the OLM.

Variable	Variable	E-bike	E-scooter	Muscular Bike
Student Status	Off Site Student	Propensity	Propensity	Propensity
	Full Time Working Student	Propensity	Not Significant	Not Significant
Sociodemographic Characteristics	Gender Female	Disutility	Disutility	Disutility
	Age Over 45 years	Not Significant	Disutility	Disutility
Transport Mode	Car Driver	Disutility	Disutility	Disutility
	Train	Propensity	Not Significant	Not Significant
	Intercity Bus	Not Significant	Not Significant	Disutility
	Pedestrian	Propensity	Not Significant	Propensity
Campus Habits	High Attendance	Propensity	Propensity	Propensity
	Engineering Department	Propensity	Not Significant	Propensity

5 Discussions and Conclusions

In this paper analysis on University Students towards micromobility have been reported. A survey has been conducted among the Student of University of Cassino and Southern Lazio. Then a statistical analysis has been carried out alongside with the calibration of three choice models with OLM to highlight the most important contributing factors related to micromobility propensity. Comparative analysis of OLM models highlights distinct propensities for the three modes of micromobility transport. The main driver is off-site student status, which shows the highest and statistically significant propensity for each mode considered. On the contrary, resistance is observed from regular car

drivers, for whom the transition to micromobility represents the most complex modal challenge. A marked gender gap emerges: female users show a lower propensity than male ones, with a greater criticality for conventional bicycles. It emerges that there is the need to guarantee continuity and geometric protection to cycling routes, especially to overcome the modal resistance found in female users. Regarding age variables, the e-bike stands out as the only vehicle capable of neutralizing the effect of age, proving attractive even for the over-45 age group, who instead significantly reject the use of scooters and traditional bikes. Finally, the e-bike and scooter show strong synergy with public transport, highlighting themselves as ideal solutions for the last mile.

From Table 6 it can be seen that the e-bike is the transport mode with the highest degree of propensity. Unlike the conventional bike, it does not suffer from the aversion of suburban commuters and, unlike the scooter, is not penalized by age. The adoption of the muscle bike presents an obstacle for the female gender and the suburban bus. This suggests that physical fatigue, or perceived safety and distance are barriers to the conventional bike. The electric scooter has fewer significant variables than the e-bike. It is not influenced by department or work, but is heavily driven by off-site attendance and frequent attendance. This identifies it as a mode for students living in Cassino to move quickly between home, cafeteria, and classrooms, but it loses effectiveness as soon as the movement becomes more complex or the user is older.

One of the main limitations of the study is the a quite high presence of missing values and not responding student. In future work this could be solved by providing a more stable method to administer survey to students, but also to try to implement more advanced discrete choice models to evaluate propensity towards micro mobility in University Campuses.

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Addressing Mobility-as-a-Service Inclusive Design through the Engagement of Vulnerable Users: Future Perspectives for Italian MaaS

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Abstract. Mobility-as-a-Service (MaaS) has been targeted for long for its transformative potential for enhancing accessibility and social inclusion by addressing physical, economic, spatial, and digital barriers faced by vulnerable users, including the elderly, disabled individuals, and those in marginal areas. This paper examines Italy's MaaS4Italy initiative, funded under the Italian National Recovery and Resilience Plan, thus revealing that initial pilots prioritized early adopters (e.g., commuters, younger users) while lacking systematic engagement with vulnerable social groups (VSGs). Drawing on literature review and empirical analysis -including Sardinia-based surveys with NGOs- the authors identify key digital accessibility requirements (WCAG compliance, universal design principles) and engagement barriers (digital divide, mistrust, consultation fatigue). A three-phase governance and deployment framework is therefore proposed: (i) public authorities setting accessibility standards; (ii) co-design via partnerships with NGOs; and (iii) centralized audits with iterative VSG involvement for monitoring. Findings underscore the need for hybrid public-private governance, integrating Artificial Intelligence for bias-mitigated user profiling and tailored services. Policy recommendations advocate tailor-made strategies to ensure equitable MaaS deployment, fostering inclusive national pilots and long-term sustainability.

Keywords: Mobility-as-a-Service · VSGs · NGOs · accessibility standards

1 Introduction

Mobility-as-a-Service (MaaS) has been targeted from the very beginning as a powerful driver for accessibility improvement and social inclusion, shifting the transportation focus from private car ownership to flexible, user-centric, and integrated multimodal

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mobility solutions [1]. By aggregating different transport providers into a single digital platform for planning, booking, and payment, MaaS addresses multiple dimensions of transportation disadvantage [2], stemming from objective factors (such as territorial divide) up to individual conditions.

In details, it may mitigate physical, economic, spatial, and temporal barriers leading to transport poverty, by offering affordable, integrated alternatives to private vehicles [3]. In this context, transport poverty can be conceptualized as a lack of accessibility that prevents individuals from meeting their basic needs and participating in society [4]. It does not only concern the lack of means of transport, but the lack of adequate access to essential activities. In other words, it adopts accessibility as a central operational concept for translating social justice into design practice. In the long term, MaaS gives policymakers the opportunity to shift from broad supply-side subsidies to user-based, person-centered incentive models, directly improving the equity and efficiency of transport subsidies for disadvantaged groups [5]. Territorial inequalities may be addressed, as well.In rural, remote, or island communities, where sprawling geography and low population densities make traditional fixed-route transit financially unviable [6], MaaS systems integrate flexible, crowd-sourced, and Demand-Responsive Transport (DRT) with high-capacity transit, effectively solving "first and last mile" gaps [7].

Within an intersectional perspective, similar context-related disadvantages may also overlap with personal conditions. In this direction, MaaS allows also vulnerable population empowerment through two main lines of action: i. reduction of physical and cognitive effort and ii. improvement of universal accessibility by design [8].

Door-to-door services may indeed be included within MaaS offer, restoring independence for those unable to operate a private vehicle [9]. At the same time, the combination of route planning, booking, and real-time updates into a single interface, should also drastically reduce the logistical effort and anxiety associated with trip chaining, which benefits elderly users and those with intellectual vulnerabilities [10].

Similar goals may indeed be pursued only mainstreaming universal design principles [11] from the initial steps of the process, thus considering the psychological, physical, and cognitive needs of individuals, creating a system usable by everyone without the need for specialized adaptation [12].

In this direction, as highlighted by [13], MaaS potential in terms of social inclusion and universal accessibility may be measured through a multi-dimensional approach focusing on transport service and infrastructures accessibility, as well as on digital platform design. The present contribution aims at applying a similar framework to MaaS4Italy initiative, funded by National Resilience and Recovery Plan (NRRP) and launched in 2021 [14]. Currently in the pilot phase, similar project aimed at defining a national platform for Italian MaaS, supporting data standardization and best-practices sharing among cities and territories involved in the experimentation [15].

Targeting effective pilot deployment, particular attention has been paid to the engagement of early adopters (e.g. younger users, commuters, etc.) [16]. Nevertheless, similar approach may translate into poor accessibility of the comprehensive system, both on the physical and digital sides, thus hampering the inclusion potential of a nationwide MaaS proposal for Italy.

In this direction, the present research addresses the identification of accessibility requirements for inclusive MaaS platforms, focusing on the engagement and needs of vulnerable users (Sect. 2). Subsequently, potential barriers to the design and deployment of accessible MaaS will be addressed in Sect. 3, thus identifying potential recommendations that guide policymakers through inclusive and accessible MaaS pilots. Conclusive remarks will be provided in Sect. 5.

2 Background

MaaS inclusive potential mainly relies on the mainstreaming of universal design principles from the very first steps, as well as on the engagement of vulnerable users within a participated co-design process [17].

2.1 Digital Accessibility

The main factors affecting the digital accessibility of mobility apps can be divided into two broad categories: technical and interface design factors (indicating how the app is built) and user-centric factors (depending on the resources and capabilities of the people using the app) [18].

Technical and interface design factors generally align with Web Content Accessibility Guidelines (WCAG) and usability heuristics tailored for mobile interfaces. To be more precise the main factors to consider are as follows:

- Perceivability and Visual Design: an accessible app requires sufficient text size, the ability for users to customize font sizes, and high colour contrast between text and backgrounds [19]. Common accessibility violations in mobile apps include low text colour contrast and the lack of alternative text (alt-text) for images, which prevents screen readers from describing visual content to visually impaired users [20]. Content should also not be placed too tightly on the screen.
- Operability and Navigation: The app must be easy to navigate and control. This includes providing adequate spacing between elements, sufficiently large buttons or icons (touch targets), and consistently placed navigational markers like “back” and “next” buttons [21]. Additionally, elements must have proper technical “focus” enabled; otherwise, they cannot be navigated using external keyboards or recognized by assistive technologies [22].
- Understandability and Clarity: Apps should use plain, everyday language, avoiding technical jargon and complex expressions [23]. Accessibility is also enhanced by intuitive features like autocorrect, clear error messages with constructive recovery solutions, and step-by-step guidance or pop-ups that assist users in completing tasks without confusion [24].
- Robustness and Assistive Technology Compatibility: The app must be technically built to work smoothly with integrated assistive technologies, such as Android’s TalkBack or iOS’s VoiceOver [25]. To achieve this, all interactive elements, input fields, and visual graphics must be correctly labelled in the application’s underlying code [26].

User-centric factors' accessibility is also heavily influenced by the digital inequality gap, which dictates whether a user can actually access and successfully operate the technology according to individual features and resources. Digital literacy and skills are identified as one of the strongest predictors of access to mobility services [27]. Users need "medium-related skills" (knowing how to operate a smartphone or browser) as well as "content-related skills" (knowing how to search for routes, assess the reliability of real-time info, and manage privacy settings) [28]. Material access to the physical technology is a prerequisite. This includes owning a capable smartphone, having a reliable data plan, and managing battery life and operating system updates [28].

From an individual perspective, a lack of trust can severely hinder accessibility. Fear of cybercrime, data leaks, phishing, and general privacy concerns often dissuade users from engaging with digital mobility platforms, especially when online payments or credit cards are required [29]. Digital flexibility is required to adapt to constant changes in the digital landscape. Frequent app updates, shifting to entirely cashless ticketing systems, or navigating sudden platform changes can create significant barriers for users with low digital flexibility [30]. Finally, as far as users' segments are concerned, vulnerability to digital exclusion in mobility frequently correlates with age (e.g., older adults facing cognitive or motor decline), lower income and education levels, physical or cognitive disabilities, language barriers, and lack of social support networks to help them learn the technology [31].

Being individual barriers not valuable aprioristically, a subsequent step would require users' engagement and involvement to address them properly.

2.2 Vulnerable Users' Engagement

In the context of transport digitalization, there is a risk that these systems, rather than helping, may increase the disadvantages of the most vulnerable groups [32]. In this sense, it is vital to involve all potential user groups in the design, testing and evaluation of innovative mobility solutions if inclusivity and accessibility are to be ensured [33].

In order to properly engage VSGs [34] in the planning process, their recruitment requires the adoption of diversified and inclusive strategies. One effective approach consists of creating partnerships with local associations that can operate as facilitators and can act as intermediaries between researchers, policy makers, and target groups [35]. These associations often have a direct relationship with local communities and vulnerable users, allowing them to facilitate communication, build trust and mediate [36].

A series of strategies have been identified from the literature based on direct experience [37]. n particular, studies emphasize the importance of integrating online and offline recruitment channels, especially when involving the elderly since digital-only approaches, such as emails, may exclude people with limited digital skills. Collaboration with organizations and associations, the use of attractive images, visuals and storytelling techniques as well as the employment of snowball sampling methods have been identified as effective instruments for participant recruitment [38]. he provision of incentives, including vouchers, discounts or minor gifts, has been demonstrated to facilitate the recruitment process and enhance the level of interest in participation. Furthermore, the organization of face-to-face events and the dissemination of the research outcomes may

enhance the likelihood and willingness to contribute to subsequent activities and engage in long-term initiatives.

Another effective strategy in reaching vulnerable population groups is through Communities of Practice. This concept has found numerous practical applications in a variety of fields including business, organizational design, public administration, education, professional associations, development projects and civil life [39]. As [40] highlight, the CoP constitutes a functional space in which diverse actors convene with a view to resolving actual problems. This approach constitutes an alternative operational method that can be employed to incorporate vulnerable groups within the planning process.

Finally, to address this challenge effectively, it is essential to adopt a 'tailor-made' approach calibrated to the specific characteristics of the reference population with a thorough understanding of its needs and a particular attention to the social groups at risk of exclusion.

2.3 MaaS4Italy User Profile

MaaS4Italy is a nationwide funded program that was launched in 2021, stemming from Italian NRRP resources (on their turn descending from Next Generation EU financing). It aims both at the design and deployment of a national database and repository supporting shared data standards on a national level, the so-called Data and Service Repository for MaaS (DSRM) [41]; as well as at implementing several pilots across the country. In detail, two subsequent selection rounds were implemented, the former one addressing capital cities and the latter in 2022 addressing regions on a wider scale.

As far as users' profile selection is concerned, MaaS4Italy envisages the engagement mainly of volunteer citizens recruited through information campaigns, mobility habit surveys, and experimental panels, with a minimum target of 1,000 users per pilot project.

During first phase (completed by the end of 2023), the pilot cities engaged users on a voluntary basis and at their own expense, forming panels through ex-ante, ongoing, and ex-post surveys to assess impacts on attitudes and mobility habits. Participation was low but qualitatively positive, as users reported satisfaction, increased travels, and reduced private car use [14]. Average users were recruited from metropolitan or partial populations, profiled by age (>16 years), gender, residence, employment, and transport modes used. Nevertheless, on an individual basis, selected cities and regions identified peculiar target groups to be addressed preferentially.

In details, three pilot cities and one pilot region explicitly refer to vulnerable target segments.

The city of Bari [42] for instance addresses among selected users' groups students, commuters, tourists and disadvantaged residents. Specifically, the latter group includes people with disabilities, pregnant women and families with children under the age of four, refugees and asylum seekers, unemployed people.

Turin, as well, targets two main clusters of users [43]: citizens and corporate users. Among the former group, particular attention has been paid to people with disabilities that benefit from dedicated incentives and support.

Rome, in its turn, addresses commuters, tourists, students and people with mobility impairments [44].

Emilia-Romagna region [45], finally, targets three main categories of resident commuting to larger cities, with particular attention paid to people with disabilities, people living within inner areas using Demand-Responsive-Transport for their daily mobility and tourists.

First phase of MaaS4Italy does not show comprehensive and systemic commitment to vulnerable users' engagement. Despite fragmented references to people with disabilities and other fragile categories, an integrated approach towards vulnerable targets is lacking, thus leaving behind relevant users' groups, such as the elderly. In this direction, early adopters –commuters and tourists, above all, appear to be preferable testers of project first round [16].

3 Methodological Approach

Stemming from similar premises, proposed approach targets MaaS accessibility and inclusion potential through three main critical dimensions: i. the assessment of mobile apps features in terms of universal accessibility; ii. ways to engage vulnerable users' associations and NGOs within the co-design process; iii. role of public authorities and actors to foster the implementation of inclusive MaaS. These three steps indeed cover the entire process from the design of interface and functionalities to the deployment of mobility services.

3.1 Accessibility Checking Tool in European Legal Framework

Although WCAG are widely recognized, public authorities and regulators in both the European Union and beyond (e.g. in the USA) do not provide a single, fully automated official tool for assessing the accessibility of mobile mobility apps; instead, they define legal frameworks, standards and monitoring methodologies that combine automated checks with structured human evaluation [46].

In the EU, mobile apps -especially those of public sector bodies, among which MaaS apps may be listed- are covered by the Web Accessibility Directive and are expected to comply with the harmonised standard EN 301 549, which in turn references WCAG 2.1 AA (and is being updated in line with WCAG 2.2), while national monitoring methodologies prescribed by the Directive require in-depth audits and simplified checks carried out by trained evaluators, optionally assisted by automated tools (European Commission, 2016; European Commission, 2018).

In this direction, the European Accessibility Act (Directive (EU) 2019/882), by incorporating international technical standards of the WCAG 2.2 and EN 301 549, transforms accessibility from an accessory requirement to a primary functional requirement. In this sense, it shifts the focus from "assistance services" to an interface that can be used by anyone: if a website or platform such as MaaS is designed for a visually impaired person, it will be easier to use for everyone, including tourists or elderly people in low light or poor readability conditions. However, while the EAA provides the minimum legal framework for introducing minimum standards it must necessarily be accompanied by local policies that guarantee access and address the economic and cognitive barriers faced by the most vulnerable people [47]. The EAA goes beyond the fragmented view

of accessibility by imposing uniform, European-level requirements that are not limited to removing technological barriers but promote the structural adoption of the principles of inclusive design, design for all and universal design. These guidelines are particularly relevant for MaaS platforms, as the directive stipulates that the perception, operability and comprehensibility of digital services must be guaranteed for all users, regardless of their sensory or cognitive abilities. Italy transposes the European Accessibility Act (EAA) with the Legislative Decree n.82 of 2022, which implements the Directive (EU) 2019/882 on the accessibility requirements of products and services.

The adoption of these regulatory standards guarantees an inclusive user-centered digital infrastructure and ensures the same level of accessibility across different channels, reducing barriers for those with cognitive or sensory limitations. Although digital accessibility is an increasingly important issue in the European regulatory landscape, it cannot be separated from accessibility in real contexts. The website is only part of the experience, and having platforms that are truly inclusive and accessible continues into the physical environment.

In this direction, therefore, official practice converges on hybrid, standard-based evaluation -anchored in WCAG and EN 301 549- where automation is used mainly for large-scale or low-level checks (e.g. missing labels, colour contrast), and human judgement remains essential to assess more complex aspects such as operability, understandability, meaningful focus order, gesture complexity and real compatibility with assistive technologies in domain-specific apps like those for urban mobility [22]. Empirical analyses confirm that automated tools identify only partially issues in real mobile apps, underscoring the irreplaceable role of manual and user-involving evaluations [48].

Similar aspects hinder evidently the possibility to implement large-scale monitoring within MaaS4Italy initiative due to the high number of apps that aver been included into the different implemented pilots nation-wide. Despite some of the MaaS providers are present in more than one pilot, general structure of the initiative has the aim to implement an open ecosystem that could include incrementally more and more providers and respective apps.

In this sense, going beyond basic technical accessibility checks, could be extremely critical to assure equal access conditions to every app, within every pilot. Moreover, the absence of automated standardized process, may lead to a fragmented framework where traditional accessibility inequalities are transferred to the digital dimension [49].

Being human intervention unavoidable to perform similar evaluations, a potential step to be taken could be to engage vulnerable communities also within the design process to grant statistical representation of the target groups within every pilot, thus bypassing manual technical accessibility checks and corresponding arbitrary risks. In this direction, similar approach could indeed integrate official centralized audit that could support universal accessibility compliance from a more institutional perspective.

Going further with accessibility checks, is should be highlighted how being MaaS a mobility app, user-interface does not represent the only element to be evaluated in this direction. The possibility to include within user profile potential mobility impairment selecting by default universally accessible alternatives should be considered, as well [13]. Effort reduction principle implies indeed the presence of default options supporting seamless selection of journey options by different groups of users.

3.2 NGOs and Associations Role and Criticalities

Engaging associations from the early stages of the planning process is fundamental for ensuring a more inclusive and representative participation of users. These associations can play a key role as intermediaries between researchers, plannersand end users, facilitating communication and helping to reach groups that are often difficult to involve through traditional engagement channels. However, in practice, their involvement does not always occur in a systematicand effective way. Nevertheless, it should be recognised that vulnerable social groups, are frequently designated as "hard-to-reach", signifying groups that are underrepresented and marginalised in public debate [36]:

- Structural barriers: resulting from the use of inadequate communication channels, the so-called "digital divide" and a widespread lack of specific skills within institutions.
- Psychological and social factors: such as scepticism towards authorities, systemic mistrust and the absence of representation that truly reflects the needs of these groups.
- Methodological limitations in engagement: late planning that excludes VSGs from decision-making stages as well as poor inclusivity due to inadequately trained staff, and a lack of incentives to encourage participation [50].

Exploring the nature of these barriers, as highlighted by [33], time constraints often represent a significant challenge, as consultation processes can be long and time-consuming, potentially leading to what is commonly referred to as "consultation fatigue" among participants.

In addition, local authorities and project coordinators may lack the necessary skills to effectively plan and manage participatory processes, while limited financial resources and insufficient personel capacties within public administrations can further constrain the organisation of meaningful engagement activities.

Dissatisfaction among participating organisations may also arise from shortcomings in the management of the participatory process itself.

As noted by [51], associations may feel excluded when they are not consulted with sufficient notice, do not have full visibility of the tasks involved, or are not actively included in the planning stages of the process. Such conditions may weaken trust and reduce the willingness of organisations to participate in future initiative [52].

Another critical issue concerns the risk of bias in the recruitment of participants, which can occur when it only relies on a single communication channel. For instance, the exclusive use of online channels for participant recruitment may primarily reach individuals with higher levels of digital literacy, thus excluding segments of the population with lower digital skills [37]. This limitation is particularly relevant when attempting to involve vulnerable social groups, such as older adults or individuals with limited access to digital technologies.

3.3 Role of the Public and Private Authorities Operator Agreements

Lack of control and monitoring to equal and universal access to MaaS platforms and services may also depend on the role and relevance that private and public actors playwithin the MaaS ecosystem.

MaaS4Italy initiative acts in this direction in a quite ambivalent way: data-sharing standards and platform are provided centrally, so that pilots share a common infrastructure, nevertheless, each of the involved territory is autonomous in defeding their governance mechanisms and models.

Public authorities should indeed define and identify data standards and accessibility mandates, complementing private firms' expertise in app development and real-time integrations [53, 54].

From an operational point-of-view, public-private partnerships in this direction prevail, since only few pilots have the aim to deploy a public-control app (Florence and Tuscany region are working in this direction), thus complicating the framework in which accessibility evaluation and vulnerable users engagement should be planned and implemented.

Similar approach positions users as active co-creators, particularly in rural settings, to enhance feedback-driven inclusivity [53]. This division bridges operational silos for broader service coverage [55].

It is therefore self-evident that similar hybrid approach leaves some relevant issues unsolved, not only in terms of governance and business effectiveness [56] but also in terms of social sustainability of the proposal.

In this direction, within a diverse society, public entities and policy-makers are required to act on multiple levels [57]:

- Set accessibility standards both in terms of physical and digital infrastructures, thus playing the fully public role of assuring equitable and universal access to new urban mobility services;
- Define public-private agreements with providers and actors involved within the ecosystem that include standards define at step 1. thus including universal accessibility criteria related to MaaS apps, mobility services and vehicles, equitable fares taking into account different mobility profiles. In this direction, similar elements would represent a pre-requisite and/or a rewarding element guiding providers selection;
- A third step of the enabling/monitoring role played by public promoter of the initiative should deal with the deployment of centralized audit and evaluations of universal accessibility conditions offered to users within the various pilots, thus engaging also vulnerable groups in the assessment process to feed an iterative approach.

Similar three steps' process aims at building a structured path for co-design and deployment of inclusive MaaS, to ensure proper involvement and empowerment of vulnerable categories that could benefit from MaaS paradigm, but that have been partially left behind from the initial pilots. An institutional and demanding workflow that aims at representing diverse mobility needs and behaviors, thus requiring at the same time a shared responsibility during the entire process.

4 Discussion

Identifying the workflow could therefore be crucial in supporting the progressive implementation and deployment of an inclusive MaaS approach during the pilot and subsequent phases.

In this direction, three different steps of recommendations have been identified:

- Empowerment and strategic framework: Public Authorities should play the role as primary coordinator who sets requirements and rules for societal equity and the compliance with accessibility standards. PA should also set the strategies for properly involving VSGs;
- Co-design process: a second step in which to translate the standards set in step 1 in operational requirements for a collaborative engagement. It translate standards in official agreement. In this step association play a key role as parties of interest by defining requirements with the PA;
- Institutionalisation and accountability: monitoring and long-term governance with association actively designated since the initial phases.

Adopting a structured, multi-step approach ensures that inclusivity is incorporated across all stages of MaaS development, from strategic planning to long-term governance. The ensuing sections of this paragraph will explore how these principles can be operationalised to create requirements for inclusive travel planning. These criteria are then enhanced through the use of AI-driven solutions for profiling users' needs and delivering tailored, on-demand services.

Similar tool may support in the long run the transition from the preliminary pilots based on early-adopters experiences to wider public applications, thus including vulnerable users. The analysis of massive data concerning mobility behaviours performed by AI tools could indeed support policy makers and MaaS providers to identify relevant factors and variables related to specific potential barriers for vulnerable groups (such as physical effort; presence of slopes; safer routes, etc.).

An AI-based transition roadmap from early testbeds to regular and inclusive MaaS proposal could indeed feed and speed-up participatory workflow, through the capitalization of the collection and processing of massive behavioural data and preferences.

At urban level AI-based solutions could also impact physically on users' experience of multi-modal journeys. The co-design process could indeed benefit from massive data collection and processing to improve both available transport services and platform universal accessibility, through a crowd-sourced approach.

4.1 Participatory Approach for Defining Criteria Oriented to Vulnerable Users' Needs

In the context of the design of inclusive transport systems, the establishment of a multi-step process has been identified as a fundamental prerequisite. A subsequent investigation into the mobility needs of vulnerable groups is recommended, with the objective of defining criteria for the development of tailored travel alternatives. In this context, co-creation processes represent a key strategic approach, enabling the active involvement of end-users throughout the design phases [37].

As [58] stated, these processes are typically operationalised through a combination of participatory methods, including interviews, focus groups, interactive workshops, and living labs, which allow for the collection of both qualitative and contextualised insights [37, 40, 51]. Such approaches facilitate a deeper understanding of users' experiences, constraints and preferences.

In this perspective, interviews and focus groups can be regarded as qualitative tools which are considered essential for the purpose of gathering first-hand experiences and gaining an in-depth understanding of individuals' capabilities, limitations and requirements [40, 59, 60]. The utilisation of these methods facilitates the identification of needs that are frequently eluded by quantitative surveys [61]. Specifically, focus groups are frequently considered as a functional approach for discussing and validating previously collected data through the interaction among participants, while also facilitating discussions within a selected small group [47].

The recommendations resulting from participatory methods and user engagement activities provide the empirical basis for defining a set of criteria designed to guide the design of inclusive MaaS travel options. In this regard, the potential of artificial intelligence to dynamically profile users' needs and enable adaptive, on-demand mobility services is significant.

The issues highlighted in the literature are also reflected in the empirical activities conducted as part of this research. As part of the PNRR-funded project to develop a MaaS platform for Sardinia, a survey was conducted to analyse the mobility habits of vulnerable people and their propensity to use digital tools for this purpose.

The questionnaire was developed and designed in collaboration with the Italian Multiple Sclerosis Association (AISM) whose contribution helped refine both the structure and the language of the survey in order to improve accessibility and comprehension for participants with different cognitive and physical. The survey was disseminated both at local and national level, using a multi-channel strategy integrating both online, via digital platforms and official social media channels and face-to-face administration methods to ensure wide dissemination and facilitate participation among users with varying levels of digital literacy.

AISM played a particularly important role in this phase, helping to reach people with disabilities and other vulnerable groups through its local branches and communication channels. The University of the Third Age (UTE) of the city of Alghero (Sardinia, Italy), played a significant role in facilitating communication with elderly people at a local level. For their involvement a face-to-face event as being organised in order to present the research project and distribute the questionnaire.

Despite the involvement of associations that acted as intermediaries between researchers and potential end users, as well as the use of both online and offline dissemination channels, the sample actually reached was limited. In the case of the questionnaire on mobility habits, 31 responses were collected, while the second questionnaire recorded 23 participants. The limited sample size can also be partially ascribed to the temporal constraint, as the involvement of vulnerable groups requires long-term engagement process capable of establishing trust between the different parties involved [37]. Therefore, the empirical phase was not intended to achieve statistical representation but rather to gather preliminary insights into mobility habits and attitudes towards assistive technologies among vulnerable users thorough the involvement of key informants.

Future research should involve a larger sample of vulnerable users to ensure statistical validity.

4.2 AI for Profiling Users' Needs and Managing on-Demand, Tailored Services

Artificial Intelligence (AI) may play a crucial role in profiling vulnerable users' behaviours and needs more precisely, thus enabling a more tailored, effortless and seamless travel experience. AI-driven profiling in MaaS extends indeed far beyond basic demographic data to capture the dynamic, context-dependent nature of individual mobility necessities.

From a methodological point-of-view, the mainstreaming of similar algorithms into the centralized repository of MaaS4Italy initiative – one of the distinctive features of the project- may support increased levels of accessibility and inclusiveness, thus relying on public action, only.

By leveraging Machine Learning (ML), for instance, AI synthesizes massive volumes of heterogeneous data -including historical travel patterns, real-time traffic, passive smartphone sensors, and socio-economic characteristics [62]. Through unsupervised learning and Natural Language Processing (NLP), AI can mine unstructured, crowdsourced data like app reviews to extract latent behavioral patterns and psychological traits [63].

By processing this detailed data, AI enables a more effortless and seamless experience specifically tailored for vulnerable groups in several critical ways. In this direction, AI deployment could effectively support the three-phase pathway towards a more inclusive MaaS proposal, especially referring to the two latter steps. Both within the co-design and institutionalization phases AI could contribute to detect and mitigate potential biases in service allocation and bundle proposal.

Knowledge-based AI frameworks use logic rules to combine a user's specific profile with contextual data (such as weather or traffic disruptions) to automatically filter out unsuitable transport modes and recommend personalized alternatives [64]. For elderly users or those with disabilities, AI can learn routine behaviors and autofill travel parameters or pre-select options, significantly reducing the cognitive burden and digital literacy required to navigate complex apps [65]. Furthermore, potential integration with wearable sensors deploying ML can monitor stress levels in frail older individuals, providing data that could be used to suggest more comfortable, less congested, and safer routes. During field operations -both during pilot as well as further upscaling steps- AI could also contribute positively in the perspective of MaaS providers to optimize service supply and bundle, deploying effectively anonymized mobility behavioral data and preferences, through dynamic and site-specific pricing mechanisms.

AI optimization reduces operational waste for MaaS providers, potentially lowering service prices to levels that attract users from economically disadvantaged regions [62]. AI-driven dynamic pricing models can analyze a user's price sensitivity and offer tailored mobility bundles, monthly allowances, or targeted subsidies, ensuring that shared transportation remains a financially viable alternative to private car ownership for low-income households [66].

For vulnerable users living in suburban communities or transit deserts with poor public transport access, AI models can identify unmet demand and optimize the placement of shared mobility options [67]. AI dynamically deploys services like ride-hailing or micro-mobility to provide essential first- and last-mile connectivity.

Notwithstanding, to guarantee that deep profiling benefits vulnerable groups without reinforcing existing inequalities, AI systems must be carefully designed to mitigate algorithmic bias [68]. If a dispatch algorithm is trained predominantly on data from affluent neighbourhoods, it may inadvertently learn to offer fewer services or longer wait times to marginalized areas, exacerbating social inequality. By embedding fairness constraints -such as equalized odds or demographic parity- into machine learning pipelines, MaaS platforms can ensure that resources and vehicles are fairly allocated, preventing the system from disproportionately denying services based on a user's demographic or socio-economic background [69].

5 Conclusion Remarks

In light of the experience gained from the MaaS4Italy and Sardinian MaaS projects in transport planning, the involvement of associations and organisations representing vulnerable users emerges as a key element in bridging the communication gap between policymakers and end users for the deployment of a universally inclusive Italian way to MaaS. In particular, the collaboration with AISM and UTE highlighted the importance of combining digital and non-digital engagement methods, involving trusted intermediaries and promoting long-term participatory process capable of fostering trust and participation over time.

These actors fulfil a pivotal intermediary function, aiding in the overcoming of mistrust, language barriers, and physical or cognitive limitations that frequently compromise the efficacy of conventional participation channels for the vulnerable social groups. At the same time, a critical issue has been identified. Despite the presence of regulatory frameworks addressing accessibility, particularly in relation to digital systems, the lack of effective enforcement mechanisms still limits the practical implementation. In this perspective, public authorities should assume a central coordinating role in the development of inclusive MaaS initiatives, as demonstrated by selected case studies. Their responsibility should extend beyond mere regulatory compliance, encompassing the active facilitation of stakeholders' engagement and integration of accessibility requirements from early design stages.

This is particularly relevant when addressing the needs of vulnerable users who require a tailor-made approach based on the target group involved in the process. In this regard, analysing vulnerable users' needs is essential for developing criteria for designing travel alternatives tailored to their actual needs [70].

Finally, the development of inclusive MaaS is best achieved by a structured and coordinated approach combining institutional leadership, stakeholders' facilitation and user-centered design to deliver tailored mobility solutions. It is therefore important to understand inclusive MaaS not merely as a technological innovation but as a governance challenge requiring coordinated, multi-actor and user-centered approaches.

Despite representing a preliminary study on potential inclusion and accessibility improvement for Italian MaaS proposal, the present research provides a comprehensive framework for future phases of MaaS4Italy. Limitations of the work are represented by the consideration of grey official literature from MaaS4Italy project, without the possibility to access pilot field data. Moreover, territorial focus has been represented by one case-study only.

Further steps would concern the analysis of pilot field data from the different territories, as well as the mapping of primary stakeholders to be addressed within the different territorial contexts, as well as the deepening of potential policy implications.

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Assessing Accessibility to Primary Education and Healthcare Services: A Comparison of EU Datasets and Network-Based Analysis.

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Abstract. European medium-sized cities are increasingly affected by shrinking dynamics, characterized by sustained population decline, ageing and selective out-migration, which challenge their capacity to remain attractive and competitive in the long term. In this context, everyday accessibility to essential services such as primary education and healthcare becomes a key component of urban livability, social equity and territorial resilience, shaping residential choices of families, older adults and mobile households. This paper investigates these issues proposing a novel approach through an integrated assessment of accessibility to primary schools and healthcare facilities in two mid-sized European cities, Genoa (Italy) and Karlsruhe (Germany). Present choice descends from the aim to evaluate potential attractiveness of urban areas, as well as local administrations commitment against shrinking and ageing trends. Building on Eurostat's 2025 road-based accessibility dataset, the study compares harmonized EU driving-time indicators with fine-grained, network-based analyses and walking-time maps developed at the urban scale. The methodology adopts a proximity perspective and explicitly considers demographic trends, urban morphology and welfare governance arrangements. Results show that while EU-wide indicators are valuable for macro-regional benchmarking and cohesion monitoring, they tend to conceal significant intra-urban inequalities, particularly in morphologically complex contexts such as Genoa. The paper argues that multi-scalar and multimodal accessibility assessments, integrating EU datasets with local network models and context-specific service typologies, are needed to support more equitable, age-friendly and place-sensitive planning of primary education and healthcare in European shrinking cities.

Keywords: Accessibility, Primary Education · Healthcare · EU Datsasets

1 Introduction

European medium-sized cities are increasingly entering a phase of demographic competition [1]. Recent demographic research shows that sustained population decline is no longer an anomaly, but a structural trajectory for many European regions. Newsham and

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Rowe [2] demonstrate how sub-national depopulation is now widespread across both rural and urban areas; thus, concluding that natural decrease (low fertility combined with population ageing) is ubiquitous, while net migration determines the pace of decline. Urban shrinkage has become a new normality for a growing number of European cities, affecting roughly 40% of large cities and especially older industrial regions [3]. At EU level, projections to 2050 suggest that around 45% of Functional Urban Areas could face population decline, driven increasingly by low fertility and ageing rather than by de-industrialization alone [4]. In a context marked by population ageing, shrinking regions, and growing inter-urban mobility, cities must compete not only in economic performance but also in terms of quality of life, service provision, and everyday accessibility [5]. In the coming decades, accessibility to essential services - such as primary education and healthcare - will represent indeed a key determinant of urban attractiveness, social equity and long-term resilience [6]. Healthcare and education services are among the most fundamental components of urban welfare infrastructure. Ageing population would indeed reflect into a widespread need of proximity-based health and care facilities [7]. Older adults report a higher incidence of unmet health-care needs related to distance and transport barriers than younger cohorts, underscoring the importance of local accessibility for this group [8]. On the other hand, the will to attract families and younger couples would translate into the re-organization of a high-quality primary education system [9] as primary education and childcare are increasingly framed as strategic, place-bound services that shape residential decision of mobile households, not just as neutral welfare provisions. However, their spatial distribution is often uneven, producing differentiated access times and mobility burdens across neighborhoods [10]. Moreover, urban shrinkage, ageing and structural changes in population composition, which in turn reconfigure welfare needs spatially, would amplify the spatial and equity dimensions of demand [11]. Reliable and comparable information on geographic accessibility is therefore crucial for EU regional policy, territorial cohesion strategies, and the monitoring of the UN Sustainable Development Goals (SDGs) [12]. In this direction, present contributions aim to assess accessibility conditions to primary education and healthcare facilities following a proximity perspective, where similar equipment represent a key factor influencing city livability and attractiveness within a shrinking and ageing EU context [13]. Stemming from EUROSTAT dataset [14] including driving times to basic education and healthcare facilities, the authors will provide a comparison between the proposed approach and the results of a network analysis taking into account two territorial case-studies: Genoa (IT) and Karlsruhe (DE). Territorial similarities and similar demographic trends allow to assess how different administrative structures and basic services management schemes may translate into different accessibility conditions. The proposed novel integrated approach enables further evaluation of the potential attractiveness of cities in terms of essential services asset and accessibility.

2 Background

Shrinkage literature has increasingly focused on the mismatch between inherited infrastructure and changing demography. Rink et al. [3] conceptualize urban shrinkage as the interaction of macro-level economic restructuring, demographic change and suburbanization, leading to under-used housing, oversized technical networks, and fiscal stress.

Among the most visible consequences, the authors highlight pressure to downsize social infrastructures such as schools, nurseries and child-related services in the face of falling child cohorts, while at the same time demand for healthcare and care services for older adults increases. JRC [4] extends this analysis by distinguishing between the hardware (physical infrastructure), software (social and demographic fabric) and mindware (the city's image) of shrinking cities. On the hardware side, population loss leads to vacant housing, declining property values, and the closure of small local shops and services; financial constraints often trigger consolidation of local facilities and a reduction in service levels. On the software side, selective out-migration of young and educated residents produces an ageing, lower-income population with higher health-care needs and lower mobility, thereby increasing dependence on local services. As cities shrink and age increase, some services can be centralized for efficiency, but core everyday services -particularly primary healthcare and basic education- are difficult to withdraw or relocate without significant social and territorial costs [15]. Population ageing is the key demographic mechanism linking shrinkage to proximity-based health and care. Following a neighborhood-scale approach, focus groups with older residents across these cities reveal that proximity to essential services and amenities- especially medical services, social activities and public transport- is perceived as one of the main advantages of urban living [10]. More fine-grained empirical work quantifies this link between proximity and older people's everyday health behavior. Referring to the Basque country, Machón et al. [7] show that having park/green spaces and other community facilities within walking distance is positively associated with physical activity and satisfactory social life, controlling for age and health status. From a service-provision perspective, Guida et al. [16] develop an elderly-oriented multimodal two-step floating catchment area method to measure accessibility to primary healthcare in Milan; they find that about 40% of older residents experience poor accessibility to primary health services, with the worst conditions in peripheral neighborhoods. The authors argue that accessibility deficits, rather than merely aggregate supply, are critical to the quality of life of an ageing urban population and call for age-friendly, proximity-oriented planning of healthcare networks [17]. Recent neighbourhood-scale applications further emphasise the role of sustainable mobility in shaping accessibility to essential services [18]. Policy shifts from hospital-centric models to community-based and age-friendly approaches, where neighborhood-scale primary care, long-term care and social support are seen as prerequisites for ageing in place in shrinking and ageing cities. On the families and children side of the equation, research has begun to connect demographic decline, school networks and local attractiveness for young households. From an accessibility perspective, García-Palomares et al. [19] analyse public primary schools in four large European cities, showing substantial spatial and social imbalances in accessibility once population density and socio-economic vulnerability are taken into account. Their results indicate that, even in large metropolitan areas, access to schools is uneven, and that austerity-driven rationalisation of school networks risks worsening spatial inequalities [20]. At a broader European scale, studies on geographic inequalities in access to essential services confirm that proximity to primary schools declines sharply in demographically shrinking regions, with relatively small changes in child population leading to large increases in travel times for remaining families [21]. The shrinkage literature interprets

these dynamics within a wider welfare–territory framework. Financial logic of rightsizing encourages concentration of schools and childcare facilities [22], this can accelerate depopulation by making areas less attractive for young families, thereby undermining attempts to stabilize the age structure. With respect to attractiveness and competitiveness of cities in shrinking contexts, this work goes beyond the sectoral approach mainly found in the literature, proposing an integrated analysis considered more effective in capturing the full range of welfare policies and their impacts at the urban scale.

3 Case Studies

Italy and Germany share European demographic challenges, including rapid population ageing, persistently low birth rates, and mounting pressure on welfare systems and urban public services. These trends strain the sustainability and equitable delivery of essential services such as healthcare and education, particularly in mid-sized cities where resource allocation must balance physical constraints with territorial coverage.

Despite notable differences in economic performance, migration balance, and regional policy frameworks, a direct comparison between Genoa (Italy) and Karlsruhe (Germany) offers valuable insights. Both are mid-sized university cities with established academic profiles -the University of Genoa (UniGe) and the Karlsruhe Institute of Technology (KIT)- that attract significant student populations and contribute to local economies. Yet the two cities diverge sharply in their urban morphology and topography, as well as in demographic structure.

This combination of similarities and contrasts makes the pair particularly suitable for examining how different expression of demographic challenges, together with differences in urban form and accessibility conditions, shape strategies for the equity and resilience of essential public services for residents and families.

This paper compares the Eurostat 2025 road-based accessibility dataset with network-based accessibility analyses conducted specifically for Genoa and Karlsruhe.

Both cities prove particularly representative of the investigated phenomenon, thus allowing for a more detailed analysis of accessibility data and metrics provided on a EU level by Eurostat. Moreover, the choice of open and EU-wide dataset supports research transferability to other any other urban contexts covered by the dataset.

Next sub-sections will present the two case studies.

3.1 Genoa

Genoa, the capital of the Liguria region, has ancient origins dating back to pre-Roman times and developed around its major historic port. Today, the city exhibits a highly constrained spatial configuration: a narrow coastal strip compressed between the Mediterranean Sea and the steep slopes of the Apennines. This dense and morphologically fragmented landscape has generated a complex, winding street network that poses persistent infrastructural and mobility challenges, These logistical barriers prove critical when addressing the vulnerabilities of a rapidly aging population. With approximately 564,000 inhabitants [23], Genoa faces a chronic demographic contraction and is currently one of Europe's oldest urban areas. Low birth rates and the continuous out-migration

of young professionals have driven the old-age dependency ratio to nearly 48.5% [24]. Although the presence of around 32,000 students at the University of Genoa and an immigrant population (11.4% foreign residents) provide a modest buffer, they are insufficient to reverse this structural imbalance.

Advanced aging has triggered a surge in demand for chronic and geriatric care, overwhelming the city's major hospitals. To mitigate this pressure, the region is implementing decentralized 'Community Houses' (*Case di Comunità*), offering integrated primary care, specialist outpatient services, nursing, social support, vaccinations, and point-of-care testing to reduce inappropriate hospital use and improve local access. However, their full deployment is still in progress, long waiting lists remain systemic, and topographical constraints hinders equitable spatial access, especially for elderly residents in remote areas. The demographic decline also impacts primary education, forcing the consolidation of schools into broader administrative units (Istituti Comprensivi). This rationalization reduces the capillary presence of neighborhood schools, subtly eroding the local social fabric. Furthermore, a large portion of school buildings date back to the early-to-mid 20th century, presenting severe accessibility shortcomings that are further aggravated by transport issues for those living in the inland valleys.

3.2 Karlsruhe

Founded in 1715 by Margrave Karl III Wilhelm as his retreat (Karl's Rest), Karlsruhe features a distinctive fan-shaped layout situated on the flat, open terrain of the Upper Rhine Plain. Unlike topographically constrained cities, this radial structure facilitates efficient land use and barrier-free accessibility. Karlsruhe exemplifies demographic resilience, with a growing municipal population of over 309,000 residents [25]. This vitality is heavily fueled by its robust tech-university ecosystem, notably the Karlsruhe Institute of Technology (KIT). With a student body comprising 12.5% of the total urban population and a high retention rate of skilled international graduates, Karlsruhe successfully maintains a balanced age structure, actively mitigating broader national ageing trends and population decline.

The city's balanced demographics and flat morphology ensure high, equitable spatial access to its comprehensive healthcare network. Karlsruhe effectively supports citizens through well-established outpatient nursing services (*Ambulante Pflegedienste*) that deliver care directly to patients' homes. Consequently, the city avoids shrinkage-driven service closures and the spatial isolation of the elderly, allowing authorities to focus on technological integration rather than demographic emergencies, though national challenges regarding nursing staff shortages persist. Benefiting from favourable demographic trends, Karlsruhe sustains a dense, decentralized network of neighborhood primary schools. Guided by the urban planning principle of "short legs, short distances", this capillary distribution preserves local community cohesion. The absence of topographical barriers, combined with a highly integrated transit and cycling infrastructure, ensures safe, active, and highly accessible mobility for young students across all districts.

4 Materials and Methods

In January 2026, Eurostat released a new geospatial dataset describing accessibility to healthcare and education services by road transport [14]. The dataset identifies potential population clusters with low or limited accessibility based on driving time to the nearest facility. It combines the 2021 Census population grid at 1 km resolution with road network data to calculate driving times to healtchare services and primary education for the reference years 2020 and 2023. This release follows the 2023 launch of a harmonised geospatial database of healthcare and education services across the EU, including detailed attributes such as service name, type, capacity, address and geographic location, derived from national administrative registries.

To better interpret the results of the geodataset, it is important to understand how it was set. Specifically, accessibility is defined as the driving time to the nearest facility; for healthcare facilities, only those offering first aid and specialist clinics are included; for education, the term 'primary' covers all levels from nursery school to adult education, effectively excluding higher education institutions such as universities, research centres, and specialist schools.

These choices and definitions affect the use of the tool in decision-making and strategic assessment processes. When applying this framework to the selected case studies, the following key insights emerge:

4.1 Healthcare

As shown in Fig. 1, both cities present adequate healthcare coverage, with a high probability of reaching a facility within a 5 min drive. It is important to note that healthcare services are less accessible in the outlying areas of Karlsruhe. In contrast, the linear development and morphology of the city of Genoa results in less equitable service distribution as one moves away from the coast. For instance, a substantial area in the north-west of the city is characterised by high population density; however, the nearest healthcare facility is located more than 15 min away by car.

4.2 Primary Education

As shown in Fig. 2, the observed scenarios are evidently favourable in both contexts, resulting from a pervasive distribution of facilities that ensures travel times of less than two minutes for the majority of the territory. In terms of comparison, while Karlsruhe show almost homogeneous results, the city of Genoa again suffers from the impact of the hilly terrain, resulting in increased travel times for students living in the outskirts of the city.

4.3 Overcoming Dataset's Issues

The Eurostat visualization is therefore readily comprehensible and practical, yet there are some critical issues that could hinder one of the potential applications for which the dataset was produced, namely to support local administrations and authorities in the spatial analysis of their territory as an aid tool for decision-making:

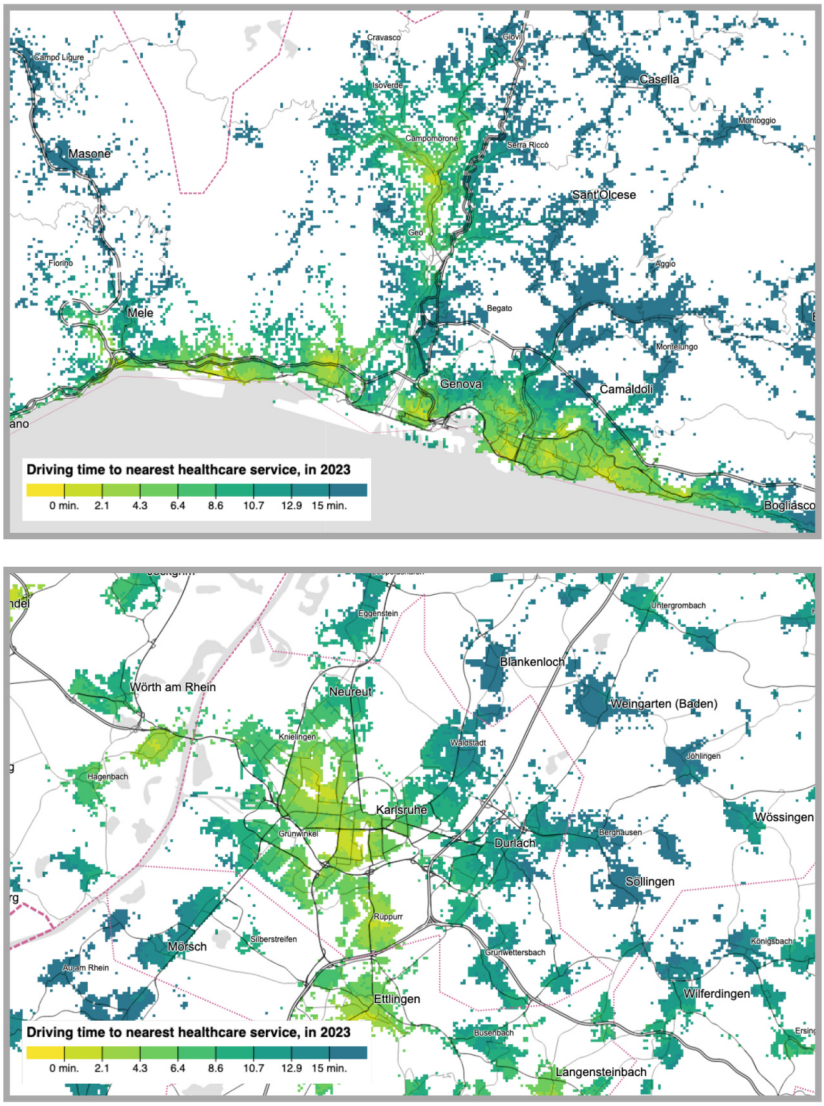

Fig. 1. Driving time to the nearest healthcare service in 2023 for the city of Genoa (above) and Karlsruhe (below). Source: [14]

- The 'driving time' metric used by Eurostat contrasts with the logic of proximity and sustainable mobility. In this sense, an assessment based on walkability could provide a clearer and more accurate picture of the possibilities for accessing primary services without necessarily having to rely on private transport.
- The selection of healthcare facilities included in the dataset seems biased; the inclusion of hospitals only appears to suggest an emergency-based approach, thus excluding a network of outpatient and primary care services that would be more appropriate

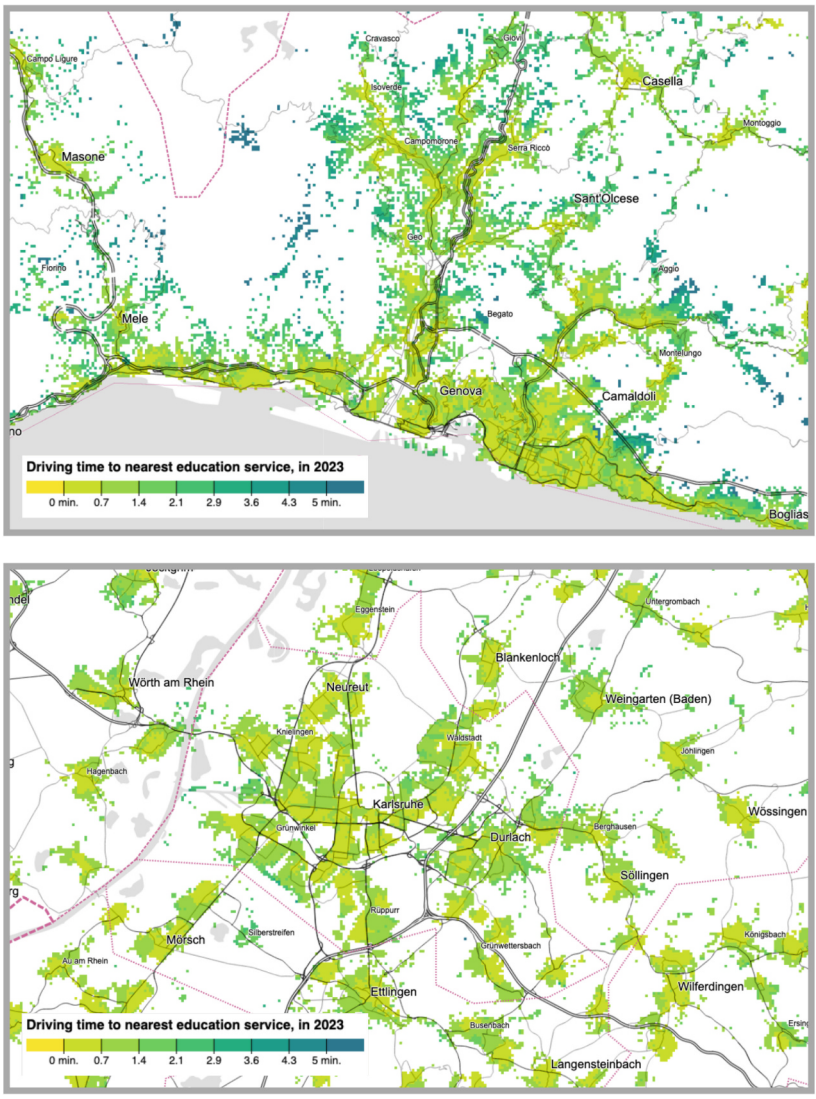

Fig. 2. Driving time to the nearest education service in 2023 for the city of Genoa (above) and Karlsruhe (below). Source: (Eurostat, 2026)

for capturing a picture of proximity and equitable distribution of essential services across a certain territory.

- The dataset's inclusion of all schools, regardless of level, under the umbrella of 'primary education' demands attention: the visualisation provided offers no differentiation based on user category, thereby diminishing the tool's capacity to accurately depict access possibilities in relation to the age and mobility asset of students.

In light of the aforementioned considerations, it is the intention of the authors to propose a network-based analysis approach as a solution to the issues found in the Eurostat dataset. The purpose of this approach is to provide a more effective representation of local accessibility to essential services. This approach will ensure better targeted decision support aimed at ensuring resilience in the demographic challenges that cities face.

The proposed methodology consists of generating pedestrian isochrones from healthcare and education facilities selected from the EU dataset. These isochrones are produced through a network-based analysis implemented in a GIS environment, using the ArcGIS Network Analyst tool. The road network was constructed by integrating data from the Liguria Region Geoportal with OpenStreetMap (OSM) layers, transformed within ArcGIS into a Network Dataset. Each network segment was assigned a travel-time cost based on its length, assuming an average walking speed of 4 km/h, thus enabling a time-based accessibility analysis. Service Area analysis was then applied by loading facilities as origin points and generating isochrone polygons along the network, reflecting actual pedestrian accessibility conditions. Pedestrian isochrones were calculated with thresholds of 10, 20, and 30 min for healthcare facilities, and 5, 10, and 15 min for a selected subset of education facilities (levels 0–1 in the EU dataset, namely nurseries and primary schools). These thresholds were defined in line with proximity-based planning principles and with the literature on walkable neighbourhoods and 15-min city frameworks, which identify different acceptable travel times depending on the type of service and user group. Resulting isochrone layers were finally exported and aggregated to produce continuous accessibility maps, which were then used to assess spatial coverage, identify underserved areas, and compare results with the Eurostat driving-time dataset.

This step of the analysis was conducted only for the case of Genoa, due to the lack of detailed EU geospatial data for the facilities in Karlsruhe. Despite the abovementioned similarities, differing administrative structures and governance mechanisms hampered the performance of a complete analysis for both cities. The decision to maintain Karlsruhe as a case study is due to the aim to highlight the limitations of the EU tool, which may be effective for visualization purposes and preliminary evaluations, but limited in terms of processing capabilities. The outputs, presented in the next section, consist of walking-time accessibility maps for both healthcare and education services.

5 Results

The following section presents the results of applying the proposed methodology to the city of Genoa, where all required data were available and the authors' contextual knowledge allowed for informed interpretation beyond purely technical outputs.

Unlike the Eurostat tool, which relies on driving times, the present analysis adopts walking time isochrones at 10, 20 and 30 min intervals for healthcare and 5, 10, and 15 min intervals for primary education. This choice was made to evaluate accessibility to essential services from the perspective of everyday needs rather than emergency scenarios or car-dependent trips. In the case of healthcare, the focus is on care provision for an ageing population; in the case of primary education, the analysis is restricted to facilities serving the youngest residents -from nurseries through to lower-secondary

schools- thereby concentrating on the needs of families with children and excluding upper-secondary institutions.

The resulting maps, presented in Fig. 3, diverge markedly from the Eurostat visualisation. For healthcare, coverage within a 30 min walk is largely confined to the dense central neighbourhoods, where the high concentration of facilities creates redundancy. Along the coast, however, even densely populated districts show walking times exceeding 30 min because of the spacing between hospitals. Additionally, the paediatric hospital Istituto Gaslini (south-east) was excluded from the analysis, as it serves a specialised paediatric population rather than the elderly demographic demand; its removal further accentuates the aforementioned gap areas that appear well-covered in the Eurostat tool. For primary education the differences are less pronounced: the great majority of the inhabited territory remains within a 15-min walk of a nursery or lower-secondary school, and the few uncovered zones are mainly low-density, industrial or commercial areas where low or absent demand makes the shortfall acceptable.

Two important limitations must nevertheless be acknowledged. First, at this stage, the analysis does not incorporate terrain topography -a factor of critical importance in Genoa's hilly and valley landscape- and therefore presents a more optimistic picture of actual walking accessibility than residents experience on the ground. Second, the dataset used does not yet include the Community Houses' described in Sect. 3.1. These proximity facilities are specifically designed to expand the network of local care, manage lower acuity needs close to home and channel only the most critical cases to hospitals; their omission underestimates the level of territorial coverage that Genoa is progressively achieving. Future studies will need to integrate both topographic correction and updated geospatial layers for these community-based structures in order to provide a more realistic assessment of service equity in morphologically complex urban settings.

6 Discussions

This paper examines accessibility to healthcare and primary education as a central pillar of urban livability, social equity, and territorial resilience in European cities facing current challenges of population shrinkage and ageing. In this context, Eurostat remains an essential reference, offering harmonised cross-national data to support evidence-based policy-making across Europe [26]. Its 2026 geospatial accessibility dataset represents a major milestone in large-scale assessment, attempting to provide a clear and homogeneous picture of accessibility across different regions. EU datasets effectively support macro-territorial benchmarking and the development and monitoring of cohesion policies. Nevertheless, the interpretative power of macro-level datasets at the intra-urban scale remains limited [27].

Administrative unit discrepancies (often not complying with the EU NUTS classification) and diverse service provision schemes (varying public-private roles and responsibilities) lead to unequal data availability on a national level. Consequently, a multi-scalar approach is required for accurate accessibility measures and evaluation.

While macro-data is useful globally, an urban planning perspective requires proximity-based assessments [16, 28, 29]. Fine-grained, local network-based analysis is essential for targeted urban interventions [30], particularly within morphologically complex cities like Genoa.

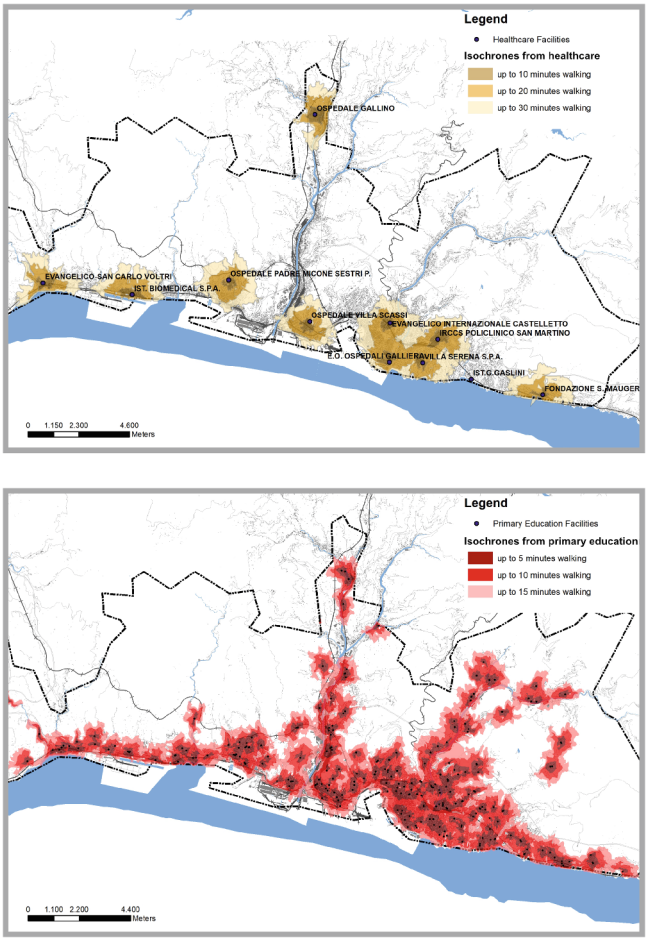

Fig. 3. Results of the analysis for Genoa. Walking time to the nearest healthcare facility (above) and primary education (below) in 2023. Source: authors' elaboration.

Applying downscaled evaluations requires a rigorous understanding of how key terms such as accessibility, primary education, and healthcare are defined. When assessing spatial access to hospitals and schools, macro-level datasets like Eurostat's would arguably offer greater utility for decision makers if they evaluated true active proximity rather than driving times.

Shifting the focus to proximity would better align with '15-min city' paradigms [31] and avoid reinforcing car-centric mobility habits [32]. Furthermore, the current categorization of services within the dataset lacks the granularity required for targeted strategies. For instance, the 'primary education' category indiscriminately covers everything from nursery schools to adult evening classes, obscuring the distinct spatial needs of different user demographics [19]. Proximity evaluations must account for facility types,

as being close to a high school serves an entirely different demographic requirement than being close to a kindergarten.

Similar issues arise in the healthcare domain, where the dataset primarily focuses on hospital care operating on a macro-territorial scale. For the Genoa case study, for example, the dataset includes the Gaslini Institute, a specialized pediatric hospital that authors argue must be explicitly distinguished from general acute care to avoid skewing local accessibility metrics. Moreover, it remains unclear whether the Eurostat dataset adequately captures decentralized, such as German non-facility-based home care services and Italian outpatient proximity network. Due to these methodological issues, the EU dataset alone is insufficient for conducting the granular, neighborhood-level assessments.

To address these limitations, this work mapped walking-time isochrones for the Genoa case study, setting thresholds at 5, 10, and 15 min for education, and 10, 20, and 30 min for healthcare. To accurately reflect the true proximity needs of the community, we rigorously filtered the input datasets. For the education sector, we included only nurseries, kindergartens, primary, and lower secondary schools, excluding high schools and professional institutes to focus on essential services required by young families. For the healthcare sector, the highly specialized pediatric hospital was excluded to prevent skewing the accessibility metrics for general acute care, which would otherwise obscure the actual healthcare gaps faced by Genoa's rapidly aging population.

The results of the local, walking-based assessment reveal a significantly less favorable accessibility landscape in Genoa than what is indicated by the macro-level Eurostat tool. These discrepancies are particularly pronounced in the healthcare sector compared to education. These results demonstrate how in-depth knowledge of the local context is indispensable for accurately evaluating citizens' accessibility to essential public services.

7 Conclusions

This study examined accessibility to primary education and healthcare services in two mid-sized European cities -Genoa and Karlsruhe- against the backdrop of demographic shrinkage and population ageing. Drawing on the Eurostat 2025 road-based accessibility dataset, authors demonstrate that, while such macro-regional indicators are valuable for cross-country benchmarking and EU cohesion monitoring, they frequently obscure substantial intra-urban disparities, especially in morphologically complex settings such as Genoa.

Fine-grained, network-based analyses and walking-time isochrones developed at the urban scale reveal pronounced differences between the relatively homogeneous picture provided by the Eurostat data and the lived realities of local populations. Although both cities exhibit broadly adequate accessibility when measured in terms of driving times, a walking-based perspective uncovers marked inequalities in service coverage and identifies areas where residents -particularly children, older adults and individuals with reduced mobility options- encounter significant barriers to essential services. These findings emphasise the critical role of context-sensitive data and multi-modal assessment in producing reliable accessibility estimates.

The comparative analysis highlights the necessity of moving beyond macro-scale, private mobility-centric evaluations towards multi-scalar, place-based approaches that

integrate European datasets with detailed local street network models, while explicitly accounting for urban morphology and ongoing demographic trends.

The proposed framework, which combines EU-level indicators with high-resolution network analysis tailored to walking (and extensible to other modes), constitutes a robust and transferable methodology for supporting equitable, age-friendly, and resilient urban planning in shrinking and ageing European cities.

Several limitations of the present work point to promising directions for future research. First, incorporating topographic variables into walking-time calculations would markedly improve model accuracy, especially in hilly cities such as Genoa. Secondly, extending the network analysis to encompass cycling infrastructure and public transport timetables would yield a more comprehensive representation of accessibility understood as effective proximity across transport modes.

Further development of the present study may widen the application of the proposed approach to accessibility evaluations to healthcare and education facilities in Karlsruhe, as well. Nevertheless, the lack of EU dataset coverage in this area would require collecting specific data though a dedicated campaign (or validation of OSM data). Moreover, an in-depth and systematic comparison between EU accessibility thresholds and isochrones calculated though local network analysis could be deployed to optimize data-driven decision-making process.

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Towards a Multidimensional Assessment of Urban Bikeability: Integrating GIS and User Perception

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Abstract. Cycling is widely acknowledged as a key component of sustainable urban mobility, but its adoption remains limited in many high-motorization Mediterranean cities. In these contexts, bikeability cannot be evaluated only through cycling infrastructure provision, but should be interpreted as the result of the interaction between spatial, environmental, and perceptual dimensions.

This paper proposes a multidimensional framework for the assessment of urban bikeability through the integration of spatial evidence and user perception data. The analysis is applied to the case study of Catania, combining the current and planned cycling network derived from the official Biciplan with the distribution of vegetated areas obtained from regional cartography as a proxy for environmental quality and survey-based evidence on mobility habits, perceived barriers and cycling incentives.

The findings point out a fragmented existing cycling network and a broader but still spatially uneven planned configuration. Moreover, they highlight an unequal distribution of vegetated areas, with more extensive green coverage in peripheral zones than in the dense urban core. Survey findings show that cycling still plays a marginal role in everyday mobility and the most relevant barriers are safety-related concerns due to the interaction with motorized traffic and inadequate infrastructures.

The study reveals a mismatch between planning intentions and experienced cycling environments by users. Thus, improving bikeability requires an integrated approach which combines infrastructure provision, environmental quality and perceived safety. The proposed framework can be transferred to other urban contexts characterized by high motorization rates and limited cycling uptake.

Keywords: Bikeability · Cycling Infrastructure · Perceived Safety · Green Infrastructure · GIS · Sustainable Mobility

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1 Introduction

Cycling is ever more recognized as a key component of sustainable urban mobility because it can contribute to reduce emissions, mitigate congestion, improve public health and use urban space more effectively. This perspective has also been strengthened at the European level by the European Declaration on Cycling, which recognizes cycling as a fully-fledged transport mode and as a relevant component of wider urban sustainability strategies [1]. This broader view is consistent with studies that frame sustainable urban development as an integrated process involving transport systems, green infrastructures, and new forms of metropolitan governance [2].

Despite the growing attention, the transition toward cycling-oriented mobility remains highly uneven across cities. In many Southern and Mediterranean urban contexts, cycling still plays a marginal role in daily mobility because of a mix of structural, cultural and institutional barriers. These include high motorization rates, fragmented or insufficient cycling infrastructure, low perceived safety and the in general car-oriented travel habits. Recent review reports confirm that the built environment strongly affects cycling behaviour, with street connectivity and the presence of cycling facilities among the most consistent explanatory factors [3].

In this regard, Catania offers a relevant case. The city and its wider metropolitan area are characterized by a strong dependence on motorized private transport and a weak cycling demand, with the existing cycling network limited and discontinuous. The Biciplan of the Metropolitan City of Catania explicitly identifies safety, connectivity, and network coverage as key conditions for increasing cycling demand and acknowledges that cycling usage is currently well below national averages in the metropolitan area. Therefore, the plan outlines cycling promotion as part of a broader transition toward more sustainable and inclusive mobility.

However, beyond infrastructure, urban cycling conditions are also influenced by the environmental quality of routes. Recent studies suggest that green infrastructure and linear green elements may influence route attractiveness, environmental comfort and perceived safety, indicating that bikeability should be understood not only through network provision but also through the quality of the surrounding urban landscape [4]. This is particularly relevant in Catania, where the relationship between environmental awareness, mobility behaviour and urban sustainability has already emerged in recent survey-based and governance-oriented studies [5]. Therefore, assessing cycling conditions only in terms of network extension may provide an incomplete picture. An existing route may still be unattractive or weakly used if it is fragmented, embedded in adverse traffic conditions, or located in urban environments with poor environmental quality. Likewise, planning strategies may grow the cycling network, but their practical effectiveness depends on how those interventions are perceived and experienced by users. This is especially important in cities where cycling demand is still weak and where cultural and perceptual barriers remain substantial. More generally, this is coherent with broader approaches to urban sustainability that emphasize the need to consider environmental resources as active components of regeneration, livability, and local development [6, 7].

Against this background, this study proposes a multidimensional framework for assessing urban bikeability by integrating GIS-based spatial evidence with user perception data, applying to the case of Catania. The work investigates to what extent the current and planned cycling networks provide spatial continuity and territorial coverage within the urban context, whether existing and planned routes are in areas characterized by adequate vegetation coverage and environmental quality, and whether the environmental context may act as a potential driver of bikeability. Moreover, we explore how this spatial picture can be linked with users' perceptions about safety and comfort. By jointly addressing these issues, the paper aims to capture bikeability considering the interaction between network structure, environmental context and user experience.

In this regard, the study contributes to the broader literature by combining three dimensions that are often examined separately: the spatial structure of the current and planned cycling network, the distribution of vegetated areas as a proxy for environmental quality and survey-based evidence on users' perceptions. Although applied in a specific Mediterranean context, the proposed framework is intended to be transferable to other cities characterized by high motorization rate and, limited cycling uptake with ongoing efforts to expand cycling infrastructure.

2 Literature Review

2.1 Bikeability as a Multidimentional Concept

The concept of bikeability has progressively evolved from a limited focus on cycling infrastructure toward a broader understanding of the urban conditions that make cycling feasible, attractive and safe. Relevant studies showed that bikeability depends on a combination of variables related to the built-environment, including connectivity, topography, land-use patterns and, thus, the availability of cycling facilities. In this regard, bikeability is not linked only to the presence of bicycle lanes, but the extent to which an urban environment supports cycling as a viable and desirable transport mode for daily movements. One of the most influential attempts to operationalize this concept is the work by [8], who developed a spatial tool to map bikeability considering infrastructure, slope, connectivity and attributes related to the destination. Their later work on Bike Score further demonstrated that bikeability measures are associated with cycling mode share both within and across cities, highlighting the usefulness of composite measures for planning and policy support [9].

More recent studies confirm that cycling behaviour is influenced by multiple dimensions of the built environment. Street connectivity and cycling infrastructure are among the strongest correlates of cycling uptake, but the literature also emphasizes density, accessibility, route directness and the quality of urban design [3]. This multidimensional reading is especially relevant in contexts where cycling remains marginal. In such cases, isolated routes or short infrastructural interventions may have limited impact unless they are part of an intelligible system able to support continuous trips. For this reason, recent contributions increasingly argue that bikeability should be assessed as the combined outcome of infrastructural provision, spatial continuity, and the broader quality of the urban environment [10]. This is also consistent with urban studies that highlight the standing of integrated planning approaches, especially in metropolitan contexts where

mobility, environmental quality and governance are strongly interconnected [11]. In this respect, bikeability cannot be interpreted only as a transport-related attribute, but also as a component of wider sustainable urban transition processes.

2.2 The Role of Perceived Safety in Cycling Behaviour

Alongside objective spatial conditions, perceived safety has emerged as one of the most important determinants of cycling behaviour. A substantial body of literature shows that potential and actual cyclists respond not only to measurable infrastructural attributes, but also to how safe, stressful, or comfortable a route feels in practice. This implies that objective provision and subjective experience do not necessarily coincide [12].

The distinction between observed and perceived cycling safety has been discussed explicitly in recent research. The authors [12] show that cycling safety can be assessed through both objective and perception-based methods, and that these two dimensions capture different but complementary aspects of the cycling experience. Their contribution is especially relevant because it supports the need to integrate infrastructural assessment with users' perceptions in order to obtain a more realistic understanding of cycling conditions.

More broadly, recent reviews on safety technologies and cyclist behaviour suggest that users consistently value solutions that improve safety, especially in contexts where traffic exposure and interaction with motorized vehicles are perceived as critical. However, these studies also indicate that technological or behavioural improvements alone are insufficient if the broader infrastructural and traffic context remains hostile [13–15].

This line of research is particularly important in cities with weak cycling cultures. In such contexts, perceived risk associated with traffic, discontinuous routes, and low-quality urban environments can strongly discourage bicycle use even where some form of infrastructure exists. For that reason, bikeability cannot be assessed through network maps alone; it must also account for how routes are perceived in terms of safety, continuity, and comfort. This is in line with recent evidence from Catania showing that mobility choices are also influenced by environmental awareness and by users' broader attitudes toward sustainable transport options [16].

Therefore, the perceptual dimension is not an accessory component of bikeability assessment, but a necessary complement to spatial analysis, especially where cycling demand is still weak and user confidence remains limited.

2.3 Green Infrastructure and Cycling Environment

A third and more recent strand of literature concerns the relationship between cycling and green infrastructure. While traditional bikeability studies have focused mainly on infrastructure and land use, growing attention is now being devoted to the environmental quality of cycling routes, including shading, landscape attractiveness, thermal comfort, and the presence of green corridors [17, 18].

In this regard, green infrastructure is not simply an aesthetic addition to cycling provision. It may influence how routes are experienced, how comfortable they are under local climatic conditions, and how safe they feel, especially for more vulnerable or less

confident cyclists. Recent research on linear green infrastructure suggests that green elements can positively affect perceived cycling safety and improve the overall quality of the cycling environment.

Evidence from route-based and spatial analyses also suggests that green areas can interact with the built environment in shaping cycling patterns. In particular, the co-location of cycling routes, attractive destinations, and green areas may foster more supportive urban conditions for everyday cycling, especially when these factors operate together rather than in isolation [4].

For Mediterranean cities, this issue is particularly relevant. Climatic exposure, summer heat, and the uneven distribution of urban greenery may affect the attractiveness of cycling routes more strongly than in cooler contexts. This makes the integration of cycling planning and green infrastructure relevant, not only in terms of visual quality but also in relation to comfort, urban livability and daily network serviceability. In this regard, Copenhagen is often cited as a leading example of integrated cycling planning. Its planning framework clearly considers green cycle routes as an alternative to congested roads, combining mobility and recreational functions while improving route quality and user experience. Official planning documents describe green cycle routes as corridors running through green areas or along the harbour, thus offering more pleasant and less stressful cycling conditions [19, 20]. Such examples are useful not because they demonstrate that cycling policy can move beyond the simple provision of lanes and incorporate environmental quality into route design. For cities like Catania, where cycling conditions are still fragile and uneven, this is valuable as a strategic benchmark.

The literature suggests that bikeability should be interpreted as a multidimensional concept resulting from the interaction among network structure, perceived safety, and environmental quality. However, these dimensions are often investigated separately. This paper addresses that limitation by integrating the spatial configuration of the current and planned cycling network, the distribution of vegetated areas, and user perceptions within a single analytical framework, with specific attention to a high-motorization Mediterranean context.

3 Materials and Methods

The methodological approach combines spatial and perception-based evidence in order to develop a multidimensional assessment of bikeability. The analysis is based on three main data sources: the cycling network, cartographic information on vegetated areas, and survey data on users' mobility habits and perceptions, with the aim of comparing the planned spatial structure of cycling provision with the conditions experienced by users.

3.1 Study Area

Catania is a Mediterranean urban context characterized by high levels of private motorization and a still limited role of cycling in everyday mobility. As highlighted in the Biciplan of the Metropolitan City of Catania, cycling in the area remains well below national averages, while the current transport system is still strongly oriented toward

motorized travel. Local planning documents identify cycling as a strategic component for the transition toward safer and more sustainable mobility.

In this regard, Catania represents an interesting and relevant case for the assessment of bikeability. On the one hand, the city is characterized by structural constraints typical of high-motorization urban contexts, including discontinuous cycling provision and, thus, weak cycling habits. On the other hand, the recent Biciplan provides a clear strategic vision aimed at expanding and reorganizing the cycling network at the metropolitan scale, with particular attention to aspects related to safety, connectivity and territorial coverage. In addition, the study area is characterized by a marked spatial heterogeneity in environmental conditions, e.g. the uneven distribution of vegetated areas across central, peripheral and peri-urban zones. This aspect is remarkable in Mediterranean contexts, where environmental quality and climatic exposure may influence the attractiveness and comfort of cycling routes.

3.2 Data Sources

Cycling Infrastructure
We reconstructed the spatial layout of the cycling network from the official Biciplan of the Metropolitan City of Catania, accessed through the institutional online interactive map and supported by the related technical report. The network was not available as a fully georeferenced analytical dataset for direct quantitative network processing. Nevertheless, the sources provide a reliable representation of existing routes, planned corridors and local interventions. The Biciplan explicitly distinguishes between the current network, the planned metropolitan-scale cycling system and additional local projects and it frames cycling planning in terms of safety, connectivity, and coverage.

Vegetated Areas
Vegetation data were derived from the official regional technical map (i.e. CART2000) provided by the Sicilian Regional Geographic Information System ("Sistema Informativo Territoriale Regionale" - SITR). The vegetation layer includes different types of vegetated areas and was used as a proxy for environmental quality in the study area. In particular, the analysis considered both structured vegetation classes (G1), representing more defined and organized green areas, and more general vegetated surfaces (G0), which may also include natural and agricultural land uses. The dataset does not distinguish between public, accessible, and non-accessible green areas; therefore, it was interpreted as a representation of vegetated environmental context rather than as a measure of urban public green provision.

Survey Data
Survey data were collected through a structured questionnaire aimed at investigating mobility habits, cycling behaviour, and user perceptions related to bicycle use and technological innovation. The questionnaire consisted of 24 questions and was organized into three main sections: (i) travel habits and transport mode preferences, (ii) knowledge and propensity toward technological innovation in cycling, and (iii) socio-demographic characteristics.

The survey was administered in 2025 online using Google Forms. It was disseminated through multiple channels, including cycling associations and informal networks, in order to reach both regular cyclists and non-cyclists. The participation was voluntary and anonymous. A total of 56 responses were collected. Although the sample is not statistically representative of the entire population because it could be affected by potential biases, it provides useful evidence on mobility patterns, perceived barriers and attitudes toward cycling within the analyzed local context. This is a work in progress, and thus future survey waves will enlarge the sample to reduce potential bias and increase the robustness and interpretability of the results.

3.3 Analytical Framework

The study implements a multidimensional analytical framework where bikeability is considered through the integration of spatial evidence and user perception. Therefore, this approach is grounded with the assumption that cycling conditions cannot be adequately captured only through infrastructural provision but rather emerge from the interaction between physical network structure, environmental context and how these elements are perceived by users.

In this work, the spatial dimension considers the current and planned configuration of cycling network, as identified by the Biciplan, and on its relationship with the distribution of vegetated areas. The analysis was developed within a GIS environment and is based on a qualitative spatial interpretation of the network, considering aspects such as territorial distribution, continuity and coverage. Attention is given to the comparison between the existing network and the planned configuration, in order to identify differences in spatial structure and potential improvements in connectivity.

Due to the features of the available data, the cycling network could not be processed as a fully georeferenced analytical network suitable for the computation of formal graph-based indicators. For this, the analysis relies on an interpretative spatial assessment of fragmentation, concentration, and expansion patterns. This exploratory and planning-oriented approach aims to evaluate the spatial logic of cycling provision.

The environmental component is integrated by considering the distribution of vegetated areas derived from the regional technical cartography. Vegetation is interpreted as a proxy for environmental quality, allowing the analysis to characterize the context in which cycling routes are embedded. The combined analysis between cycling infrastructure and vegetated areas allows us to identify whether current and planned routes are located in more favorable environmental conditions, particularly with respect to the distinction between central urban areas and peripheral or peri-urban zones.

The perception-based dimension is integrated through the analysis of survey data, with the aim of capturing users' attitudes, constraints and expectations regarding cycling. The questionnaire results investigated mobility habits, frequency of bicycle use, perceived barriers, and factors that may encourage a greater adoption of cycling. A focus is given to aspects related to safety, which are consistently identified as key determinants of cycling behaviour, as well as to the relative importance attributed to infrastructural improvements and other potential incentives.

From a methodological perspective, the integration of spatial and perception-based evidence represents the core. The study develops a comparative analysis aimed at identifying convergences and divergences between the spatial structure of cycling provision and users' perceptions. In particular, the analysis explores whether areas characterized by higher potential cycling demand are supported by adequate infrastructure and environmental conditions, and whether these align with factors that users consider most relevant for cycling.

Thus, through this integrated approach, bikeability is interpreted as a multidimensional concept resulting from the interaction between infrastructural, environmental, and perceptual components. This allows the analysis to move beyond a solely infrastructure-based evaluation and to highlight possible mismatches between planning strategies and actual conditions experienced by users.

4 Results

This section presents main findings by combining spatial and perception-based evidence. Firstly, we focus on spatial configuration of the current and planned cycling network and the distribution of vegetated areas. Secondly wet report the main survey results related to cycling behaviour, perceived barriers and incentives. The final subsection integrates these dimensions in order to provide a multidimensional interpretation of bikeability in Catania.

4.1 Spatial Analysis

Figure 1 shows the spatial distribution of vegetated areas in Catania, derived from the regional technical map (i.e. CART2000). The dataset includes both structured vegetation, identified asG1, which represents more defined and organized green areas, and more general vegetated surfaces named G0, which may include natural and agricultural land uses.

The spatial pattern highlights a clear irregular distribution of vegetation across the study area. More extensive and continuous vegetated areas are mainly located in peripheral and peri-urban zones, while the central urban area is characterized by a limited presence of green spaces. In addition, structured vegetation (G1) appears more spatially concentrated and discontinuous, whereas general vegetation (G0) covers larger portions of the territory, particularly outside the dense urban core. This configuration provides an initial representation of the environmental context in which the cycling network is embedded, allowing for a qualitative assessment of the relationship between cycling infrastructure and surrounding landscape conditions.

Figure 2 shows the cycling infrastructure in Catania based on the official Biciplan of the Metropolitan City. Existing routes drawn in blue, planned network in purple and local interventions in orange are represented over the urban road system. As shown in Fig. 2, the current cycling infrastructure in Catania is mainly concentrated in the central area and consists of several disconnected segments. This spatial pattern is consistent with the limited role of cycling reported in local planning documents, which remains significantly underneath the national average.

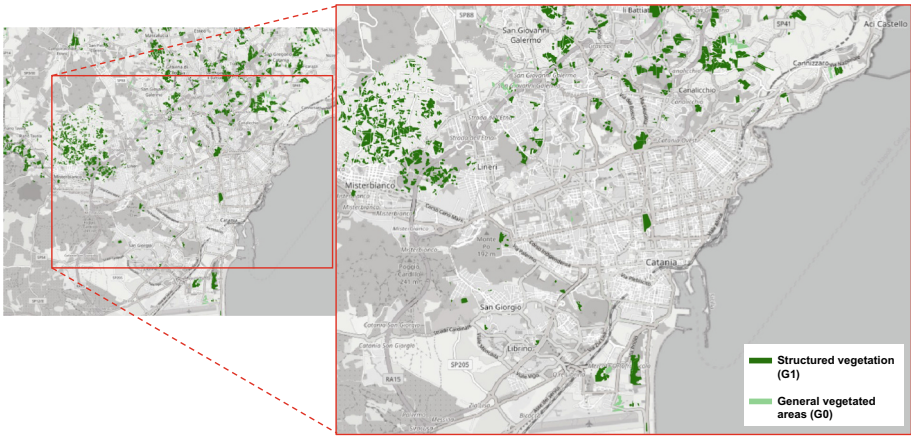

Fig. 1. Spatial distribution of vegetated areas in Catania derived from the regional technical map (CART2000)

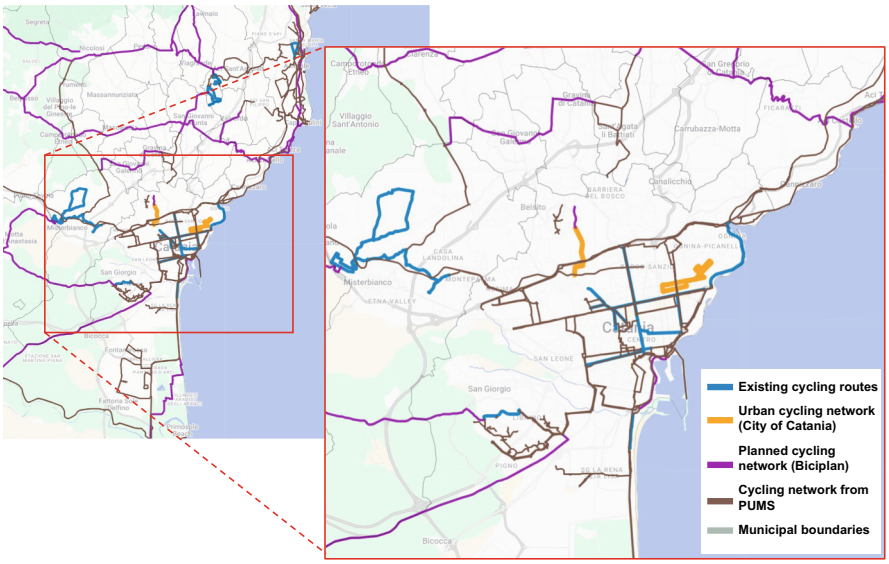

Fig. 2. Cycling infrastructure in Catania based on the official Biciplan of the Metropolitan City.

Peripheral and peri-urban sectors appear less served by dedicated cycling infrastructure, while some interventions are spatially isolated from the main network.

This fragmented configuration contrasts with the more extensive network proposed in Biciplan, which aims to improve connectivity across the metropolitan area. This planned configuration increases territorial coverage and introduces a more structured network layout. The presence of isolated interventions indicates that some discontinuities remain within the current spatial configuration. Therefore, understanding how users perceive the

cycling environment becomes essential to assess the actual effectiveness of the planned interventions and to support the transition toward more sustainable mobility patterns.

4.2 Perception Analysis

This subsection examines the perceptual dimension of bikeability through survey-based evidence. Attention is given to mobility habits, frequency of bicycle use, perceived barriers and conditions considered most effective for encouraging greater cycling uptake.

The sample shows a noticeable dependence on private motorized transport for daily travel. As illustrated in Fig. 3, cars and motorcycles are the prevalent modal choice associated with the daily trip, accounting for 71% of responses, while walking and personal bicycle use represent about 9%, and public transport remains marginal at around 5%. These results confirm the limited role that cycling has in daily mobility patterns.

This overview is consistent with the frequency of bicycle usage emerged by respondents. A substantial share of them declared that they do not use a bicycle on a regular basis, while only a smaller group reports occasional or frequent usage. More specifically, 42.9% of respondents state that they do not use a bicycle, whereas the remaining share is distributed between occasional and more regular usage. This confirms again the marginal role of cycling.

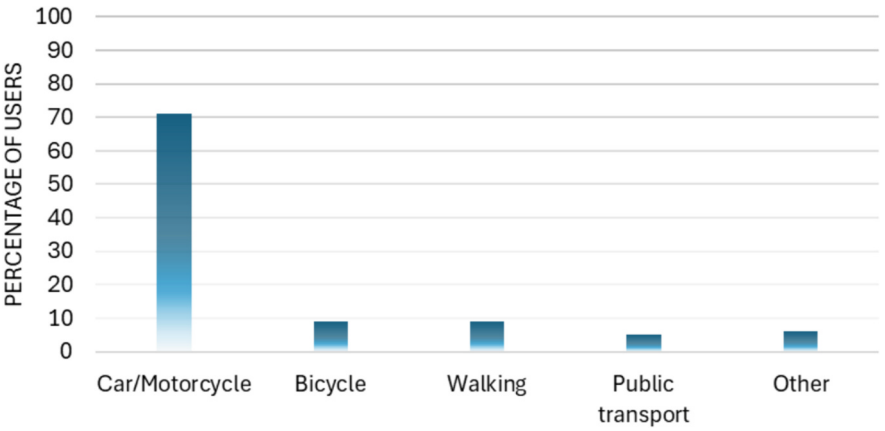

Fig. 3. Distribution of transport modes for the most relevant daily trip

Perceived barriers to bicycle use are summarized in Fig. 4, which presents a qualitative ranking based on the relative importance attributed to different deterrents. Safety-related factors emerge as the most critical obstacles; in fact, traffic danger is identified as the main barrier, with 43% of respondents assigning a high level of importance, followed by the lack of cycling infrastructure and interaction with other road users, both reported by 34% of respondents. By contrast, economic cost and physical effort appear to play a less relevant role and are placed at the lower end of the ranking.

A complementary perspective emerges from the analysis of perceived incentives to cycle. As shown in Fig. 5, respondents clearly prioritize measures related to safer

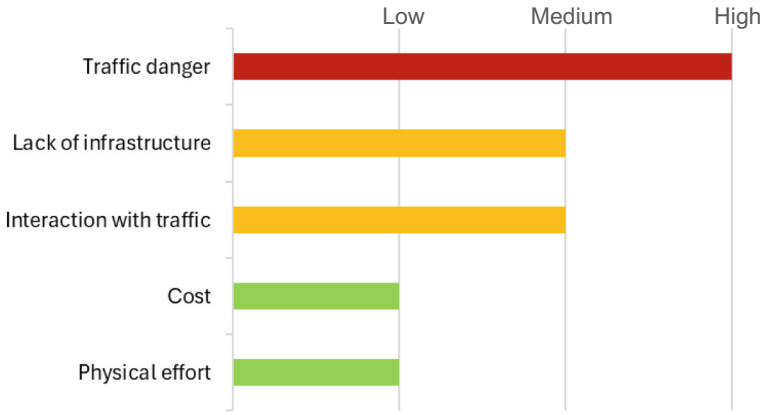

Fig. 4. Qualitative ranking of main perceived barriers to bicycle use

and better-quality cycling conditions. Road safety improvement is identified as the most relevant incentive, mentioned by 84.1% of respondents, followed by the improvement of cycling infrastructure, indicated by 65.9%. Secure parking facilities are also positively perceived, although with lower intensity, while financial incentives appear less important than infrastructural and safety-related measures.

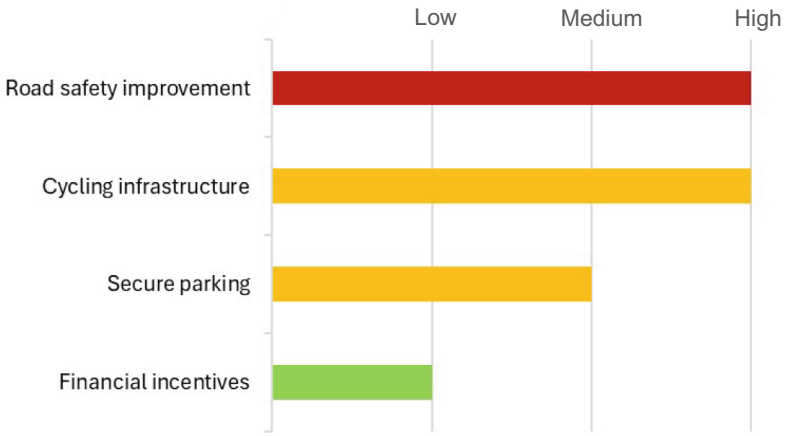

Fig. 5. Perceived incentives to increase bicycle use

Beyond the basic barriers and incentives, the survey also provides useful indications on attitudes toward technological innovation in cycling. Awareness of integrated bicycle technologies is split, with 50% of respondents declaring familiarity with such solutions and 50% reporting no prior knowledge. Among the proposed technologies, the most

appreciated are those directly associated with safety and trip support, especially collision-detection radar systems (75%) and GPS/navigation tools (60.7%).

However, this positive attitude does not automatically translate into a strong willingness to pay. Most respondents express interest in smart technologies only under conditions of economic affordability: 48.2% report being willing to spend up to €200 more for a bicycle equipped with such systems, while overall about 80% consider technological innovation a potential incentive only if associated costs remain accessible.

These findings indicate that the main constraints on cycling are associated more with infrastructural and safety conditions than with individual or purely economic factors. Additionally, the survey suggests that technological innovation may support cycling uptake, but only as a complementary factor within a broader context of safe, continuous and attractive cycling environments.

5 Discussion on Integrated Bikeability Assessment

The integrated assessment combines the spatial and perceptual dimensions discussed in the previous subsections in order to evaluate whether the current and planned cycling system in Catania corresponds to the conditions that users identify as necessary for bicycle use. Infrastructure, environmental context, and user perception are therefore interpreted jointly, so that bikeability can be examined as a composite urban condition rather than as a simple matter of route provision.

A first point concerns the relationship between the strategic vision outlined in the Biciplan and the cycling conditions currently observable in the study area. The plan proposes a broader and articulated cycling system, organized around hierarchical logic aimed at improving safety, connectivity and territorial coverage. This reflects an effort to move beyond isolated interventions and to frame cycling infrastructure as part of a wider metropolitan mobility strategy. However, the current spatial structure remains fragmented, with existing routes mainly concentrated in the central urban area and several segments disconnected.

Therefore, the transition from the current network to the planned one cannot be considered as a simple increase in route supply. Although the Biciplan expands territorial coverage, the practical value of the network depends on how continuity is achieved within the urban fabric, where daily trips are most likely to begin and end. The stronger emphasis on metropolitan and extra-urban continuity leaves some urban connections less clearly defined, even though these segments are pivotal for everyday cycling. In a context where bicycle use is still limited, local discontinuities may reduce the actual usability of the network even when the plan appears spatially more extensive.

A second point concerns the environmental dimension of bikeability. The spatial distribution of vegetated areas reveals a marked imbalance between the dense urban core and the more peripheral or peri-urban parts of the study area. Larger and more continuous vegetated surfaces are found mainly outside the urban fabric, whereas the central parts of the city show a more limited and fragmented presence of green areas. The sectors in which cycling demand is potentially higher do not coincide with city areas offering the most favorable environmental conditions. Even where cycling routes already exist, or are planned, the surrounding landscape may not provide a comfortable, attractive, or climatically favorable setting for daily cycling.

The survey evidence is coherent with this spatial reading. Cycling still plays a marginal role in daily mobility, while private motorized modes continue to dominate. Respondents identify traffic danger, lack of adequate cycling infrastructure and unsafe interaction with other road users as the main barriers to bicycle use. By contrast, improvements in road safety and cycling infrastructure are considered the most effective conditions for increasing bicycle uptake. Low bikeability level in Catania is therefore linked not only to the objective structure of the network, but also to safety, continuity, and comfort.

The comparison between spatial and perceptual evidence points to a clear mismatch. Planning documents describe a cycling system that is more connected, safer and more comprehensive than the existing one. The areas where cycling could be most relevant for daily mobility, however, are still characterized by fragmented infrastructure, limited environmental quality and low perceived safety. Bikeability cannot therefore be reduced either to the presence of cycling routes or to the planned extension of the network. It depends on the relationship between infrastructural continuity, environmental quality and how cycling conditions are perceived by users.

The case of Catania shows that improving bikeability in high-motorization urban contexts requires more than the network expansion. Infrastructure provision remains necessary, but its effectiveness depends on the creation of continuous and intelligible urban routes, on safer traffic conditions in the areas of greatest potential demand and on a better quality of the cycling environment. The integration of green infrastructure within cycling planning may represent an environmental enhancement measure, but also a relevant component of more attractive and user-oriented cycling policies.

A multidimensional reading of bikeability makes it possible to identify not only where cycling infrastructure could be embedded in conditions that can realistically support bicycle use. This point is especially relevant in cities where cycling is still underdeveloped and where the main challenge is not simply to build infrastructure, but to make cycling a realistic, safe and attractive mobility option.

6 Conclusions

This study proposed a multidimensional framework for assessing urban bikeability by integrating spatial evidence and user perception, with application to the case of Catania. The analysis combined three complementary dimensions: the configuration of the current and planned cycling network, the distribution of vegetated areas as a proxy for environmental quality and survey-based evidence on users' perceptions related to cycling conditions.

The main contribution of the study lies in the development of an integrated analytical framework able to combine heterogeneous sources of evidence in order to interpret bikeability as a multidimensional concept. Furthermore, its replicability to other case studies can allow to improve safety and sustainability of the sector. Rather than reducing bikeability to infrastructure provision alone, we consider the interaction between infrastructural, environmental, and perceptual dimensions. This makes the methodological approach particularly suitable for contexts where detailed georeferenced data are not fully available, but where planning documents, cartographic information, and user-based evidence can still be jointly interpreted.

From an empirical perspective, the case of Catania highlights a clear mismatch between the cycling system envisioned by planning strategies and the conditions currently experienced by users. From the spatial analysis emerged a fragmented and spatially concentrated existing cycling network, mainly located in central urban areas, while the Biciplan proposes a broader and more connected system at the metropolitan scale. In parallel, the analysis of vegetated areas showed an uneven environmental pattern, with more extensive and continuous green coverage in peripheral and peri-urban zones and a more limited presence in the dense urban core.

The perception-based findings further reinforced this interpretation. Survey results indicate that cycling is still marginal within daily mobility patterns and the main barriers to bicycle use are related to traffic danger, inadequate infrastructure and unsafe interaction with other road users. Conversely, respondents identify improvements in road safety and cycling infrastructure as the most effective conditions for increasing bicycle use. These findings suggest that bikeability in Catania is constrained by the limited continuity of the cycling network and by broader environmental and perceptual conditions.

These results have relevant policy implications for planning strategies. In high-motorization contexts such as Catania, expanding the cycling network is necessary but not sufficient. Planning strategies should also address the quality of the urban environment in which cycling takes place, improve safety conditions and reduce the gap between planned infrastructure and perceived usability. Thus, the integration of green infrastructure within cycling planning may represent an important opportunity to enhance the attractiveness, comfort and overall effectiveness of cycling routes.

Despite these contributions, the study also presents some limitations. The survey sample is relatively small, which can limit the generalizability of the perception-based findings. and the spatial analysis is based on a qualitative interpretation of the cycling network, due to the lack of a fully georeferenced analytical dataset suitable for advanced network processing.

In this regard, future research could extend the proposed framework by incorporating more detailed and fully georeferenced datasets in order to calculate quantitative GIS-based indicators of bikeability, such as connectivity measures, accessibility indices, and indicators of spatial proximity between cycling infrastructure and environmental resources. Moreover, comparative analyses across different urban contexts could provide further insights into how the interaction between infrastructure, environmental quality, and user perception varies across cities with different mobility patterns, planning traditions, and climatic conditions. Such developments would support a broader validation of the framework and strengthen its transferability to other high-motorization urban contexts.

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Artificial Intelligence and New Urban planning: Interpretative Paradigms and Impacts on Urban and Territorial Systems

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Abstract. Given the current widespread development of Artificial Intelligence (AI), it is now necessary, in all fields of human activity, to study in depth the characteristics, reasoning processes, and actual potential of different Large Language Models (LLM) in order to determine and verify their effective support for humans. Relying uncritically on digital agents can lead to incorrect decisions or outcomes that harm the community. The uncritical "admiration" of the "plausible" answers provided by artificial reasoners may generate new, altered, and potentially dangerous relational dynamics, as observed in the growing use of affective chatbots. In this period of change, scholars from every research field, including experts on urban phenomena, are called to promptly undertake three activities: to understand and formalize the impacts of AI on urban and territorial systems by redefining the systemic interpretive paradigm and evaluating potential transformations of the subsystem components; to prefigure a new governance process for urban and territorial transformations, considering the appropriate and verified adoption of AI in the individual phases and in the prefiguration of planning scenarios for anthropogenic settlements; to promptly analyze the "weights" and the energy-ethical, and socio-environmental implications of the new data-processing megastructures (data centers) indispensable for the development of LLMs. Along these three lines of reflection, comparisons and debates among urban planners should be organized, in light of the transformations already underway in many territories worldwide. The paper offers reflections on these three topics that contribute to defining a new dimension in the management of urban and territorial transformations, in which the human agent appropriately adopts, drives, and validates the support that new digital agents and artificial reasoners can provide to the discipline.

Keywords: Artificial Intelligence · New Urban Planning · Data Centers

1 AI and the Management of Territorial Transformations

Territorial governance in Italy is currently at a critical juncture, urgently requiring updated methods and procedures to handle urban and regional shifts. The Italian conventional urban planning, which relies on rigid, long-term prescriptive documents introduced by a regulatory provision that is often outdated, is no longer adequate. It simply

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cannot keep pace with the rapid socioeconomic, climatic, demographic, and geopolitical changes defining our current era. A territory is no longer just a spatial blank slate where planners assign functional land uses and try to guess at unpredictable future developments.

Rather, it is a complex, dynamic system that needs careful steering toward sustainable development, remaining mindful of available resources. Cities which serve as the testing grounds for humanity's future are dealing with simultaneous and often compounding forces that would have been unimaginable just a few years ago. Armed conflicts, climate-induced disasters, migration waves, rapid population ageing, and the restructuring of urban economies are driving these new dynamics. In Italy, these shifts carry a particular weight. Against this backdrop, AI acts as a massive catalyst for change.

The rise of AI is not merely a technological upgrade; it marks a fundamental ontological shift. Italian researchers and planners must quickly understand this change and figure out the best ways to adapt to it. Recent literature on AI's role in territorial governance (Fusero, 2024; Fistola and La Rocca, 2025) emphasises the need to deliberately weave AI into urban planning. However, this means we must rigorously test the actual benefits these artificial reasoning systems can offer in practice.

Used correctly, these digital agents can play a decisive, active role in forecasting. They have the potential to contribute across all stages of the planning process, helping to navigate environmental complexity while opening up new avenues for democratic involvement in urban decision-making.

Academic discussions point to the need for a fresh methodological framework (Zingariello & Fistola, 2025). Instead of passively accepting AI outputs, planners should use the technology to build dynamic scenarios that fully acknowledge systemic complexity (Batty, 2018). Today, we have access to massive, multi-layered datasets describing human settlements. The challenge lies in extracting real meaning from this data, which is absolutely essential for prying open the algorithmic "black box" and ensuring both transparency and accountability.

2 Three Tasks for Urban Planners

Innovation Technology (IT) has always represented a driver for the development of human settlements (Batty, 2018).

The history of human evolution can be easily segmented by considering the technical and technological advancements that have progressively allowed us to experience increasingly complex activities.

In some cases, technological innovation has produced true "entropic watersheds," exponential advancements in a very short amount of time: from the Egyptian seed drill to the Internet network.

In general, it can be stated that technology represents a complexity generator in social systems that also fuels the progress of human settlements

Recently, the ability to use technologies capable of ensuring relationships and communication flows in the city was vital, as in the case of the global Covid-19 epidemic (Fistola & Borri, 2020), which transformed urban and metropolitan aggregates into ghost

towns due to the lockdown extended to all inhabitants, but nevertheless allowed almost all human activities to be carried out

Today, digital network infrastructures represent the true nervous and lymphatic system of the city, which bases a large part of its economy on the production, processing, and exchange of data.

The birth of the smart city, although initially driven by large digital multinationals, is strictly connected to the exchange of data in urban contexts and the birth of the Internet of Things (IoT).

Only a few years ago, we witnessed the latest anthropic watershed, which will characterize the entire global economic structure of the near future. The acceleration induced by the spread, in November 2023, of the first Artificial Intelligence Large Language Model produced a disruption in all areas of human activity and, consequently, also on human action and interaction in the city. Thanks to the use of artificial intelligence, the organization of work, economic processes, social relations, and more are progressively transforming.

Scholars of urban phenomena, urban planners, and city administrators have always had to chase technological change, as in the case of the smart city, elaborating ex-post methods and procedures for IT adoption (Fistola & Ronsivalle, 2017).

The capillary spread of AI and the sudden diffusion of this innovation shorten adaptation times, requiring a total change in perspective and the elaboration of new dimensions of action. Modern urban planners are therefore called to a complex commitment that primarily involves the in-depth study of new LLMs and their operational processes.

The acquisition of solid and dynamic knowledge of the new technology must allow for the appropriate adoption and inclusion of AI in the methods and governance processes of territorial transformations, including those determined by AI itself (Fistola & Zingariello, 2025). In summary, considering the reflection this study intends to propose, it can be stated that urban planners must commit to three main tasks:

- Identify, choose, and/or reconsider the interpretative paradigms of urban transformation that consider the characteristics and potential of AI.
- Understand how to effectively adopt and integrate AI in the processes of prefiguring and governing urban development.
- Evaluate the new functional weights generated by physical infrastructures, and in particular the substantial use of (ecosystemic) resources necessary for training and maintaining LLMs across various urban components.

This last topic, which deserves specific and more extensive reflection, informs a task that urban planners must take on today, which is attributable to the appropriate territorial location of data centers (DCs). This commitment is of significant importance, also considering the enormous funding supporting the development, updating, and spread of new LLMs all over the world.

3 Task 1: The Systemic Approach. A New Dimension of an Old Way to Construe the City

The need to understand the new dynamics of urban systems, determined by the significant phenomena characterizing their current historical phase, has led to a new formulation of "systems thinking" (Fistola and Pennino, 2026). Today's city can be likened to a dynamic and complex system for which it is necessary to develop a control methodology to appropriately guide its evolution.

Being a complex system, it must necessarily involve continuous evolution and transformation, which places it among chaotic systems (Packard, 1998). In other words, the city can be interpreted as a dynamically complex system that evolves in space and time, requiring the preparation of appropriate governance procedures for transformation and development that are attentive to sustainability and compatibility with available resources. This definition stems from many years of study in the social sciences and complex systems (Miller & Page, 2007). By adopting a systemic approach, it becomes possible to model the components of the urban system and their active relationships, outlining a multidimensional organizational framework for urban planning. The need to adopt new paradigms for interpreting urban processes derives, as emphasized, from the observation of the substantial failure of the models adopted so far for the organization, management, and planning of human settlements.

As has happened in many fields of science, particularly in physics with quantum mechanics, considering the possibility of a different operating principle for phenomena, going beyond canonical laws, can open new dimensions in urban research. Briefly, it can be stated that cities can be seen as complex systems of interactions between people, infrastructure, economy, and environment. These systems exhibit non-linear dynamics and multiple, sometimes overlapping, emergent behaviors that make it difficult to predict their evolution over time, which is the main activity of urban and territorial planning.

The city can therefore be studied, interpreted, and probably completely assimilated into a complex system, not because of its foundational condition, but as a biotope of complex systems, a habitat of connected structures, and a settlement space for dynamic relational organizations. Adopting the systemic approach alongside complexity theory to govern urban development in a sustainable manner and compatible with available resources represents one of the most interesting possibilities currently offered to scholars of human settlement sciences. As Tullio Tinti points out: "Complexity theory is the multidisciplinary study of complex adaptive systems and the emergent phenomena associated with them" (Tinti, 2011).

Complex systems are chaotic and generally dissipative systems, in the sense that they use and dissipate energy. In this regard, I. Prigogine's reflection on the relationship between city and countryside appears illuminating. In his text entitled *The Laws of Chaos*, he writes: "The simplest example of a dissipative structure that can be evoked by analogy is the city. A city is different from the countryside that surrounds it; the roots of this individualization reside in the relationships it maintains with the adjacent countryside, if these were suppressed, the city would disappear" (Prigogine, 2008). Considering the city as a dynamically complex system (Papa et al., 2021), it is possible to identify a certain number of components and interacting subsystems (Fig. 1). The adoption of this paradigm leads to the ability to evaluate: on the one hand, the impacts that AI

produces on the subsystems and to understand ex-ante how it causes their transformation; on the other, how AI can contribute to formalizing the interactions that are generated between the different subsystems and their components, succeeding in defining urban transformation scenarios more adherent to the future urban structure.

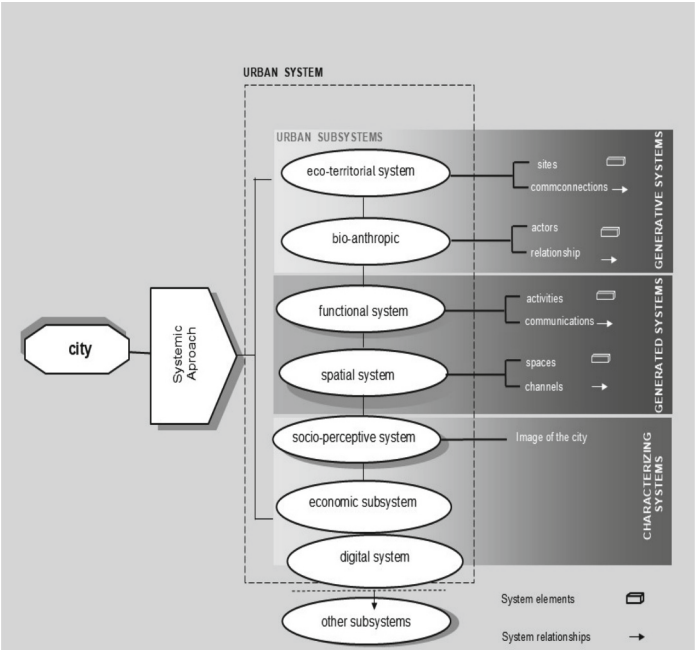

Fig. 1. The city interpreted as a system composed of subsystems

4 Task 2: AI in the Managing Cycle of Territorial Transformations

The need to govern the sustainable development of the urban system over time and space leads to adopting a cyclical process derived from systems control, used in cybernetics. This process can be divided into three fundamental phases, with a final feedback step represented by monitoring the system's evolution: knowledge, decision, and action.

In the knowledge phase, AI and Machine Learning systems revolutionize the acquisition and analysis of spatial and socio-economic data. Automated analysis allows for the rapid production of urban economy reports and the decoding of functions established within the territory. Through the processing of demographic big data and the use of advanced pattern recognition models applied to satellite imagery and point clouds, the automatic recognition of buildings, trees, and infrastructure is now possible. This is accompanied by crucial predictive analyses, such as estimating urban growth, simulating climate impacts, and forecasting socio-demographic dynamics.

In the decision phase, generative and evaluative models support development strategies. AI enables the automatic definition of transformability maps by integrating complex

data regarding territorial constraints, as well as supporting scenario simulations through the use of Urban Digital Twins (UDT).

Finally, in the action phase, computational power is translated into implementation. AI facilitates comparative analysis to select the best development scenario in strict compliance with political-administrative guidelines, assisting the planner all the way to defining technical standards and automatically drafting urban regulations. This is an interesting aspect regarding assistance in drafting regulatory provisions, made possible by training large language models on local regulatory corpora. This leads to a faster definition of technical implementation rules and the automated generation of environmental impact assessment matrices as well.

The behavior to maintain with the digital agent plays a fundamental role in the widespread adoption of artificial reasoners in the territorial transformation governance process. Enthusiasm for the machine's prefigurative capabilities must be tempered by a solid methodological foundation, which must precede any operational implementation in professional practice. To briefly describe the interaction between the human agent and the digital agent, the Choice-Dialogue-Check (CDC) cycle was introduced within the broader Urban Territory Transition Model (UTTM). This cycle involves three phases containing a series of actions that the urban planner must implement in their "relationship" with the artificial reasoner.

Choice: in this initial phase, the urban planner must select, after having previously learned and studied the vast and constantly evolving landscape, the LLM most suited to the activity they are undertaking and the purpose they intend to achieve. Therefore, a near LLM (vertical model) must be identified, whose knowledge domain is specifically characterized by descriptive tokens and variables of urban planning activity (Fig. 2).

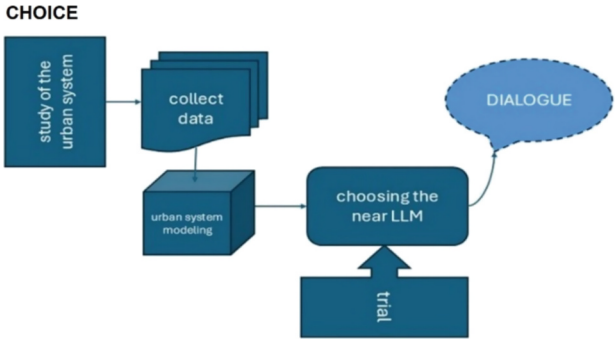

Fig. 2. The steps that make up the choice phase

Dialogue: this is the phase of dialectical interaction with the machine. This phase branches out into three sub-phases: profiling, prompt construction, and guiding the chain of reasoning. There is no space here to describe these sub-phases in detail, but suffice it to say that in the first, the reasoner is told the role it must assume in providing answers; in the second, questions are constructed by specifying what must and must not be provided; in the third, the machine's reasoning is progressively guided by considering the chains of thought developed and the answers progressively provided (Fig. 3).

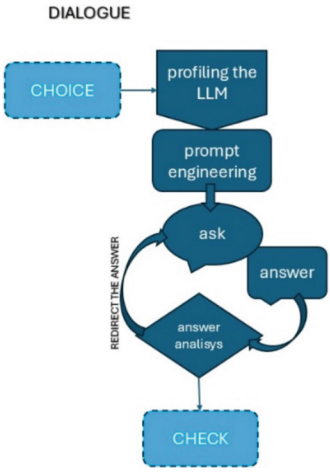

Fig. 3. The steps that make up the dialogue phase. The "Choice" and "Check" blocks represent the input and output of this phase

Check: this final phase informs the rigorous human validation of the provided answers, distinguishing the true from the plausible and identifying and declaring any hallucinations and biases they may contain (Fig. 4).

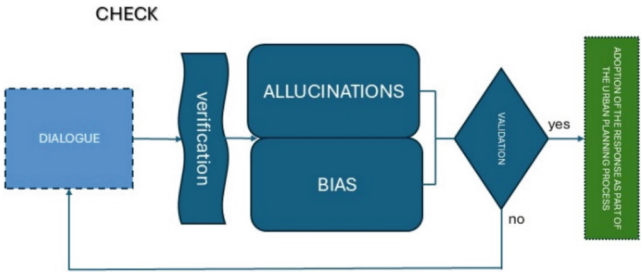

Fig. 4. The phase of checking the oriented responses provided by the artificial reasoning LLM. The green block represents the end of the cycle

It seems appropriate to point out that the use of AI can also effectively intervene in the final stages of the governance process for urban and territorial transformations, particularly in the phase of communication and support for understanding the plan. Already in the decision-participation phase, by operating in an ethically evaluable manner, it is possible to consider using chatbots to gather collective sentiment in order to formalize the emotional perceptions of citizens, transforming them into useful data to guide public decisions in a more inclusive way. However, this requires strengthening the public governance of urban algorithms, which must rest upon three pillars: the traceability of algorithmic decisions, continuous independent audits, and democratic public access to datasets and predictive models. Regarding communication, the creation of digital agents capable of conversing with the population to describe the forecasts of the governance

tool is an active field of research (Holland & Miller, 1991) and represents one of the activities developed with commitment by Italian researchers for many years now (Fig. 5).

Fig. 5. An initial experiment from 2010 on the creation of virtual agents
Source: Fistola, R. (2010). "Virtual Agents for Urban Planning Communication".

5 Task 3: AI Training Factories

The ethical and energy issue connected to the spread of AI represents perhaps the main problem of the new technology, which also produces significant impacts on the territory and the manifestation of new and justified forms of the NIMBY syndrome among populations. The energy demand and water consumption for the operation of Data Centers (DCs), the nerve centers of the new digital society, present worrying figures. In many countries around the world, enormous investments are driving the creation and establishment of these new territorial infrastructures, sometimes outside of any locational rules.

We are witnessing a rapid phenomenon of polarization of investments with a massive concentration of capital towards areas with ultra-resilient power grids. In 2026, it is estimated that data centers will absorb about 2% of global electricity (TTMS, 2026), creating tensions on local tariffs for citizens. In the United States, where there are approximately 4,000 DCs, the price is also borne by local communities, as they are potentially public infrastructures. In this way, the price of energy rises, the community pays for it, but the extra energy is used by AI companies. In a sense, the economic value produced

through the exploitation of the territory's material is transferred, in an immaterial way, through data, elsewhere. An indicative example is the current commitment of META in Louisiana, where it is building a $3 billion power plant for the needs of its DCs.

In Europe, different experiences can be found. In Ireland in 2023, DCs consumed more energy than all the homes in the nation (Coin, 2025). In Italy, referring to the research conducted by the Polytechnic University of Milan, there are currently about 200 data centers, almost all located in the northern part of the country. In the Milan metropolitan area alone, there are 33 active data centers, equal to 67% of the total 49 in Lombardy. These are infrastructures distributed across 32 municipalities in the Milanese metropolitan area. These infrastructures, present in the Milan area, alone represent about 68% of the installed capacity at the national level, equal to approximately 414 megawatts.

The location of a data center can no longer be dictated solely by land market logic or proximity to fiber optic backbones but must respond to criteria of "territorial symbiosis". The data center must become an energy donor (waste heat) for district heating or adjacent industrial processes, transforming a negative externality into a circular resource. The territorial location criteria for DCs must be codified within national urban planning regulations and adopted by regional legislation. It is not difficult, beyond specific technical and disciplinary matters, to indicate a series of actions that must inform the locational decision of new energy infrastructures:

Use abandoned industrial areas or defunctionalized sites that avoid land consumption and can potentially utilize already existing infrastructures and underground services. Consider territories with low mean annual temperatures to drastically reduce the need for active cooling and the consequent water consumption. Plan for synergistic district heating systems, favoring their location near urban or agricultural districts that can reuse the waste heat. Emerging examples in 2026 include data centers in Sweden that heat entire residential areas through thermal recovery.

Utilize alternative energies by establishing and connecting the DC directly with wind and/or photovoltaic plants in order to lighten the energy demand from the public grid or even act as a storage battery to stabilize the grid during peak times. Locate DCs in areas where it is possible to use treated wastewater or zero-consumption closed circuits. Similarly to the location techniques for plants with high territorial vulnerability (Fistola & La Rocca, 2017), it is important to map the infrastructures that host sensitive population groups, such as schools or hospitals, and consider the acoustic impact and potential electrosmog. Furthermore, analyzing the local economy allows one to foresee induced employment and any potential synergies with energy communities.

A brief concluding note is necessary to point out two contiguous fields in which research is developing interesting projects. The first concerns the possibility of developing Open Source LLMs open to collective use. In this context, the European project Apertus should be noted; a European LLM developed in Switzerland and trained using the Alps supercomputer cooled by the lake's temperature, which is totally open source regarding the data used to train it and respects European AI regulations. It was created as a digital public infrastructure for researchers, businesses, and citizens, offering an ethical and transparent alternative to closed US or Chinese models.

Apertus is a large language model officially launched in September 2025 through the collaboration of the main Swiss scientific institutions: the EPFL, the ETH of Zurich,

and the Swiss National Supercomputing Centre (CSCS). The main features of this LLM are: Total Transparency: unlike many models defined as "open source" that release only the final weights, Apertus is a completely open model. The code, model weights, and training procedures are made public.

Size: the model has 70 billion parameters, a scale designed to balance high performance and manageability compared to giants like DeepSeek (about 700 billion). Multilingualism: it is designed to be natively multilingual, covering over 1,800 languages, with a focus on data sovereignty and European cultural inclusiveness. The other area in which intensive work is being done is energy saving. In fact, to save energy, it is also possible to act directly on the algorithms through neuromorphic computing, designing new computer architectures equipped with transistors that save energy by behaving like neurons and modifying themselves according to light, rather than electrical, stimuli they receive.

Moreover, so-called “in-memory computing”, without data transfer, saves a lot of energy. The possibility of using live neurons in computers, the so-called bio-chips, is the current frontier. The biological computer that uses neuronal processing for computing consumes much less energy.

6 Conclusions

AI is an achievement of technological advancement towards which we must not adopt an attitude of excessive concern, considering that the positive or negative use of technology is always a prerogative of human free will. It is essential that territorial governance maintains human supervision (Human-in-the-loop) to validate that the proposals generated by AI are consistent with the public good and not just with the optimization of a single parameter. In any case, it must be strongly reiterated that AI must be studied, ethically adopted, and taught to new generations, highlighting its potential and risks. In China, 200 billion dollars have been invested in AI. Thanks to this funding, in 2024 AI is being introduced and taught as early as middle school, and consequently, 12-13-year-old students are then able to program and design robots with AI.

The conscious adoption of new technologies can lead to envisioning a dynamic and integrated process for governing territorial transformations, warding off the risk of a dangerous automated urban planning, alongside the emergence of Urban Planning Service Companies, which are already spreading in Italian territories hosting small municipalities.

Today, it is necessary to consider the territorial impacts of the new power and survival infrastructures of AI on the territory and to pay the utmost attention to the ethical and energy implications of digital transition. These new places of production, for which mature formalizations of "territorial weight" do not exist, present massive energy consumption and significant physical impacts that the urban planning discipline must be able to govern. In conclusion, it is worth emphasizing and acknowledging that this paper focuses primarily on a theoretical reflection on the relationship between artificial intelligence and urban planning, without referring to empirical processes or real-world case studies. However, the paper aims to highlight the current lack, in this specific field, of a theoretical framework that could serve as an initial roadmap for urban planners. In other

words, it seems necessary to define a framework for reflection that can avoid (as has already happened in the case of the Smart City) chasing after and refuting definitions developed in contexts far removed from scientific research. Future research must, in any case, focus on the empirical validation of the proposed methodology, also with the aim of defining a new dimension of city and territorial governance. Between mind and algorithm (Zetti & Martino, 2025), the future of urban systems will depend on the ability to understand and consciously adopt AI not as an infallible oracle, but as a powerful tool for exploring the complexity of the contemporary city and prefiguring sustainable developments for the future structures of human settlement.

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Rethinking Inner Areas Through AI: Hybrid Approaches for Inclusive Planning

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Abstract. This paper critically examines the implications of Artificial Intelligence (AI) for inner area regeneration, serving as a vital testing ground for AI's contradictions in territorial planning. As non-neutral technologies, AI systems prioritize quantifiable data, often rendering invisible those local resources that resist simple encoding. In these regions, territorial value is deeply rooted in relational, cultural, and ecological dimensions that risk being overlooked by quantitative models. As spatial planning increasingly relies on AI-driven predictive models, there is a danger of standardizing territorial narratives and flattening local specificities. Moreover, predictive models trained on historical data often perpetuate existing inequalities. Inner areas face a "double disadvantage": scarce, low-quality data produces distorted, self-referential forecasts that reinforce marginalization. To counter these risks, engaging local communities in dataset creation and the rediscovery of cultural specificities is essential.

Drawing on the PRIN INSITE project, this paper proposes Hybrid Intelligence (HI) practices where AI systems and local knowledge coexist through participatory processes. The objective is to shift territorial development from an efficiency-centric model toward an inclusive, contextual paradigm that accurately interprets the unique potential of inner areas.

Keywords: Inner Areas · Artificial Intelligence · Hybrid Intelligence

1 Introduction: Planning beyond Efficiency

Inner areas act as testing grounds in the face of paradoxes arising from the use of Artificial Intelligence (AI). These regions should no longer be viewed simply as "peripheries" to be explored, but rather, as generative sites for redefine the interaction between technology, community, and cultural heritage. They are complex regions that hide unique networks of relationships, cultural heritage and ecological values, and underneath their surface edges deep human, historical and natural connections, i.e. the immaterial context that shapes their essence (Italy's National Strategic Plan 2021–2027).

This perspective permits us to shift the focus from the shortcomings of simple quantitative indicators to a qualitative paradigm in which relational networks acknowledge cultural heritage and ecological diversity as strategic resources in modern spatial planning. The real challenge is to overcome a single urban development model (Fistola &

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La Rocca, 2024), abandon a single functional efficiency goal, and explore a "situated" approach in order to preserve the identities of these regions from homologation.

Indeed, in inner areas intangible heritage represents their own resilience force. Currently, AI-enabled planning tends to be limited to optimization logic (for example maximizing agricultural production through land use models). This excessive focus on quantitative data threatens to marginalize or even erase the entrenched cultural heritage present in inner areas (Fistola & La Rocca, 2025). In the age of AI, a rethinking of urban planning is required to move from data and efficiency fascination to Hybrid Intelligence (HI) models, combining algorithmic intelligence with local knowledge.

Moving from these considerations, this study deals with the possibility of drawing new research paths for regional planning and territorial transformation government. The central point is a critical but constructive analysis of the potentialities that AI offers being aware about the loss of information that is inevitably associated with a digital process, however sophisticated. The final proposal of the study, thus, consists of investigating the coexistence between the perfection of the AI model and the nuanced perfection of the social aspects that emerge in a participative process.

This study contends that the "productive imperfection" of human decision-making remains indispensable for capturing the socio-cultural nuances that algorithms, by their very nature, are designed to smooth away, proposing a hybrid method to move toward a more resilient and authentic urbanism.

Driven by the goal of bridging the gap between algorithmic precision and human agency, this paper is structured in three main parts. In the first part, a theoretical framework about the concept of hybrid intelligence is establishes, both to situate the study within the contemporary debate on AI, and to support a caution approach to the "technocentric" paradigm.

The second part discusses the methodologic approach developed within a previous research project (INSITE), here adapted to capture the nuances of human-computer interaction using participative living lab aimed at involving local communities in the design for a territorial development plan. The third part describes the main results relating to hybrid fruition methods for places representative of specific territorial contexts.

Conclusions highlight that the proposal of this study should be understood as a path of research that still needs to be fully explored, but which aims to underline the need for a precise methodological choice in using AI to support territorial planning, particularly in inland areas.

2 Theoretical Framework

The concept of Hybrid Intelligence (HI) emerges as a critical and operational perspective capable of overcoming the dichotomy between automation and the local dimension, proposing a form of cooperation between artificial intelligence and human intelligence.

2.1 Hybrid Intelligence for Inner Areas

In the inherently fragile contexts of inner areas, HI can play a strategic role in rebalancing the asymmetries produced by predictive models that tend to prioritize what is measurable

and quantifiable in data, at the sacrifice of the relational, cultural, and environmental dimensions of the territory (Zingariello & Fistola, 2025).

Within this paradigm, by moving beyond the conception of AI as merely a technical tool preparatory to the automation of planning processes, we can recognize a dual configuration of artificial intelligence, particularly significant in a dialogic perspective between AI and citizens.

On the one hand, AI can serve as an information interface that is, as a tool capable of translating the systemic complexities of a territory that, especially in non-expert contexts, otherwise preclude access to territorial knowledge. The informational dimension allows residents to interrogate and interpret information related to their territory. In this sense, AI helps reshape the relationship between citizens and planning, bringing the latter closer to a dialogic and shared process.

From another perspective, AI can be seen as a facilitator of participatory processes, playing an active role in structuring and reporting local feedback. In this second configuration, artificial intelligence does not merely provide answers but actively contributes to the creation of participatory contexts by initiating and guiding conversations, bringing forth a variety of viewpoints, identifying relevant insights for planners, and highlighting user contributions and concerns that might otherwise go unheard. This is particularly relevant in inner areas, where the scarcity of structured data can be compensated for through the production of local data, generated directly by the communities. The mediation between these two dimensions can serve as an example of the definition and application of HI, in which human intervention manifests itself both in the design of the knowledge domain, with the informational dimension structured to make sources explicit and avoid uncertainties in the information provided, and through the collection and systematization of user feedback, which, when made available to planners, enables the participatory process to be activated.

These reflections are directly linked to another highly topical issue concerning the tension between over-trust and under-trust in artificial intelligence systems (Figoli et al., 2022), a crucial factor for the efficiency of participatory processes mediated by digital technologies. Excessive trust (over-trust) can lead both citizens and planners to attribute excessive authority to AI, uncritically accepting interpretations or directions emerging from conversational interactions. This risk is particularly relevant in the contexts of inner areas, where the lower availability of data and technical expertise among citizens can amplify trust in AI, reinforcing dynamics of decision-making delegation.

At the same time, a condition of widespread distrust (under-trust) can compromise the effectiveness of participatory tools limiting the involvement of local actors and reducing the availability to share considerations and points of view.

To overcome these dynamics, the conceptualization of AI as both an informational interface and a catalyst for participatory engagement can foster the emergence of "relational trust". Unlike traditional, *a priori* trust, this dynamic form of confidence can be continually renegotiated through the synergetic interaction between artificial and human intelligence. The informational conversation between citizens and AI allows, in fact, for the testing, verification, and questioning of the information produced, favoring a continuous process of calibrating trust. At the same time, the participatory facilitation

function helps shift the focus of trust from the technological system alone to the citizens themselves, recognizing their active role in the production of new information.

Based on insight from the research project INSITE (www.insiteprin2022.org), work has begun on the development of an AI-based chatbot (named "Heidy") designed to perform the dual function of an information interface and a facilitator of participatory processes.

3 Methodology: from the INSITE Project toward the Hybrid Intelligence Application

Methodologically this study represents the evolution of a long-term research trajectory initiated within the project INSITE (INtegrated Shared knowledge: from geo-paleontological herItage to present TErritorial challenges) aimed at the definition of a multidisciplinary protocol for the knowledge and the enhancement of cultural heritage in inner territories in Campania (South Italy). By integrating geo-paleontological data, structural vulnerability indices, and intangible values, INSITE established a robust, expert-led knowledge base aimed at identifying "hidden" territorial resources.

Figure 1 illustrates this continuity, showing how expert data is not merely stored but processed and returned to the community through a recursive loop of reciprocity. The methodology is structured into three sequential and interconnected levels, moving from the INSITE project input toward the definition of an inclusive planning process.

3.1 The Inputs of the INSITE Project

INSITE is a funded research project (PRIN 2022) whose main objective was to indagate the how geo-paleontological heritage could play as promoter for territorial regeneration in inner areas. The project particularly focused on two case study sites in Campania: the ichnosite known as "Ciampate del diavolo" (in Tora e Piccilli, CE), which preserves Pleistocene human and faunal fossil footprints; the paleontological site "Le Cavere" (in Pietraroja, BN), known to be the place where the first fossil sample of *Scipionyx samniticus* has been discovered. These two important sites for scholars and scientists remain practically unknown for non-experts and often for locals too. Both sites exemplify inner areas where exceptional scientific and cultural uniqueness coexists with territorial vulnerability, limited institutional capacity, and planning neglect, making them ideal contexts for examining the limits and possibilities of AI-assisted planning.

Thus, one of main objectives of the research was to involve local communities into a larger territorial revitalization design, starting from the assessment of the local territorial awareness and empowerment.

The project's structure integrated multiple targets (La Rocca & Amore, 2026) that can be summarized in:

- The definition of quantitative vulnerability and scientific relevance indices for defining the real enjoyability of the geosite also referred to the territorial context they were inserted into.
- The use of participatory techniques of "Living Lab" that involve local communities, government agencies and key stakeholders.

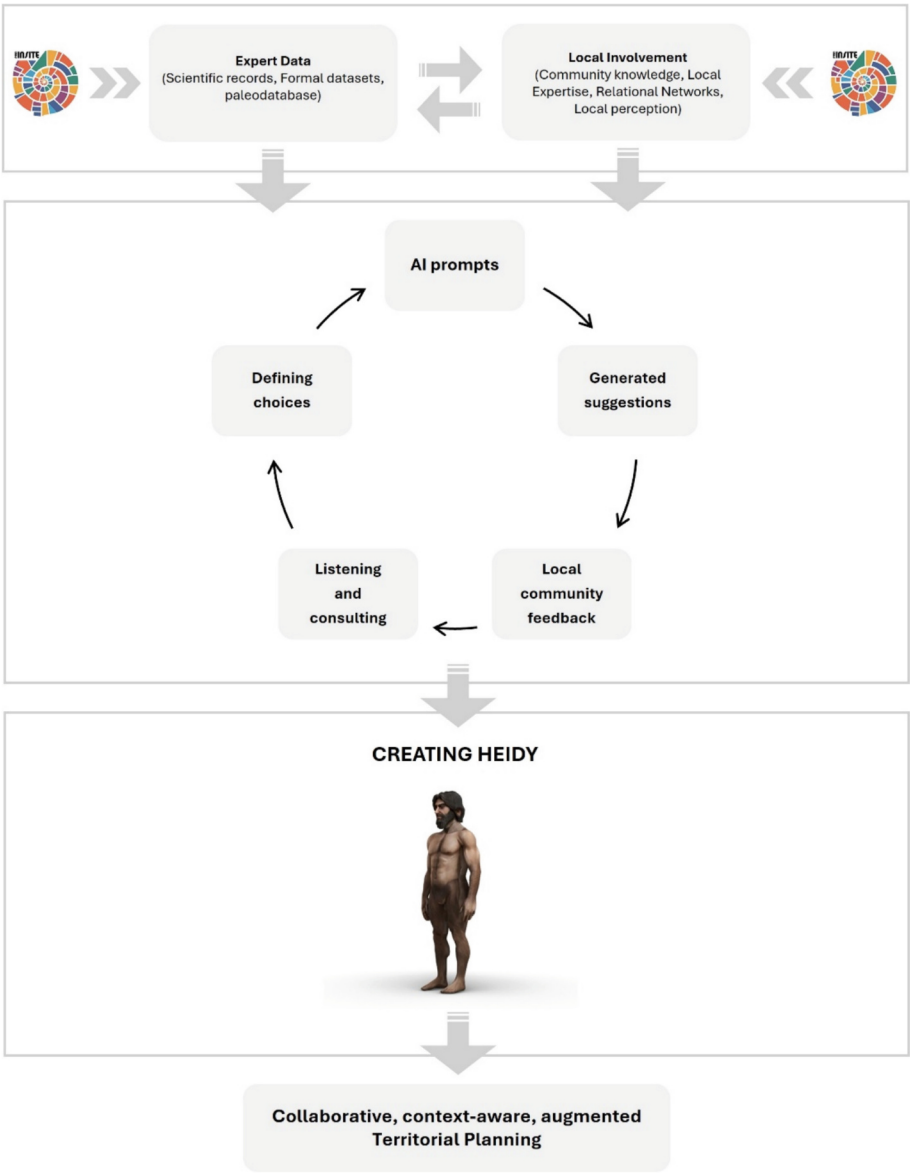

Fig. 1. The methodological phases of the study's development: in the initial phase, inputs derive from the research results previously developed in the INSITE project. The second phase indicates the information processing cycle aimed at building the "Heidy" prototype. The output of the process is the definition of a collaborative and inclusive planning process

- The design and the production of digital tools using augmented and virtual reality to propose innovative and captivated way to know and visit the geosites.

- The design of a Paleo-Cycle Path connecting the two sites and promoting other points of interest within the territorial context, exploring the possibilities for sustainable archaeological tourism and transportation.

In the framework of these targets, the whole project dealt with three main research questions:

- Epistemological: how AI systems can foster territorial knowledge, both for the local community's awareness and for the dissemination of this knowledge to a wider public.
- Spatial: how to overcome the marginalization by making "intangible" socio-territorial resources visible and transforming perceived limits into strategic opportunities.
- Processual: how HI practices can generate more inclusive and context-aware planning outcomes.

In this regard, the INSITE's approach can be intended as a proposal for a shift from exclusive expert data to inclusive shared knowledge, where Hybrid Intelligence serves as the catalyst for territorial empowerment.

Starting from the INSITE experience and focusing on the innovative proposal, the following sections describe the design process used for the development of an AI-based chatbot designed to perform the dual function of an information interface and a facilitator of participatory processes.

3.2 The Central Phase: the "Heidy" Chatbot as Preliminary Result

The design of the "Heidy" chatbot (named after *Homo heidelbergensis*) was thought to address both dissemination goals and those of actively engaging the public, thus assuming the dual role of an informational interface and a conversational facilitator.

The modeling of "Heidy" was the focus of the digitization activities carried out within the project INSITE. Based on validated scientific sources (Aidonis et al., 2023; Mietto et al., 2021), the modeling (and subsequent animation) of *Homo heidelbergensis* was carried out, in line, from an anthropometric standpoint, with the characteristics of the trackmaker of tracks A and B at the "Ciampate del diavolo" (Zingariello et al., 2026) (Figs. 2 and 3).

Augmented reality applications have already been designed within the project INSITE for *in situ* visualization – both static and dynamic - of the "Heidy" three-dimensional model, aligned with broader strategies for territorial valorization and knowledge dissemination.

Although the ongoing research objective is to evolve "Heidy" into an AI-driven avatar representing *Homo heidelbergensis*, its current iteration is configured as a Google Gemini GEM, primarily functioning as a text-based chatbot.

To evaluate the efficacy of the "Heidy" prototype, this study delineates two methodological aspects: *a)* the construction of the knowledge domain as a process of semantic delimitation and epistemic organization of content, and *b)* the assumption of role as a strategy for configuring the chatbot's identity.

3.3 The Construction of the Knowledge Domain

A non-specialized chatbot tends to produce generic and inconsistent responses; for this reason, the construction of an explicit and delimited knowledge domain was fundamental to ensuring the correct functioning of "Heidy". The construction of the knowledge domain was defined through an in-depth not automated interpretative framework to ensure epistemic accuracy. This process required a rigorous systematization and translation of INSITE's results into a structured knowledge base.

The documentation supporting the knowledge domain was organized into discrete information chunks, that is, autonomous units of knowledge, designed to be self- sufficient. Each chunk addresses a specific micro-query, ensuring internal coherence and independence from other chunks. Thus, the content structure follows a Question & Answer (Q&A) framework, organized into knowledge clusters such as:

- the strategic objectives and structural framework of the INSITE project;
- representative case studies and empirical research outcomes;
- prototyped digital tools and technological applications developed;
- educational and participatory engagement initiatives;
- dataset deriving from end-users surveys.

With regard to the final point on the list, in order to complement the scientific dimension with an experiential and context-specific component, the perceptions and assessments expressed by local users have also been incorporated into the knowledge domain; these were gathered and organized on the basis of responses to questionnaires administered throughout the project.

For each topic, multiple chunks have been prepared, not repetitive but capable of addressing the subject from different perspectives, to facilitate information retrieval and overlay processes.

Understanding how to structure the various chunks and optimize their accuracy is the key to improving the effectiveness of the RAG (Retrieval-Augmented Generation) system supporting the chatbot (Moreno-Cediel et al., 2026).

Within the RAG framework, the system retrieves the most relevant content from the knowledge domain and incorporates it into the response, ensuring contextual consistency and adherence to reliable and verifiable information.

The structure of the chunks was also subject to an iterative validation process conducted by the research team, aimed at verifying both their semantic consistency and their effectiveness in supporting the generation of responses. In particular, the content underwent an internal review to ensure its scientific accuracy and relevance to the project's objectives, and was tested through simulations of interactions with the chatbot to evaluate the quality of the responses produced. This process enabled the identification of any ambiguities, redundancies or gaps in information, allowing for the progressive refinement of the chunk structure.

Finally, in addition to the chunks, which are essential for a rigorous systematization of content, a large series of documents produced during the project activities was uploaded to further expand and consolidate the knowledge domain (Fig. 4).

All sources, in accordance with the principle of transparency, are cited by "Heidy" and shared with users.

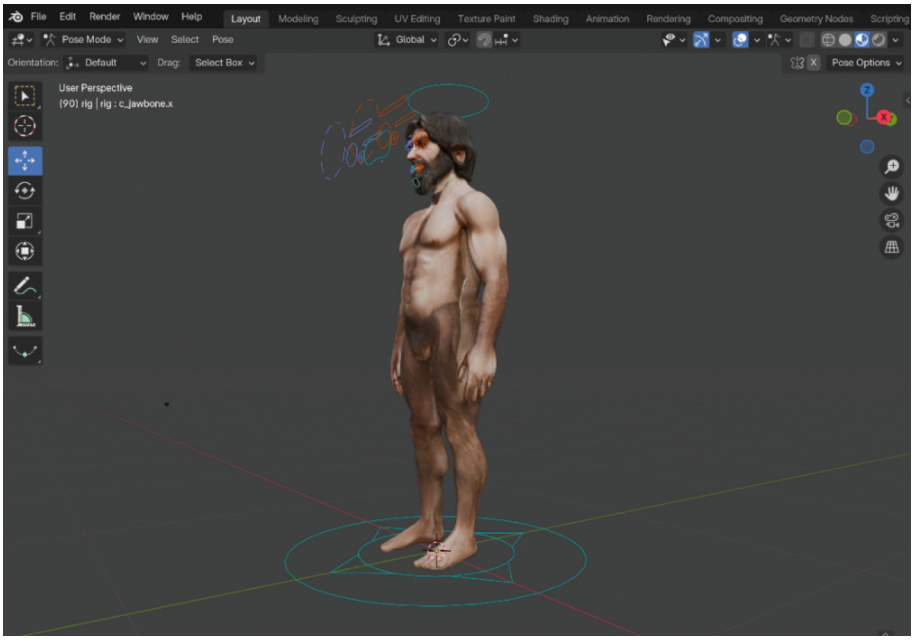

Fig. 2. Modeling and animation of the 3D model of 'Heidy' in Blender

Fig. 3. 3D model of "Heidy"

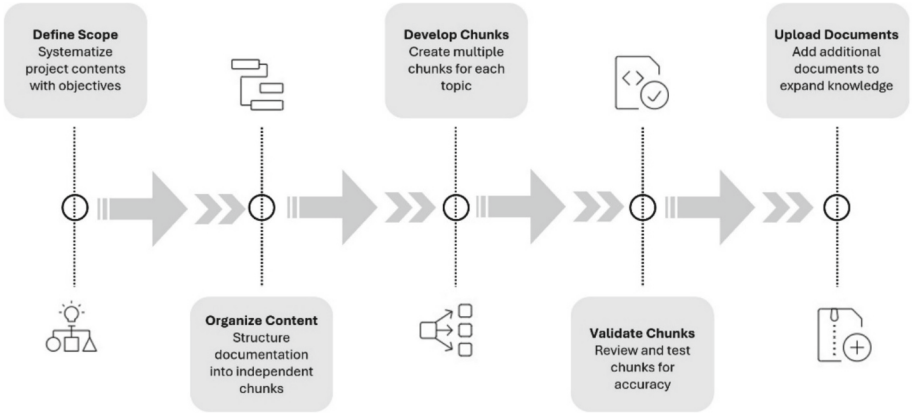

Fig. 4. The process for the construction of the knowledge domain

3.4 Assumption of Role

In parallel with the development of the knowledge domain, we proceeded to define the instructions necessary to characterize "Heidy" in her dual role as an information interface for the INSITE project (which provides answers) and a facilitator of participatory processes (which asks questions).

Although the two profiles required distinctly different instructions, a general definition of Heidy's identity was established that is common to both, defined by the following instructions: *a)* assume the role of "Heidy", a figure inspired by *Homo heidelbergensis*; *b)* introduce yourself as a spokesperson for the INSITE researchers; *c)* do not use an emphatic, promotional, or overly narrative tone; *d)* maintain a high level of scientific rigor in your explanations (Fig. 5).

To configure "Heidy" as an information interface, a series of instructions were defined regarding the type of language to use, the logical structure of the responses, and the priority to assign to the content.

An important part of the design involved defining the limits of competence; in this regard, "Heidy" was instructed to: *a)* declare the absence of information when necessary; *b)* not arbitrarily complete incomplete data; *c)* not simulating scientific authority on content not present in the project corpus; *d)* in the event of missing information, direct users to consult the project website (Fig. 6).

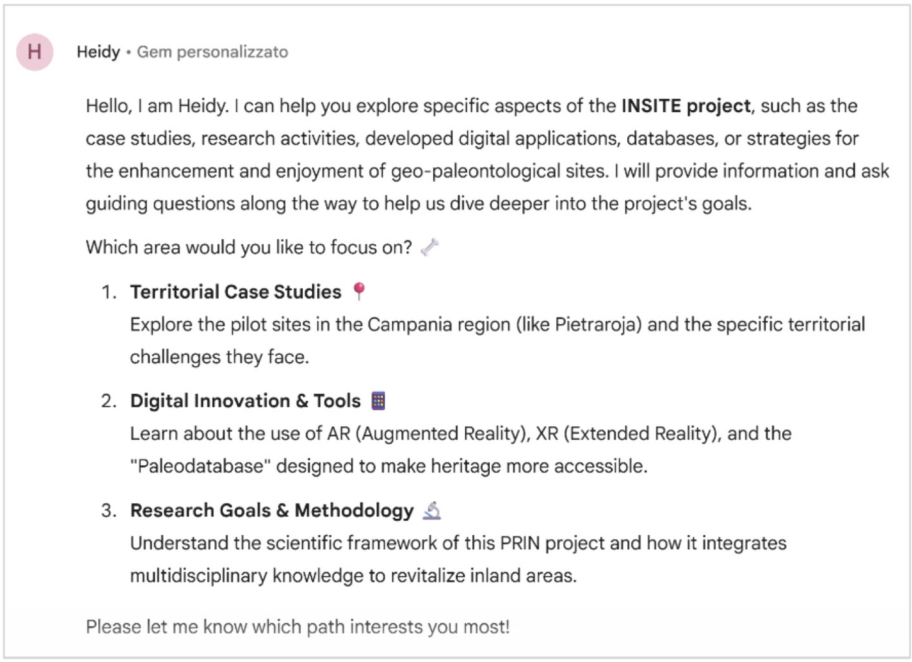

Fig. 5 How the "Heidy" chatbot introduces itself during the initial interaction

Subsequently, instructions were included on how to activate facilitator mode. Specifically, "Heidy" was instructed to activate facilitation if the user: *a)* shows interest in a particular topic*; b)* expresses an opinion or judgement; *c)* comments on the responses provided (Fig. 7).

It was essential to explain clearly some facilitation rules, including: *a)* ask only one question at a time; *b)* avoid generic questions out of context; *c)* do not insist if the user does not want to elaborate; *d)* adapt the level of the questions to the user's profile.

In this sense, "Heidy", acting as a facilitator, takes on the role of conversation initiator; it does not simply respond to the user's inputs, but actively shapes the interaction by guiding reflective processes through the formulation of targeted and progressive questions. This approach helps to bring to the surface perceptions and levels of awareness that are difficult to detect through direct questioning.

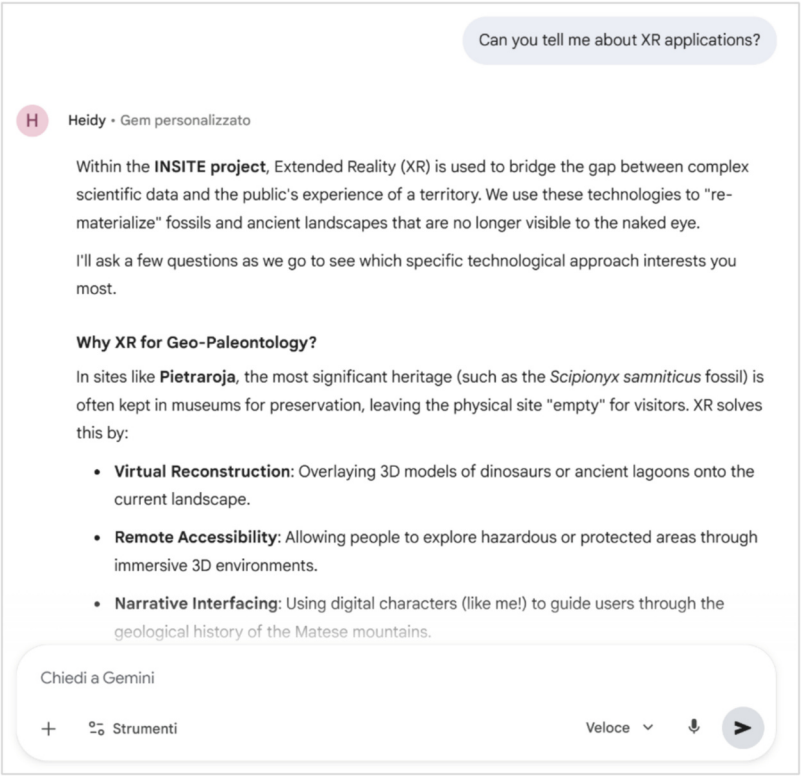

Fig. 6. "Heidy" in information interface mode

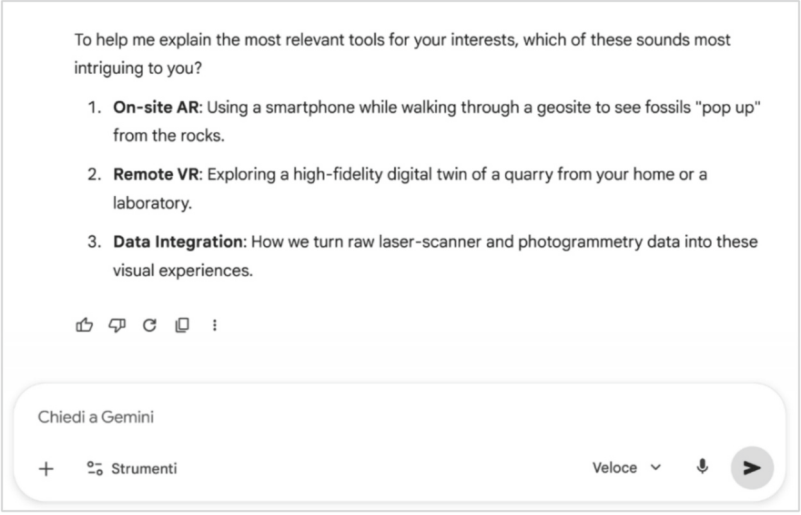

Fig. 7. "Heidy" in facilitator mode

4 Conclusions and Discussion

This paper proposed a reflection about the risk to privilege efficiency driven by the potentialities of AI especially in areas in which some important information that are relied on territorial identity context could be vanished.

It argues that Hybrid Intelligence, combining AI capabilities with participatory processes and local knowledge, provides a more inclusive and resilient alternative framework for design of regenerative planning of fragile areas like inner areas.

Findings from the INSITE project showed that even though in the presence of important cultural heritage the empowerment of local communities is fundamental to make people really part of this uniqueness, to involve them for the territorial promotion and thus, for the global success of regeneration design.

The experimental significance of "Heidy" lies in its capacity to integrate, within a single device, the dissemination of validated knowledge with a dialogic, generative interface, thereby promoting widespread reflexive awareness.

In this perspective, "Heidy" represents a pioneering application of Hybrid Intelligence in marginal contexts, where AI-mediated interaction facilitates both the democratization of knowledge and the active listening to territorial needs through innovative participatory modalities.

While the current research remains iterative, it contributes to enhancing the perceptual attractiveness of territories often excluded from conventional cultural circuits, supporting their revitalization within a competitive global landscape.

Based on our experience and findings, it appears to be a logical evolution of the ongoing work to proceed toward an initial visual and three-dimensional rendering of the chatbot as an embodied interface, aimed at enhancing its communicative recognizability and supporting more engaging forms of interaction with users, while simultaneously contributing to further implementing participatory processes.

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Urban Artificial Intelligence as a Meta-Modelling Framework: Repositioning AI in Urban Analysis and Planning

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Abstract. The rapid increase of Artificial Intelligence (AI) in the urban studies has substantially broadened the analytical capability of the urban modelling, spatial analysis, as well as planning practice. Although this has increased adoption, the conceptual place of AI in the urban planning knowledge is still not well established, tied to a solitary application of technology as opposed to an analytical system. This paper takes a conceptual and review-based approach and contends that Urban Artificial Intelligence needs to be re-valuated as a meta-modelling framework that complements and restructures existing analytical traditions and not replacing them. Drawing on a critical synthesis of recent literature, the paper examines the integration of AI with Geographic Information Systems (GIS), configurational approaches such as space syntax, and urban morphology. The review identifies the predominance of predictive accuracy, automation and computational efficiency at the expense of interpretability, spatially reasoning and planning relevance. To fill this gap, the paper suggests a conceptual framework, which considers AI as an enabling analytical stratum, which will aid data integration, pattern recognition, and exploration of scenarios, yet retain human interpretation and normative judgment as the central components to planning processes. By introducing AI to a broader urban modelling ecology, the presented framework defines the role of the former in the generation of spatial knowledge and decision support, but not the autonomous decision-making. Implications of transparency, methodological coherence and people-centered planning with a focus on explainable and situation-dependent applications of AI are also provided in the paper. The study

This paper is the result of the joint work of the authors. 'Abstract', the 'Conceptual Gap: From Tool to Meta-Modelling' (with sub-paragraphs) and 'Proposed Framework: Urban AI as Meta-Modelling System' (with sub-paragraphs) were written jointly by the authors. TA wrote 'Introduction', 'Key Limitations in Current Approaches', 'Methodological Implications', and 'Governance and Ethics'. A.P 'AI within Urban Analytical Traditions', 'AI in Urban Studies: Current Trajectories', and 'Implications for Urban Planning and Research', CG wrote 'Positioning AI within Urban Analytical Traditions', 'Integration with Established Urban Methods', 'Planning Practice', and 'Discussion and Conclusions'. CG coordinated and supervised the paper.

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contributes to ongoing debates on the epistemological and methodological foundations of Urban Artificial Intelligence and offers a planning-oriented perspective for its responsible integration into urban modelling and analysis workflows.

Keywords: Artificial Intelligence · GIS · Spatial Analysis · Urban Modelling · Urban Planning

1 Introduction

Incorporation of Artificial Intelligence (AI) into urban studies has been greatly accelerated in the last ten years due to the spread of huge volumes of spatial data, the development of computational power, and the growing need to use data to inform planning. The use of AI methods, and especially machine learning and deep learning, has become common in various areas of urban research, such as land-use classification, mobility prediction, environmental monitoring, and infrastructure optimisation. Such a fast growth has clearly amplified the analytical abilities of urban modelling, allowed the handling of multifaceted, high-dimensional data and allowed predictive information to be produced at never previously experienced spatial and temporal levels [1].

Although these developments occur, the theoretical role of AI in urban planning and analysis has not been adequately described. In a great part of the available literature, AI is still largely presented as a separate technological solution, commonly optimised in predictive quality, automation features, and computational efficiency. Although such a framing is methodologically beneficial, it runs the risk of making urban analysis a more technical procedure, rather than one that relates to the interpretative, contextual and normative aspects that define the practice of planning. As a result, AI-based solutions are often used side by side, not in combination with, existing traditions of analysis, including Geographic Information System (GIS), configurational analysis (e.g. space syntax), and urban morphology studies. Such fragmentation is obvious in which AI is applied to augment some of the analytical processes such as classification, clustering, or prediction without a due interaction with the broader epistemological foundations of urban knowledge production [2]. AI models are convenient tools when it comes to identifying spatial patterns or forecasting city dynamics. However, they lack the human-understandability and interpretability, restricting their application in decision-making scenarios.

In this framework, a gap is identified, namely, the lack of a consistent conceptual framework where AI is not considered as a tool of analysis, but rather as a component of integration in the overall ecology of urban modelling. To fill this gap, it is necessary to consider a change of perspective, that is, to stop seeing AI as an alternative to the current methodology and as having the potential to restructure and improve the old methods of analysis. This repositioning can allow AI to serve as an enabling layer that enables the integration of data, pattern recognition, and the exploration of situations, and maintains the central position of human interpretation and planning judgement.

The paper will support this purview by conducting a systematic survey of the recent literature on the use of AI in urban analysis. It also highlights its combined usage with GIS, space syntax, and urban morphology. It assumes a critical approach to determine

the current trend of methodology, limitations of the conceptual nature, and areas of overlap in these fields. Therefore, the study suggests a conceptual framework which redefines Urban Artificial Intelligence as a meta-modelling system being integrated within a multi-layered analytical framework that includes data, methods and decision-making processes.

This paper has two contributions to make. First, it offers a conceptualised epistemological positioning of AI in urban planning to address endemic uncertainties about the role of AI in knowledge generation and analytic practice. Second, it presents a conceptual framework of planning that will be able to support the responsible and contextualisation of the application of AI in the process of urban modelling. Through this, the study will add to the growing discussions on the methodological coherence, transparency, and human orientation of AI in urban studies, and it is important to note that the value of AI is not found to lie in the process of autonomous decision-making, but rather in its ability to supplement and enhance the processes of analysis that inform planning interventions.

2 Positioning AI within Urban Analytical Traditions

The integration of AI in urban studies has been both fast and unequal, with an innovative approach and conceptual vagueness. Instead of providing a coherent analytical paradigm, AI has been integrated into the existing urban traditions of analysis in a fragmented and application-focused form. In this section, a thematic synthesis of existing paths is developed based on the intersection between AI and existing methods, especially GIS, configurational analysis and urban morphology, and the shortcomings of AI as largely instrumentally applied.

2.1 AI in Urban Studies: Current Trajectories

The development of AI in the urban studies has been informed by the intersection of greater processing power, the spread of high-resolution spatial data, and the rising need to use predictive and more data-driven planning methods. In the last ten years, AI has stopped being a marginalised analysis instrument and has become the core of the research processes in cities, especially in the areas that can be described as multi-dimensional and complex datasets. This change is indicative of a wider change in urban analytics, where models-based approaches have been increasingly complemented, and in certain directions even replaced, by data-driven approaches [3].

The main aspect of this change is the massive implementation of machine learning (ML) and deep learning (DL) methods. Supervised learning algorithms are useful in classification and 0 regression problems. This includes land-use mapping, population density prediction and urban growth prediction. On the other hand, unsupervised learning methods including clustering methods and dimensionality reduction methods, are more useful. They can analyse latent spatial patterns and functional areas in cities. However, deep learning systems have also shown substantial abilities to process spatial and spatio-temporal data.

One of the major factors that inspire is the presence of geospatial big data obtained through satellite images, sensor networks, mobile phone data, social media sites and

administrative documents. The detailed information on urban dynamics is what enables the modelling of the previously inaccessible phenomena using AI techniques. They acquire the capability to capture nonlinear relationships, model complex interactions, and scale to large scale data. AI has already found application in the creation of the smart city analytics, real-time city monitoring, and optimisation of infrastructures. However, the trend in AI pursued in the urban research is very skewed towards predictive accuracy and computational efficiency. Models are commonly measured by the performance metrics of accuracy, precision, recall, or error minimisation and little thought given to their understandability or theoretical basis [4, 5]. This focus has had the effect of increasing dependence on black-box models where the inner workings of the algorithm cannot be easily accessed. Though these models can be very predictive, they lack transparency, and it is difficult to incorporate them in planning processes.

The other exciting fact behind the AI trends today is that it is inclined towards domain specific applications. AI models are trained to solve highly specific tasks, like traffic prediction or land-use classification, producing highly specialised solutions that cannot be easily generalised to new settings [6]. Although this specialisation has the benefit of improving performance in the context of tasks, it is limited to disciplinary or methodological frames.

2.2 Integration with Established Urban Methods

Although it develops very fast, AI in the field of urban studies has not been developed as an independent analytical paradigm but a complement to existing methodological traditions. It is most integrative in three prevailing areas of urban analysis that are, GIS, configurational approaches, which include space syntax, and urban morphology. Although these integrations have improved analytical capacities, they are mostly instrumental and they aim at augmentation of performance, as opposed to concept synthesis [7].

In the context of GIS urban analysis, AI has been broadly used to further the spatial data processing, classification and modelling capability. Machine learning and deep learning are among the techniques used on a regular basis to classify remote sensing data with land-use and land-cover, object detection, and change detection. These applications are very helpful to the speed and accuracy of spatial analysis, especially when dealing with large and heterogeneous datasets [8]. AI is also useful in spatial interpolation, anomaly detection, and predictive modelling in GIS environments, thus making it possible to have more dynamic and scalable analytical processes. In most instances, however, AI is used as an improvement layer on top of GIS and does not substantially change its underlying logic as a spatial data representation and analysis system. The epistemological principles of GIS based on spatial relations and cartographic reasoning have not changed much, and AI has been used to improve automation and efficiency [9].

AI has been used to reinforce the predictive and empirical validation of spatial network models in the framework of configurational analysis, especially space syntax. Space syntax has traditionally been based upon the graph-based representations of the urban form to study the patterns of movement, accessibility as well as the integration of space. With the integration of machine learning, it is possible to calibrate syntactic

measures to observed behavioural data, e.g. pedestrian or vehicular flows. This combination strengthens the explanatory capacity of configurational measures, which allows making stronger predictions regarding movement dynamics in various urban settings [10]. However, AI is not usually used in this area beyond the optimisation and validation of models. It does not radically redefine the theoretical constructs of configurational analysis, including spatial cognition, visibility, or network centrality, but rather puts them into better empirical service. Another area where AI has been popularised is urban morphology, especially in-built form analysis, spatial patterns, and urban development. Morphological features of large-scale datasets, e.g. satellite imagery, street-level images, and cadastral maps, are extracted by AI methods, e.g. image segmentation, clustering, and pattern recognition. The approaches enable the classification of the urban forms, the definition of typologies, and the examination of the temporal changes in the built environment. The scalability of AI allows morphological research to be carried out in more than one city and region, which allows comparative and longitudinal research [11]. AI applications to urban morphology are more inclined to focus on descriptive and predictive results, notwithstanding limited participation in the interpretative and theoretical facets.

AI is applied as a task-specific addition that enhances the efficiency, scalability and predictive power of the current techniques. They are implemented in each field as a consonant with the specific methodological priorities and data forms in each field. This leads to parallel developments and not convergent integration. Therefore, traditional methods remain within their respective limits of epistemology, and AI is merely an aide to the process rather than a unifying process [12].

The given form of integration indicates a larger shortcoming of the current trend of urban AI. The use of AI along with already existing approaches has delivered the quantifiable technical dividends. But it has not resulted into the logical recalibration of how various analytical tactics can be linked together. There are no well-developed possibilities of cross-domain synthesis. This includes the correlation between morphological patterns and movement dynamics or the integration of environmental performance in spatial configuration. Therefore, AI is not applied to its maximum potential as the bridging element between these areas but rather, it is an independent enhancement of both [13]. Collectively, these curves suggest that AI is mostly utilized as a performance-enhancing addition to the preexisting analytical traditions, rather than a unifying epistemological structure. Although, considerable progress has been made in the efficiency, scalability, and predictive ability, integration has continued to be largely instrumental and domain specific. Consequentially, the current working conditions of urban analytical practices remain in parallel siloing with slight conceptual overlaps, which supports the necessity of a reframing of AI as an integrative meta-modelling layer.

2.3 Key Limitations in Current Approaches

The present implementation of AI in urban research demonstrates a set of structural constraints, which are due to the overwhelming instrumental and application-oriented framing. The constraints are not just technical, but also epistemological and methodological contradictions. Therefore, they contradict the introduction of AI into the urban analytical practice. With the further introduction of AI into various fields, the issues of

interpretability, the relevance of planning, coherence in concepts and methodological fragmentation are even more acute [6].

The major weakness is the problem of interpretability. Most AI models, especially the deep learning models, are opaque systems. Such models may be highly predictive, but due to their lack of transparency it is difficult to implement using such models with the planning context where decisions must be justified. The absence of an explanation of the production of certain outputs negatively affects trust and reduces the practicality. This is a critical concern especially in the field of urban planning with long-term socio-spatial consequences of decisions [14]. Also, the poor translation of AI outputs into practical planning contexts is closely associated. AI models are very effective in producing predictions, classifications, or pattern detections. However, the results usually do not have the interpretation frameworks essential to decision-making. An example is that a model can be accurate in forecasting regions of urban development or traffic congestion, but lack contextualisation in the form of socio-economic situations, governance systems or spatial orders. Such separation indicates a larger disparity between computational analysis and planning practice where AI are not adequately congruent with the normative and strategic aspects of urban decision-making.

Besides, the current situation in AI usage in urban studies is linked to the significant degree of the methodological fragmentation. It is mostly incorporated into analytical fields including GIS, configurational analysis, or urban morphology with little interaction between the domains. This develops disconnected analytical pipes where knowledge is produced in isolation and not in a cumulative and integrated knowledge of urban systems. The lack of an overriding framework limits the possibility of AI being able to promote cross-domain synthesis [15]. This discontinuity is also supported by the fact that most AI applications are task oriented. Models are merely designed to solve small-focused problems, and this results in specialised solutions. Although this improves the performance in the context of single tasks, it restricts the wider applicability of AI.

Additionally, novel challenges relate to bias, data quality, and representational disadvantages. Bias in AI models is also based on the data that they are trained on, and any bias in these data can be multiplied by the operation of an algorithm. In urban areas, it can lead to the strengthening of existing inequalities or false representation of the underrepresented groups. These difficulties are further complicated by the uneven access to high-quality data in the different regions especially in those areas that have less established data infrastructure. These challenges bring out the importance of critical interaction between the ethical and socio-political aspects of AI in urban planning [16].

These restrictions suggest that the present-day use of AI in the context of urban studies, is technologically advanced but lack coherent and planning-oriented relevance. The issues of interpretability reduced the relevance of decision-making, the epistemological inconsistency, and methodological fragmentation demonstrate the necessity of the redefinition of the role of AI (Fig. 1).

3 Conceptual Gap: from Tool to Meta-Modelling

The fast integration of AI into the urban studies has caused its common belief as an effective analytical tool. Yet, such attitude is frequently supplemented by a conceptual mismatch, as AI is either regarded as an independent method of analysis, or perceived

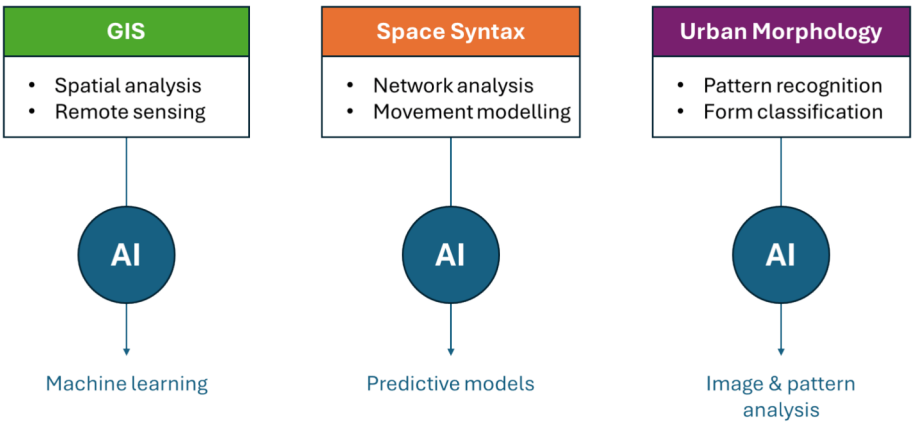

Fig. 1. Fragmented integration of Artificial Intelligence within urban analytical traditions [elaborated by the authors].

as a possible replacement of human thinking in the process of planning. To begin with, AI models are fundamentally reliant on input data, feature selection and problem framing which are informed by existing traditions of analysis including GIS, configurational analysis, and urban morphology. AI is not used to create knowledge, but to process information based on such structures and rearrange it. In the absence of the contextualisation of the outputs of AI offered by domain-specific knowledge, the products of AI will become decontextualised abstractions, which have no relevance in the actual conditions of urban life. Second, the concept of AI as a self-reliant analytical procedure ignores the interpretative aspect of urban analytical process. Urban systems are not simply purely computational systems but rather influenced by the complex socio-spatial, cultural and political processes [17]. Thus, by making it a standalone technique, it is possible to disregard the interpretative and critical elements of the planning practice.

No less problematic is the conceptualisation of AI as a substitute of human reasoning. Although AI can be used to process a significant amount of data and find patterns with great efficiency, it lacks the ability to make judgements, act morally, or understand the situation in the context of human planners. Making decisions and planning them frequently encompasses having competing interests, negotiating the views of the different stakeholders and considering the long-term implications of the society. Such processes demand reasoning that goes beyond computational optimisation, and excessive reliance on AI in the area will result in technocratic decision-making, in which algorithmic outputs are given priority without adequate critical analysis. The lack of transparency in the functioning of the algorithmic systems becomes a major issue when the authority to make decisions is implicitly passed on to them [18].

The paper highlights that AI needs to be re-defined as a meta-modelling framework in urban analysis. Under this role, AI does not act as an individual process, but as a mediating analytical level that is applied in various fields. The main contribution that it makes is that it can integrate heterogeneous datasets, improving pattern recognition, and scenario exploration, which complements existing analytical methods without replacing

them. Having been developed as a meta-layer, AI allows consolidating various data sources, which tend to be disconnected between various analytical systems. The city data are usually across different formats and scales, spatial, temporal, socio-economic, and environmental. The synthesis of such datasets is made possible by AI techniques, which can be used to come up with more comprehensive representations of urban systems. Such integrative ability is especially useful in solving multi-dimensional problems in cities that are complex.

Besides the integration of data, AI improves the ability to recognise patterns in the urban data. AI can also uncover the insights that might not be easily traced by using standard analysis techniques by establishing non-linear associations and latent structures. Notably, these understandings are to be interpreted as supplementary to but not substitutes of the current modes of spatial thinking. Pattern recognition based on AI could be used to add to the interpretative process, when incorporated into a larger analytical framework, which would be used to arrive at more nuanced interpretations of urban processes. It is also very important in assisting in scenario exploration. The process of urban planning usually requires predicting the future situation and assessing other interventions. Under various conditions, AI models can simulate possible results, which may be considered as useful contributions to the strategic decision-making. These simulations are however not to be understood as deterministic predictions. Rather, they are to be adopted as exploratory aids that inform deliberation and planning decisions in a human-centred context.

In epistemological terms, the switch of AI to a meta-modelling framework is compatible with a more integrative conceptualisation of the production of urban knowledge. Instead of giving precedence to data-driven insights above theory, this approach considers the interdependence of computational approaches and domain-specific knowledge. The AI is integrated into a wider ecology of analytics, in which alternative ways of understanding urban systems are added to an accumulative and context-specific one. In the context of the theory of planning, this view makes the role of human judgement and normative reasoning central [19]. The proposed meta-modelling framework should be differentiated with the current hybrid or AI-supported urban modelling methods. Although hybrid models are normally the integration of method at the application or workflow integration level, they are task specific and do not have an overriding epistemological framework. Conversely, the conceptualisation of AI as a higher-order integrative layer that functions across domains of analysis, interpreting data, domain-specific models, and planning, is proposed herein. This reverses the aim of AI as methodological boost, to epistemological supplement.

4 Proposed Framework: Urban AI as Meta-Modelling System

This paper presents an idea framework which redesigns AI as a meta-modelling platform in urban analysis. Instead of being a specific analytical instrument or a substitute of the currently existing approaches, AI is viewed as a middle ground that incorporates, improves, and rearranges various elements of analysis within a single framework. This framework reacts to the requirement of methodological coherence, interpretability and planning relevance by placing AI in a wider analytic ecology, which preserves the primacy of human judgement.

4.1 Framework Structure

The suggested framework is structured in the form of a multi-layered system that has four interconnected elements, such as the data layer, the analytical layer, the AI layer, and the interpretation layer. Each layer has a specific task to complete as it is dynamically connected with the rest.

The data layer is the bottom part of the framework and is the composition of various spatial and non-spatial data. These are GIS-based data, remote sensing data, socio-economic data, mobility data, environmental data and administrative data. Notably, the heterogeneity of these sources of data also indicates the multi-dimensional character of urban systems, with spatial, temporal, and socio-economic variables interacting at different scales. More to the point, this layer is not neutral, but it is influenced by the process of data collection, availability and representation, which subsequently affect reliability and inclusiveness of the future analysis.

Most importantly, the analytical layer entails developed urban analytical approaches, such as configurational approaches, such as space syntax, urban morphological analysis, and statistical modelling techniques. This layer gives the theoretical and methodological basis of the interpretation of urban phenomena. It is in this field where spatial relationship, network structures and form-function interactions are studied. Such approaches are more structured in the way they understand urban systems, in contrast to purely data-driven approaches, as they incorporate domain knowledge and conceptual reasoning, providing a way of understanding the urban system beyond pattern appearances on the surface.

The AI layer, which is above the analytical layer, is the heart of the framework meta-modelling. It does not take the place of the analytical techniques below it but traverses over it, thus making it integrate and augment. Through the processing of the results of several analytical streams, AI enables the generation of heterogeneous information, the discovery of latent patterns, and the discovery of complex relationships that might not be evident when using a single approach. This framing is important, as it re-identifies AI as a mediating process that bridges and enriches the already existing strategies as opposed to it being a self-sufficient destination.

The interpretation layer is at the top of the framework, and it focuses on the planners, decision-makers and the stakeholders. This layer involves the conversion of analytical product into actionable knowledge based on contextual understanding, normative considerations and policy goals. It supports the fact that urban planning is a human-centric process by nature, and decisions should consider social, cultural, and ethical aspects, which are not limited to computational results. The interpretation layer as well provides a feedback loop, in which planning choices and results are used in future data gathering and analysis, such that the structure is adaptive and sensitive to context.

4.2 Functional Role of AI

It is in this hierarchical system where AI undertakes some of its most important functions that in combination characterise its functionality as a meta-modelling system. Such functions are not limited to individual analytical activities and help to create and develop the overall structure. One of the main purposes of AI is data fusion, which is a combination of various datasets of various formats, scales, and fields. Urban data are naturally

discrete, stored in a range of different systems and characterised by a different degree of granularity and quality. It allows consolidating data sets which is crucial in the solution of complex urban issues facilitating multi-dimensional analysis.

The use of AI models is especially useful when it comes to the recognition of non-linear relationships and latent structures in large data sets. It reveals patterns that cannot be perceived using traditional tools directly and improves domain-specific analysis. Pattern extraction helps to develop a more detailed image of the urban processes. It allows exploring other (alternative) urban futures in different conditions. It can also be used to guide planners to examine the consequences of policy or design interventions, or environmental changes. These simulations are a good foundation in strategic planning, and it is possible to evaluate risks, trade-offs, and uncertainties. However, it is necessary to note that this type of simulation is not a deterministic forecast but a discovery tool that can guide deliberative procedures.

4.3 Conceptual Diagram

The conceptual diagram (Fig. 2) is arranged in a vertical manner to show how the raw data is transformed into a decision-making. The data layer is the bottommost layer that reflects the heterogeneous character of urban data. This is preceded by the analytical layer, which exemplifies methodological traditions configurational analysis, morphological studies, and statistical modelling. The two layers are together the pillars of the foundational elements of urban knowledge production, based on domain-specific reasoning.

The AI component is conceptualized as an analytical layer that is intermediate and not a destination. The argument of the paper revolves around this positioning. AI works on the results of the analytical layer, making it easier to integrate, better pattern recognition, and allowing scenario-driven exploration. Its operations, such as data fusion, pattern extraction, and simulation, are represented in this layer to highlight its functionality in augmenting, but not eliminating, the existing methods. The interpretation layer is the layer where planners, decision-makers and stakeholders interact with the outputs produced by the other layers. This layer emphasises the importance of human judgement in the processes of urban planning whereby the analytical insights must be put in a context of socio-political, cultural and ethical considerations. The information flow of data to interpretation upwards is an indication of how the raw inputs would be transformed into feasible decision-making. It also includes a feedback mechanism between the interpretation layer and the data and analytical components. This feedback loop denotes the iterative character of urban planning in which decisions inform the further data collection, model refinement and analysis. It strengthens the dynamic and flexible nature of the framework, so that it is responsive to evolving urban circumstances and priorities in planning.

5 Implications for Urban Planning and Research

The metamodelling of AI as a framework has important implications on the practice of urban research and planning. The shift towards positioning AI as an integrative layer, rather than an independent analysis instrument, in a larger analytical ecosystem is associated with the need to reconsider methodological and governance frameworks as well

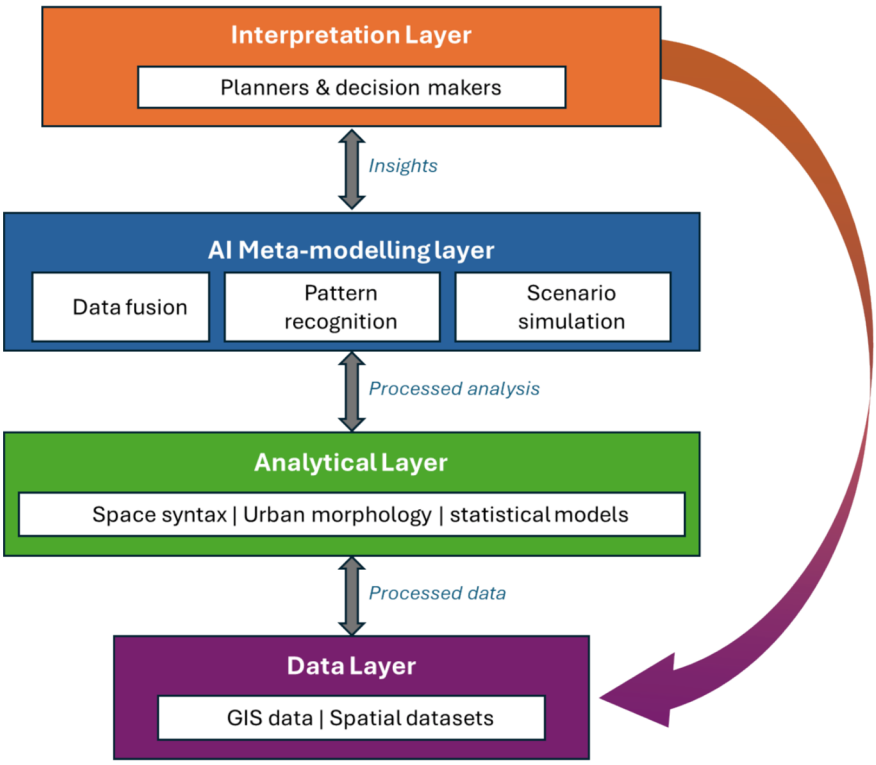

Fig. 2. Urban Artificial Intelligence as a meta-modelling framework. Source: authors' elaboration.

as the practices of various professionals, which is not merely a technical matter, but a question of epistemology and normativity in urban planning.

5.1 Methodological Implications

The key implication of the framework is that there is a necessity to transition to hybrid modelling methods. The recent trend of AI in urban studies can be largely described in terms of parallel innovations, where machine learning models are developed without the involvement of configurational methods, or morphological studies. Such a division constrains the possibility of the comprehensive analysis of urban systems [20]. The meta-modelling perspective highlights integration over substitution. Rather than replacing traditional analytical methods with AI, the framework emphasises their coordinated use within a unified structure. This involves leveraging the strengths of each approach. By enabling interaction between different configurational methods, hybrid models can produce more robust and context-sensitive insights [21].

This transition requires the development of interoperable analytical workflows and frameworks that allow for the seamless exchange of data and outputs across different modelling domains. It also requires a re-evaluation of standards of evaluation. More

emphasis should be put on interpretability, transferability and planning relevance instead of just focusing on the predictive accuracy. This also means that the performance of the model should not be measured in terms of technical performance alone but also in terms of the ability to facilitate the decision-making process and lead to the production of urban knowledge. Moreover, the implementation of hybrid methods promotes a more iterative and reflexive modelling process. The introduction of AI into a stratified structure of analysis allows one to provide a continuous feedback mechanism between data, methods, and interpretation, which helps to develop adaptive modelling practices to the changing urban environment. This is consistent with new trends in urban science that focus on complexity, uncertainty, and flexibility in the analysis.

5.2 Governance and Ethics

The application of AI in urban planning poses very important questions regarding governance, ethics, and accountability. With the growing levels of AI systems integration in the analytical and decision-support processes, the transparency and explainability is a core requirement. Making decisions with a far reaching social and spatial impact, planning decisions may also require justifications. Black-box AI models are uninterpretable and create serious challenges due to obscure conclusions [22].

The framework proposed addresses these concerns by placing AI within a broader analytical context. This layered approach enhances transparency by allowing AI-derived insights to be cross-referenced with domain-specific analyses. Another critical issue is the risk of algorithmic bias as they are inherently shaped by the data on which they are trained. These biases can be perpetuated or amplified through computational processes. In urban contexts, this may lead to the reinforcement of existing inequalities. Addressing this challenge requires careful consideration of data sources, model design, and validation processes, and incorporation of ethical safeguards within analytical workflows. Therefore, to integrate AI, it is essential to maintain clear lines of responsibility for decisions and their outcomes. The meta-modelling framework reinforces accountability by explicitly positioning AI as a decision-support tool rather than a decision-maker. This ensures that responsibility remains with human actors, who can exercise judgement, consider contextual factors, and address ethical implications. In this sense, the framework aligns with governance principles [23].

5.3 Planning Practice

Although AI may offer useful insights due to the ability to integrate data, recognize patterns, and simulate scenarios, the results need to be evaluated in the context of the overall goal of planning. This view affirms the role of planners as important decoders of analytical products. Planners will need to work more with data and models, and build the ability to interpret, analyze, and contextualize AI-generated outputs. This change has implications on professional practice, such as the requirement of interdisciplinary skills that integrate technical skills with spatial thinking and policy knowledge. The model also emphasizes that urban systems are influenced by the local conditions, cultural practices, governance structures, and socio-economic dynamics that cannot be entirely represented by data only. AI models work within the confines of input data and assumptions.

Incorporating AI into the planning practice helps to make more informed and proactive decisions. AI will be able to help planners predict upcoming challenges and see strategic opportunities. But this power must be construed as enhancing and not determining. Scenario simulations are a foundation of discussion and deliberation, not a point of prediction. Thus, the consequences of redefining AI as a meta-modelling framework go beyond methodological, governance and practical levels. The suggested strategy encourages integration, transparency and human-centred decision-making. An example is that, in a workflow of metropolitan planning, spatial data that is stored in GIS and configurational measurements such as accessibility can first be analysed using well-known methods, after which such outputs should be combined with socio-economic and environmental data using AI models to identify latent trends or simulate future scenarios. The planners then contrast these results with policy objectives and local conditions and demonstrate how AI can be an integrative layer to facilitate, but not supplant, planning judgement.

6 Discussion and Conclusions

This work can be added to existing discussions on the crossroads of urban planning and AI. The proposed perspective pre-empts integration, interpretability, and planning relevance, in opposition to the dominative approaches that focus on predictive performance and automation. The article fills an essential gap of Missing a coherent epistemological stance of AI in urban knowledge production. Practical implications of this framework can be seen in emerging applications, such as AI-assisted urban digital twins, combined GIS-AI workflows to analyse land-use and mobility, and mixed models combining configurational metrics with predictive analytics. These examples demonstrate that the meta-modelling approach can be applicable to real planning situations and retain interpretability and methodological consistency.

The contribution is topical in the context of growing dependence on data-driven methods of urban studies. Although AI has been able to enlarge the analytical powers, its implementation has been fragmented and lacked enough integration with the theoretical and normative basis of planning. The framework suggested in this paper provides a direction towards more methodological coherence. It moves the emphasis in the solitary technical optimisation to interpretive reasoning, which supports the claim that AI is an enabling, but not a determining aspect of urban analysis. Simultaneously, the research is limited to several weaknesses. To begin with, being a conceptual and review-based contribution, it lacks empirical confirmation of the suggested framework [24]. The arguments are based on a critical review of current literature, which might fail to reflect the fast-changing nature of AI applications in cities in a holistic manner. Second, the review is necessarily selective, concentrating on major traditions of analysis and representative use AIs, as opposed to an exhaustive overview of all current AI-related urban studies, which may further change the role of AI in other ways that are not fully covered in this paper.

Such limitations indicate significant avenues to future research. The next step required is empirical validation of the proposed meta-modelling framework by use of case studies. They may also investigate the impact of AI-mediated integration on decision-making, enhance interpretability, or optimize the results of planning. It further explains the significance of maintaining interpretability and logic of planning in the implementation of AI in urban analysis. Although computational models are strong instruments of complexity processing, its usefulness ultimately lies in its ability to elicit meaningful understanding and decision-making. The threat of excessive dependence on data-driven models points to the necessity of the methods that would strike a balance between computational efficiency and transparency and contextual sensitivity [25].

Finally, this paper suggests that AI can be reconceptualized as a meta-modelling infrastructure in the context of a larger urban analytical ecosystem. It helps AI serve as an integrative layer to improve data fusion, pattern recognition and scenario exploration. The proposed framework will enable more responsible and context-sensitive introduction of AI into urban research and practice due to its focus on augmentation over automation.

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Snap4City SUMI Manager: A Digital Twin-Integrated Framework for Sustainable Urban Mobility Indicator Processing and Visualization

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Abstract. Urban mobility is one of the greatest challenges modern cities face today. Traffic congestion, inefficient public transportation, high cost, insufficient road safety, and air pollution are some of the problems related to urban mobility. To evaluate current implementations and promote more sustainable solutions for reducing environmental, social, and economic impacts, and promoting efficient and fast travels, the European Commission developed the Sustainable Urban Mobility Indicators (SUMI) to provide standardized and comparable indexes to assess the actual sustainability of urban mobility in European cities, fostering a continuous improvement of mobility policies. Despite SUMI relevance, currently there is no application that allows public administrations computing SUMI in a simple and automatic way. In this paper, the SUMI Manager is proposed as a tool built on top of the Snap4City Digital Twin platform to manage required data, compute the indicators, compare them among cities and over time, and visualize their temporal evolution in interactive dashboards. The SUMI Manager can be deployed in multiple cities to support municipalities in assessing and improving their mobility policies.

Keywords: SUMI · Urban Mobility · Sustainable Mobility · Indicators · Smart City · Digital Twin

1 Introduction

Mobility plays a fundamental role in the global economy and it is essential for both citizens and businesses. Nevertheless, mobility activities also generate significant costs in terms of air pollution, greenhouse gas (GHG) emissions, noise, road accidents and traffic congestion. For example, a valuable amount of the total GHG emissions derives from mobility activities [1]. Nowadays, a transition toward more sustainable mobility systems is an urgent priority. In particular, increased public and private investments in

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the modernization and environmental sustainability of transport fleets and infrastructure present an opportunity to improve the mobility in the future. To this aim, integrated planning approaches supported by continuous monitoring and evaluation mechanisms are required. More precisely, achieving sustainable mobility solutions is one of the UN Sustainable Development Goals [2]. Then, it is required to provide municipalities and decision makers with tools and solutions to address such problems. Intelligent Transportation Systems [3, 4] combined with Smart City Digital Twins [5] can exploit the ever-increasing amount of data to implement decision support systems helping to design, test, and deploy improved mobility solutions [6].

In particular, mobility systems are characterized by the interaction of multiple actors, infrastructures, and services which determine the performance and sustainability of mobility networks. Urban mobility systems include a wide range of physical and operational components, such as road networks, cycling paths, pedestrian infrastructure, parking facilities, public transport services [7], shared mobility solutions, etc. The effective interconnection of these elements is essential to ensure that mobility services properly respond to travel demand while guaranteeing safety, accessibility, environmental sustainability, and operational efficiency.

In this context, the systematic collection and analysis of mobility data becomes fundamental for supporting data-driven decision-making processes and evaluating the effectiveness of mobility policies and interventions. For these reasons, the European Commission (EC) promoted Sustainable Urban Mobility Plans (SUMPs) [8] as strategic tools for cities to plan cleaner, safer, and more inclusive mobility systems. However, many cities lacked a consistent and comparable way to measure progress toward sustainable mobility. To fill this gap, the EU initiated the Sustainable Urban Mobility Indicators (SUMI) project [9], with support from the World Business Council for Sustainable Development (WBCSD) [10], which had previously developed the Sustainable Mobility Project 2.0 (SMP2.0) framework [11]. The SUMI project adapted and refined these indicators for the European urban context, aligning them with EU policy goals such as the EU Urban Mobility Framework, the European Green Deal, the TEN-T (Trans-European Transport Network) regulation, and the Sustainable and Smart Mobility Strategy. SUMI constitute a standardized framework of 18 distinct metrics (labeled S1 through S18), covering key dimensions such as accessibility, safety, environmental impact, efficiency, and modal balance to support benchmarking across cities for the implementation of sustainable mobility strategies. Therefore, these indicators are used to assess how well a city's mobility or transport system is progressing towards sustainability goals.

Research on sustainable urban mobility has progressively focused on sustainability planning frameworks (SUMPs) and indicator-based monitoring (SUMI and other KPI sets). A study performed in [12] on SUMPs impact assessments has shown that benefits associated to the implementation of specific SUMP measures can achieve about 9% of CO2 reduction and around 11% of external cost reduction, although overall profitability effects have emerged only after about 6 years. However, such results are often constrained by context-specific assumptions (e.g., scenario definitions), and they often omit relevant aspects (e.g., noise level, congestion) which are significant for sustainability evaluation. Moreover, relevant lacks are often reported about public administrations capacity of actuating efficient reporting strategies. Actually, a comparative analysis among European

municipalities performed in [13] shows that the adoption of SUMPs correlates with more frequent deployment of sustainable activities; nevertheless, monitoring and evaluation of such measures are often underestimated in practice.

From an indicator perspective, KPIs such as SUMI have been proven to be beneficial, since they allow to transform sustainability goals into measurable variables. In [14], 21 specific electromobility indicators have been developed through literature analysis and expert consultation, organized across three dimensions (economic, social, environmental) for three transport subsystems. These indicators demonstrated a strong predictive power with regression models, explaining over 90% of variability. However, a limitation is represented by the scarcity or lack of data and the omission of some micromobility elements such as scooters. In order to mitigate data scarcity, other works in literature rely on surveys and interviews to citizens and experts to find the most relevant indicators for sustainable urban mobility. For instance, in [15] 28 experts (including urban planners, transport engineers, environmentalists and policy-makers) have been interviewed, finding as key indicators traffic congestion, affordability of public transport, energy efficiency and multimodal integration. The main limitations of this approach are explicitly addressed by authors: outcomes can be biased by expert selection and their dominant competencies, and the process can be very time consuming, since it requires the experts' availability. Another work presented in [16] evaluates indicators of sustainable urban mobility using questionnaire-based surveys, involving road-user perceptions as a proxy for mobility conditions. The study collects about 2 thousand interviews from citizens, highlighting traffic management, road network management and sidewalk features as key factors to promote modal shift. Nonetheless, this kind of evidence is explicitly perception-driven, since it mostly relies on survey collection.

All these limitations that have been addressed motivate the necessity of more automated solutions for SUMI management, which could resolve or mitigate the issues related to scarcity or lack of data, as well as reduce uncertainty and subjectivity in measurements, while enhancing standardized processing and reporting. In particular, the collection, integration, and analysis of mobility data play a fundamental role in supporting informed planning and operational decisions. The increasing availability of real-time data sources offers the opportunity to enhance the management of urban transport systems and to respond effectively to dynamic mobility patterns.

Nevertheless, the SUMI calculation is typically performed using aggregated and static datasets, which do not fully capture the real-time dynamics of urban systems. More precisely, taking into account only periodic data collection may be a limited approach to promptly detect emerging inefficiencies or to evaluate the immediate impact of policy interventions. This limitation highlights the need for integrated digital platforms capable of continuously collecting and harmonizing mobility data to automatically compute SUMI indicators, ideally integrating such features with Digital Twin (DT) technologies and solutions. Actually, DT frameworks are widely recognized as a promising tool for the design and development of sustainable and resilient urban environments [17], providing advanced simulation and predictive capabilities that can enhance decision-making for operational and strategic planning [18].

In this paper, the SUMI Manager is proposed, as a model and tool developed on top of the Snap4City Digital Twin platform [5], to model and manage required data, compute

the indicators, and visualize their evolution over time in interactive dashboards, and make comparison among cities. The paper is organized as follows: in Sect. 2, the Sustainable Urban Mobility Indicators are illustrated in more detail; Sect. 3 describes the architecture of the proposed SUMI manager; Sect. 4 is dedicated to system validation; finally, Sect. 5 is left to conclusions.

2 Sustainable Urban Mobility Indicators

According to the final version of the SUMI Harmonization Guideline [19], 18 indicators have been defined, divided into core and non-core indicators, ranging in different multidimensional impact areas.

A first key area can be identified considering **social equity and accessibility**. Indicators such as the affordability of public transport (PT) for the poorest group, access to transport services for mobility-impaired users, collectively assess how inclusive the transport system is. Some indicators are related to the **environmental impact** of mobility services. These indicators include greenhouse gas emissions, air pollutant emissions, noise hindrance, as well as energy efficiency that measure the environmental footprint of urban transport systems, ranging from air quality to public impact. A third dimension is **transport system performance and efficiency**. Congestion and delays, commuting travel time, and multimodal integration describe how effectively the system functions in terms of time, reliability, and connectivity. These indicators are crucial for understanding the operational quality of urban mobility and its capacity to meet demand efficiently. Another important area is **safety and health**. Road deaths and traffic safety for active modes directly address the risks associated with mobility. In parallel, the opportunity for active mobility (walking and cycling infrastructure) links safety with public health outcomes, emphasizing the role of urban transport in promoting healthier lifestyles. Finally, a broader **urban quality and spatial impact** perspective is captured through indicators such as quality of public spaces, urban functional diversity, and mobility space usage. These metrics go beyond transport itself and reflect how mobility systems shape urban form, land use, and the overall livability of cities.

The multidimensional assessment of urban mobility, from a methodological perspective, implies the integration of heterogeneous types of input data and measurement approaches [20]. Some indicators rely on **quantitative and model-based data** (e.g., emissions, energy consumption, vehicle-kilometers travelled), often derived from transport and environmental models that can be also captured by third party and sensors data (e.g., Floating Car Data, Air Pollutant IoT Sensors). Others require **geographical and spatial data**, typically managed through Geographical Information Systems (GIS), such as infrastructure layouts, accessibility buffers, land use distribution, and population exposure. A further group depends on **administrative or statistical records,** including road fatalities, demographic data, and public transport usage. Several indicators incorporate **qualitative and perception-based data**, collected through surveys, to capture user satisfaction, perceived safety, and quality of public spaces. Others require **mobility** specific spatial and temporal data, such as the General Transit Feed Specification (GTFS) for the time plan and stops for PT or the network topology often modeled as graphs to support traffic flow analysis and network-based computations. The 18 SUMI indicators

with details on impact area and data requirements for their computation are summarized in Table 1.

The computation of SUMI indicators presents challenges related to data sourcing and integration. Three indicators have been chosen to discuss the main challenges related to data heterogeneity integration, spatial analysis and incorporation of expert decision-based information to calculate the indicator.

S3 for example is a challenging indicator to compute not because of the complexity of the formula, but since it requires the integration of heterogeneous data sources. This indicator evaluates the impact of transport-related air pollution on human health within an urban area and the heterogeneity of the data is due to the nature of the pollutant emissions determined by all passenger and freight transport modes, including both exhaust and non-exhaust sources (such as tire and brake wear). The calculation relies on detailed activity data (vehicle-kilometers travelled) disaggregated by mode and vehicle type, which are typically estimated through traffic models, sensor networks, or mobility datasets and are subject to uncertainty and temporal variability. This must be combined with granular vehicle fleet composition data (fuel type and Euro class), which is often incomplete, outdated, or only available at aggregated administrative levels, requiring possible approximations.

Managing spatial based information is critical in mobility analysis. Indicators such as S6 require integrating information about population distribution in different radius from public transportation stops in the urban area of study. This information is mainly acquired by GIS based proximity analysis in combination of cross-reference with the population data. Additional challenges are related to the alignment of temporal data and the management of probably disaggregated heterogeneous transport data sources.

Other complexities may arise when the computation of specific indicators requires a decision performed by transportation experts on the urban road infrastructure, such as in S8. This indicator implies the identification of 10 transport representative corridors in the area of study to base the congestion level estimation. Corridor selection could be performed on urban mobility systems capable of managing the road infrastructure data [21] by transport operators to understand the real bottlenecks of the urban area. Data on travel times and trip volumes is often sourced from multiple systems, including local transport operators, floating car data (FCD), road IoT sensors that require temporal alignment and integration of these heterogeneous data sources.

To address the inherent complexity of calculating SUMI indicators, a dedicated system, i.e. the SUMI Manager, has been developed and integrated within the Snap4City platform [5, 22], an open-source Digital Twin environment designed for Smart City monitoring and planning.

3 SUMI Manager Architecture

The complexity of calculating SUMI indicators relies primarily on the high heterogeneity of the required data. In particular, the system must be capable of integrating information from multiple domains, including socio-economic statistics, public transport operational data, and urban planning datasets. All these heterogeneous data sources require specific data acquisition and representation methods. The system must support both the direct

Table 1. SUMI indicators summary table.

SUMI	Description	Impact Area	Input	Output
1 (core) Affordability of public transport for the poorest population	Share of the household budget of the poorest quartile (25%) of the population required to purchase public transport passes (unlimited monthly travel or equivalent) in the urban area of residence.	Social equity and accessibility	Administrative: Monthly PT pass prices from authorities and average household size from municipal records; Quantitative: Average monthly income from the poorest 25%; Geographical: Spatial alignment of socio-economic data with urban boundaries	Affordability score (% household budget towards PT services)
2 (core) Accessibility of public transport for mobility-impaired groups	Determines the accessibility of public transport services for persons with reduced mobility (PRM) by evaluating the proportion of facilitated services across vehicles, stops, and ticket offices	Social equity and accessibility	Administrative: Records from local transport operators on accessible moving assets, stations, and ticket machines; Mobility: Annual ridership numbers per transport mode used to calculate modal weights; Quantitative: Percentage of accessible features across all modes	Overall accessibility score (% of services facilitated)
3 (core) Air Pollutant Emissions	Measures total emissions of Nitrogen Oxides NOx and Particulate Matter PM2.5 from all passenger and freight transport modes, including exhaust and non-exhaust sources	Environmental impact	Quantitative: Activity volume (million vkm/year), exhaust emission factors, and non-exhaust emission factors (g/km); Administrative: Vehicle stock composition (shares of fuel types and emission classes) from statistical records; Geographical: Total inhabitants (capita) and spatial alignment with urban area boundaries	Emission Harm equivalent Index (EHI in kg PM2.5 eq./cap per year)
4 (core) Noise hindrance	Measures the percentage of the population hindered by noise generated by urban transport (road, rail, air) based on exposure bands L_{den}	Environmental impact	Geographical: Population exposure per noise band (from EEA noise maps or GIS data); Quantitative: High Annoyance weight factors and hindrance factors	Hindrance Index (NI as % of hindered population)
5 (core) Road deths	Evaluates traffic safety by measuring the number of fatalities (within 30 days of an accident) per 100,000 inhabitants.	Safety and Health	Administrative: Yearly statistical records of persons killed per transport mode; Geographical: Total urban population (capita).	Fatality Rate (FR per 100,000 inhabitants)

(*continued*)

Table 1. (*continued*)

SUMI	Description	Impact Area	Input	Output
6 (core) Access to mobility services	Share of the population with appropriate access to public transport, considering both proximity to stops and service frequency.	Social equity and accessibility	Geographical: Population distribution within GIS-calculated buffers (417 m and 833 m); Mobility/Administrative: PT stop locations and average hourly departures (frequency) from timetables.	Appropriate Access Index (AccI as % of population)
7 (core) Greenhouse gas emission	Total well-to-wheels CO2 equivalent emissions produced by all passenger and freight transport modes.	Environmental impact	Mobility: Activity volume (million vkm/year) per mode; Administrative/Quantitative: Vehicle stock composition (fuel/Euro class share), energy intensity, and emission factors; Geographical: Total urban population (capita).	Tons of CO_2 eq. per capita per year
8 (core) Congestion and delayes	Measures peak-hour delays for private and public transport on representative corridors compared to off-peak or optimal times.	Transport system performance and efficiency	Mobility: Peak and off-peak travel times on 10 road and 10 PT corridors (often from Floating Car Data); Administrative: Modal shares; Mobility: trip volume per corridor	Congestion and Delay Index (% delay during peak-hour traffic)
9 (core) Energy Efficiency	Measures the total energy use by all urban transport modes per unit of transport volume, calculated as an annual average across passenger-kilometers and tonne-kilometers	Environmental impact	Quantitative: Activity volume and transport volumes, fuel consumption factors; Administrative: Vehicle stock composition (shares of fuel types) and fuel energy content constants; Mobility: Modal split data used to derive transport volumes; Geographical: Spatial alignment of transport activity with urban boundaries	Energy consumption rate (MJ/km)
10 (core) Opportunity for active mobility	Evaluates the infrastructure for walking and cycling by measuring the length of roads with pavements, bike lanes, 30 km/h zones, and pedestrian zones relative to the total urban road network	Safety and health	Administrative: Official records of 30 km/h zones and pedestrianized streets; Quantitative: Lengths of pavements (min. 0.6 m width) and bike lanes (min. 0.75 m width); Geographical: Total city road network length (excluding motorways)	Share of road length adapted for active mobility

(*continued*)

Table 1. (*continued*)

SUMI	Description	Impact Area	Input	Output
11 (core) Multimodal integration	Evaluates the average level of connectivity at urban interchange points by measuring the variety of transport modes available at each hub	Transport system performance and efficiency	Administrative: Network characteristics from PT operators and facility data from local administrations; Geographical: Identification of interchange locations and assessment of physical barriers (e.g., rivers, heavy traffic); Quantitative: Binary (YES/NO) availability of 10+ specific modes per hub.	Multimodality Index (average share of available modes across all interchanges)
12 (core) Satisfaction with public transport	Measures the perceived satisfaction of residents regarding PT affordability, safety, ease of access, frequency, and reliability	Social equity and accessibility	Qualitative: Perception survey responses from approximately 500 telephone interviews (e.g., "satisfied" to "not at all satisfied"); Administrative: Data from the EC's Urban Audit or existing operator surveys	Average reported satisfaction (%)
13 (core) Traffic safety active modes	Assesses the risk for pedestrians and cyclists by relating the number of fatalities to their actual exposure in terms of total trips	Safety and health	Administrative: Yearly fatality records for pedestrians and cyclists (3-year average); Mobility: Exposure data representing the annual number of trips in millions per mode; Quantitative: Calculated risk factor per billion trips	Risk Factor (fatalities per billion trips)
14 Quality of public spaces	Measures resident satisfaction with green spaces (parks/gardens) and non-green public spaces (markets, squares, pedestrian areas)	Urban quality and spatial impact	Qualitative: Perception survey data (Urban Audit or local surveys) regarding satisfaction with specific public space dimensions	Average reported satisfaction with green and non-green areas (%)
15 Urban functional diversity	Measures the mix of spatial functions (e.g., schools, shops, parks) within 1 km x 1 km grids to evaluate the proximity of daily activities to residential areas.	Urban quality and spatial impact	Geographical: Division of city territory into 1 sqkm grids; Administrative: Population distribution per grid zone; Quantitative: Binary presence (0 or 1) of 10 specific daily functions per grid.	Functional Diversity Score (FDS %)

(*continued*)

Table 1. (*continued*)

SUMI	Description	Impact Area	Input	Output
16 Commuting travel time	Measures the average daily duration of travel to and from work or educational establishments for all transport modes.	Transport system performance and efficiency	Qualitative: Mobility survey data regarding trip durations; Mobility: Modal breakdown (car, PT, bike, walking) and average travel times to/from destinations; Administrative: Survey metadata.	Average commuting travel time (minutes/day)
17 Mobility space usage	Assesses the proportion of land used for all urban transport applications, including both direct (roads, rails) and indirect (parking, stations) uses.	Urban quality and spatial impact	Geographical: Total number of city inhabitants (capita); Administrative: Land use records for transport categories; Quantitative: Hectares (ha) of roads, railways, ports, parking, and logistics centers.	Mobility space usage per capita m^2/cap
18 Security	Evaluates the perceived risk of crime and passenger security within the city transport system across various modes and times of day.	Safety and health	Qualitative: Perception survey data regarding feelings of safety (Very safe to Very unsafe); Administrative: Survey demographics ensuring adequate representation of mode users and gender; Mobility: Alignment of survey participants with local modal split.	Perceived Security Score (SEC)

input of pre-calculated indicators and the computation of indicators from raw data, requiring a flexible interface capable of handling different formats, measurement units, and levels of data processing. In addition, data management involves careful temporal and spatial synchronization: all inputs must be aligned with specific validity periods and clearly defined geographic contexts, such as cities like Florence, Pisa, or Siena, to ensure consistency and comparability of results. From a management perspective, the acquisition process also involves complex data flows, both internal and external, which must be authenticated, secured, and compliant with privacy requirements (e.g., GDPR). Furthermore, to transform raw data into actionable insights, the system incorporates visual analytics and interactive business intelligence tools, enabling users to engage directly with maps and charts within a dashboard environment.

The Snap4City SUMI Manager has been developed exploiting the architecture and functionality offered by the platform. Snap4City provides efficient data ingestion pipeline during which data are semantically indexed in the knowledge base and shadow stored in a NoSQL database [23]. On the other hand, ingested data are made available to processes [24] and dashboards [25] with dedicated API capable to retrieve information with relational, temporal and geographic queries, exploiting both Client-Side

[26] and Server-Side [27] Business Logic (CSBL and SSBL). To facilitate the ingestion and retrieval of entities belonging to the same category and force their adherence to a well-defined format, data model can be created and exploited to instantiate new entities.

The SUMI Manager exploits different data models. At first, each of the 18 SUMI has been represented with a dedicated model defined according to the variables required to carry out the specific SUMI computation. For example, for SUMI S1 (Affordability Of Public Transport for the Poorest Group) the data model includes the variables *avgIncome*, *avgHouseholdSize*, and *ptPrice*, respectively representing the average monthly income of the 25% poorest inhabitants, the average household size, and the monthly price for public transport services. In addition to the variables required for the computation, each data model includes a *dateObserved* variable to set the date-time. In this way it is possible to obtain temporal sequences of the data, useful to be stored and observe their evolution during time. Then, a general SUMI model is defined including a *dateObserved* variable and 18 additional variables, each one dedicated to store the computed values for each one of the 18 SUMI.

Data required to compute the indicators are information related to the urban context, like, for example, public transport stops, positions of bike sharing parking, locations of services, population income, etc. This information is modelled with additional data models and can be exploited to facilitate the computation of specific SUMI variables. Part of these data is already available into the Snap4City platform; when missing it must be ingested in order to enable the automatic computation of the SUMI.

The overview of the architecture of the SUMI Manager is provided in Fig. 1. SUMI Manager is composed by a frontend implemented using the dashboard system of Snap4City and including CSBL for managing both interface interactivity and data ingestion and retrieval. In addition, SSBL is used to implement processing logic for computing the SUMI and for elaborating possible preliminary data. All the created entities with their variable are saved in the Snap4City storages (including indexing in the knowledge base, built according to the KM4City ontology, and shadow storing in NoSQL databases).

First, the user must create an entity representing the city for which computing the SUMI, thus defining the spatial context. This is achieved exploiting the *Create new city* functionality in the dashboard. API calls, implemented in CSBL in the *Add new city* process, allow to retrieve the SUMI Model and all the 18 models of the single SUMI and then proceed to create the entities for the specific city into the Snap4City knowledge base. At this moment, all these entities are empty, without any data in their variables.

To insert data and enable the computation of the SUMI, the user must select a date-time (corresponding to the validity period of the SUMI to be ingested) and use the *Insert SUMI Data* functionality. SUMI Manager provides three different ways to ingest SUMI data. In the first solution, the user directly provides the value of the SUMI. In this case the SUMI Manager acts as a simple storing interface. A second solution allows the user to provide the information that is required for the computation of the SUMI, as for example the average household size for SUMI S1. With dedicated API in CSBL these data are ingested in the respective SUMI_X devices (with X indicating a SUMI from 1 to 18). The third solution offers a fully automatic computation: using the *Load Preliminary Data* functionality, SUMI Manger searches for available data in the Snap4City storages (considering also the selected date-time and the spatial context to retrieve data in the

correct time span), and whether all the required information is found, it automatically fills the interface fields with the retrieved values. Then the user continues as in the second ingestion solution submitting the data to the SUMI_X devices. Differently, if not all the required data are found, an error message is returned to the user.

In all the three cases, when a new data ingestion is carried out, a message is sent to the *SUMI MailBox* entity. Sending a message to the mailbox activates a listener placed in the SSBL *Proc. Logic: Compute SUMI* and starts the execution of a processing flow devoted to the computation of the indicator and their ingestion in the general SUMI entity of the city.

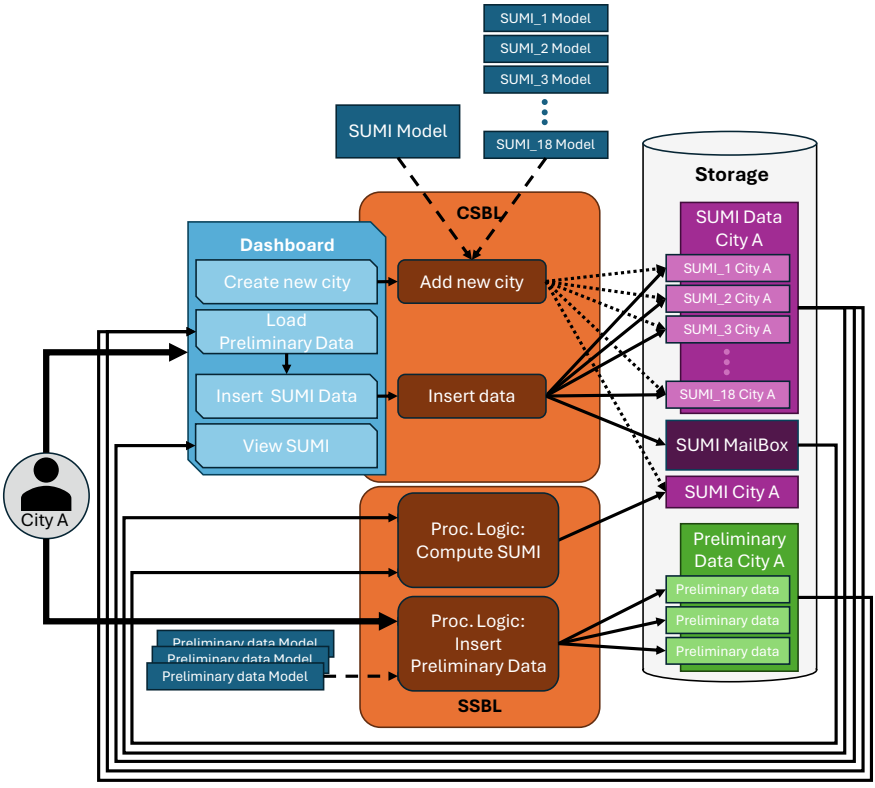

Fig. 1. SUMI Manager architecture.

Once computed and ingested, the indicators can be retrieved and visualized with the *View SUMI* functionality populating different plots including a temporal evolution of the indicators, so as to allow the user to observe the trends and identify the most critical problems. Details on the user interface with example of the SUMI Manager dashboard are provided in **Sect. 4**.

As described above, to enable the automatic SUMI computation, preliminary data must be available into the Snap4City platform. In the case such data are missing, the user has the possibility to provide by itself the required information. In this case, a dedicated

Proc. Logic flow must be developed to create and ingest new entities according to a set of predefined models. These data models must be used to ensure that the data are ingested with a format compatible with the SUMI Manager logics. Note that this responsibility is left in the hand of the user, since most of the missing data are usually provided in specific format and not always freely accessible, therefore it would be impossible to preload all these data without specific user knowledge and access rights.

Finally, it is worth noting that Snap4City is a multi-user and multi-tenant platform and enforces entity and resource ownership in compliance with privacy regulations. For this reason, SUMI Manager has been developed considering two main roles: a managing role *sumi_admin* and a user role *sumi_user*. Only one *sumi_admin* is admitted, and it is the owner of all the data models, the dashboard, the *Compute SUMI* processing logic and of the entity *SUMI MailBox*. Differently, multiple *sumi_user* are possible (ideally any municipality should have its *sumi_user*). *sumi_user* is the owner of the SUMI devices (the global one and all the 18 for the indicator data) as well as all the entity with preliminary data created and ingested by itself. To allow the SUMI Manager to work, respecting the ownership rights, the delegation mechanism of the Snap4City platform has been exploited. The dashboard and the data models have been made public, so as to be accessible by any user. Note that a user can load and visualize in the dashboard only its owned data. The *SUMI MailBox* has been delegated only with write permission to any *sumi_user* to allow them to send messages into it and prevent them to read messages from other users. On the other hand, all the SUMI entities have been delegated to the *sumi_admin* to allow the *Proc. Logic Compute SUMI* to retrieve the necessary data and ingest the computed indicator.

Figure 2 shows the sequence diagram of the SUMI Manager. A user interacts with the SUMI Dashboard, CSBL initializes the widgets and retrieves the list of available cities. When a new city is added, the system creates the corresponding city SUMI entity with the 18 SUMI_X entities used to store the indicator input data. The user can enter the data required for the indicators either directly or by calculating it from the input variables, optionally retrieving information from the Snap4City knowledge base. After submission, a message is sent to the SUMI MailBox, which triggers the Compute SUMI *Proc. Logic* (SSBL). The *Proc. Logic* retrieves the input data, computes the SUMI indicators, and saves the final values in the 18 SUMI_X entities. Finally, the dashboard retrieves the indicators and updates the visualization widgets, allowing the user to observe the last values and their temporal trends.

4 SUMI Dashboard and System Validation

An interactive dashboard (as shown in Fig. 3) is provided by the SUMI Manager built on top of the Snap4City platform [25]. Within the dashboard, data management operations such as adding a new city are supported; SUMI values can be computed by defining the validity period, selecting the computation mode or directly inserting the indicator value; besides, both the indicator values and their trends over time can be visualized across different cities.

In the SUMI Manager dashboard, a new city can be added (Fig. 3-d) and multiple cities can be managed (Fig. 3-a), enabling comparative analysis between different urban

contexts. When a new city is added, the entities required to store the values of all SUMI indicators and the related input data are automatically generated, as described in **Sect. 3**.

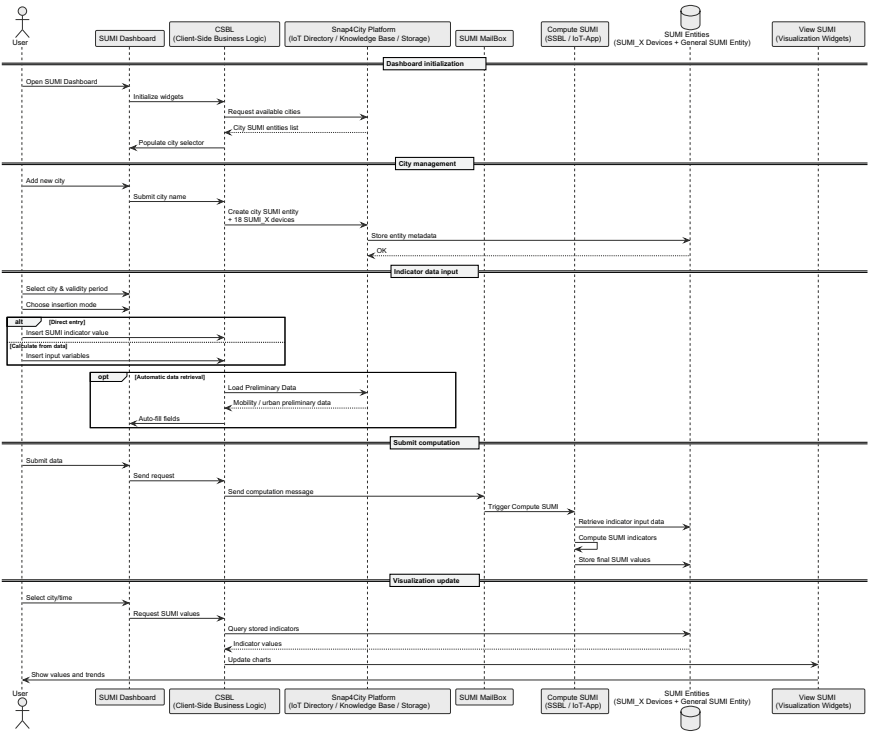

Fig. 2. SUMI Manager sequence diagram.

In addition, users can manually enter indicator values or provide the input parameters necessary for automatic indicator calculation. In Fig. 3-e, the indicator, the validity period (start and end date), the computation mode and the city can be selected. The SUMI Manager supports three data ingestion modes: (i) indicators can be directly inserted manually; (ii) they can be computed from user data: in this case, for each selected indicator the system requests the specific input variables required for its computation, corresponding to the parameters listed in Table 1 (column Input); (iii) finally, if the required data are available within the Snap4City platform, the system can automatically retrieve them from the knowledge base, enabling the automatic pre-filling of the fields required for indicator computation**.** Figure 3-f shows an example of input variables for indicator S12.

Finally, the dashboard provides data visualization tools (Fig. 3), allowing users to analyze indicator values over time and across different cities, both in terms of the latest available value (Fig. 3-b) and their time trend (Fig. 3-c). The visualization area includes time-series, bars, and radar charts, supporting the identification of SUMI indicators.

The proposed SUMI Manager has been validated through functional testing by creating multiple city instances (Florence and Pisa), using partially simulated data for different

Fig. 3. SUMI Manager dashboard.

SUMI indicators, and entering values in both direct mode and indicator calculation mode. It is worth noting that the process of retrieving all the required involves a considerable complexity, and this is typically entrusted and carried out by public administration officers. The validation focused on verifying the correct integration of the various system components, including data acquisition, indicator calculation and visualization (comparing values of indicator over time and among cities), as well as the correct management of data ownership and delegation permissions. A broader validation on fully real-world datasets, including a comparison with traditional manual SUMI computation workflows, is left to future work. The scalability of the system is ensured by the Snap4City platform, which currently manages a large number of users, entities and services. In particular, it

includes 25 organizations, 3,127 users and developers, over 122,000 entities, 885 processing logic instances, and 2,316 dashboards/views, with approximately 2.6 million data entities ingested per day [26, 28].

5 Conclusions

In this paper, an innovative framework for computing, managing, and monitoring the Sustainable Urban Mobility Indicators (SUMI) has been presented. This work addresses a practical and widely recognized gap in the adoption of SUMI: despite their relevance as a standard framework for assessing urban mobility sustainability, public administrations still lack solutions that enable their computation and monitoring in a simple, systematic, and scalable way. To bridge this gap, the SUMI Manager has been proposed, implemented on top of the Snap4City Digital Twin platform, with the goal of supporting municipalities in managing the heterogeneous data required by the indicators, computing SUMI values, and visualizing their temporal evolution through interactive dashboards and the comparison of the SUMI indicators among different cities. The SUMI Manager provides a unified operational framework that supports multiple ingestion modes (i.e., manual insertion of indicator values, computation from user-provided input variables, and automatic pre-filling and computation when preliminary data are available within the platform), thus enabling gradual adoption under different data availability conditions. In addition, the integration with the Snap4City knowledge base and data models supports reproducibility and standardization, by allowing structured representations and facilitating the computation of SUMI variables. The validation of the proposed system included functional testing on multiple city instances, verifying the correct integration of the various components, for instance: data acquisition, indicator computation and visualization. The results highlight the feasibility of deploying the SUMI Manager as a reusable service across different municipalities, leveraging the multi-tenant and scalable nature of the Snap4City ecosystem, while respecting ownership and privacy constraints through its delegation mechanisms.

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AI-Enabled Video Analytics for Urban Mobility Digital Twins: A Microsimulation Study of the Via Caronda Corridor in Catania

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Abstract. Urban traffic cameras are increasingly available in metropolitan areas, yet their potential as operational data sources for simulation-based planning is still underexploited. This paper proposes an integrated framework that converts fixed-camera video streams into microsimulation-ready traffic inputs, combining AI-based vehicle detection, tracking, and movement counting with scenario-based traffic modelling. The proposed framework advances AI-driven urban analytics for transport planning by bridging urban video analytics and planning-oriented microsimulation. We move beyond approaches focused either on traffic detection alone or on simulation based on manual counts, linking data acquisition, model input generation and scenario-based decision support within a unified workflow. The work is framed within the broader UISH (Urban Intelligence Science Hub) perspective for the city of Catania, where existing municipal surveillance cameras are envisaged as part of a future pervasive and privacy-aware urban sensing infrastructure. The aim is to assess the technical feasibility of video-based traffic monitoring and demonstrate its operational value for urban planning by embedding AI-derived traffic observations into a microsimulation environment for ex-ante scenario evaluation.

The methodological workflow converts video observations into directional traffic flows. Then, data is used to feed and calibrate a microsimulation model for ex-ante scenario assessment. The approach is tested on a real-world case study in Catania (Italy), on Via Caronda corridor, considering the hypothesis of reopening a direct access to the ring road. Results demonstrate that the tested intervention, although envisioned to improve direct accessibility, produces a reduction in effective road capacity and a worsening in traffic performance during peak-hour conditions. We registered a decrease in levels of service and increases in average travel times along selected movements. Beyond the specific case study, the paper highlights the value of integrating urban video streams into simulation environments as a scalable solution for control rooms, traffic management in the view of mobility digital twins.

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1 Introduction

Urban mobility planning involves timely spatially detailed and operationally reliable traffic data to support evidence-based decisions. In modern cities, traffic conditions change rapid for recurrent congestion with local bottlenecks and infrastructure changes which create temporary disturbances. Traditional traffic surveys, even if still used, depend on manual counts or short observation campaigns on selected sections. These approaches are useful for calibration, but they are constrained by significant human-resource requirements, limited temporal coverage and a reduced ability to capture the full dynamics of complex intersections with multiple movement traffic patterns. Therefore, they give only a partial representation of the real traffic conditions, especially when planners need continuous observation for scenario assessment.

In this context, fixed urban cameras represent a promising yet underexploited source. Municipal traffic cameras can observe in continuous the critical nodes and give a fuller description of the traffic dynamics. Their value becomes greater if the video streams are combined with artificial intelligence (AI) for vehicle detection tracking and movement recognition. Through these techniques, the raw footage is transformed into structured traffic information: directional flows, turning movements trajectories and speed indicators. This makes the urban video streams relevant not only for traffic monitoring, but also for transport modelling and simulation-based planning.

In this regard, the developments in computer vision have expanded the video analytics for traffic observation. Research shows that AI-based detection can get reliable vehicle recognition in complex environments enabling more automated traffic data collection. The diffusion of digital platforms and the emergence of mobility digital twins are changing how we monitor transport systems. Cities want data pipelines connecting observation technologies traffic models and decision-support tools, but the operational use of fixed-camera streams for simulation planning remains less explored. Many studies focus on the technical performance of the detection pipeline: object recognition, accuracy, counting precision, tracking robustness. These aspects are very relevant, but they do not answer a key planning question: how to translate video-derived observations into model-ready traffic inputs for scenario assessment? And the microsimulation models used for evaluating road changes and traffic measures are still fed by manual counts or short surveys? This is a gap between AI-based traffic observation and simulation-based decision support. Bridging this gap is relevant for the urban mobility digital twins where data streams should not stay isolated monitoring outputs but should actively update and inform the simulation environments.

Starting from this, the paper proposes an integrated framework that transforms urban video streams from fixed municipal cameras into directional traffic inputs for microsimulation-based scenario analysis. The framework puts together AI-enabled video analytics with a transport simulation model to support urban planning decisions and the development of mobility digital twins. The idea is that urban cameras are not passive

observation devices but strategic parts of a decision-support architecture able to feed traffic control rooms calibration and policy evaluation.

This research also fits within a broader urban-intelligence perspective currently being developed for the city of Catania in the framework of the UISH (Urban Intelligence Science Hub) project. Within this ecosystem, mobility monitoring is conceived as part of a wider Digital-Twin-oriented architecture in which heterogeneous sensing layers, shared data infrastructures, and future decision-support functionalities are expected to interact continuously. In this perspective, the use of fixed urban surveillance cameras already installed across the city represents a particularly promising opportunity for the progressive development of pervasive, privacy-aware traffic observation pipelines capable of feeding both localized simulation models and future city-scale mobility analytics.

The approach is tested on a real case study in Catania (Italy), i.e. the Via Caronda corridor and considering the idea of reopening a direct access to the ring road. This case is important because it is a critical node where an intervention that looks good for direct accessibility can create broader effects on the network operations. Microsimulation helps to see these effects before doing the work and video-derived traffic flows show how AI-based observation can make more realistic simulation inputs.

The contribution is double. First, it shows that traffic information elaborated from fixed-camera video streams can be structured as input for microsimulation models linking computer-vision with transport planning. Second it demonstrates how this integration can help ex-ante assessment of local road changes and provide evidence on impacts of alternative scenarios. Our framework bridges the two aspects in a planning view, unlike studies that consider only at video traffic detection or only at microsimulation with manual counts. Beyond this, the paper also contributes on AI-supported urban analytics. It highlights the role that video data continuously available can make more robust the analytical capabilities of public administrations, especially if integrated with simulation tools and digital twin logics. This is relevant for cities that want to improve responsiveness of mobility management, make better infrastructure choices and move toward data-driven governance. Therefore, our research framework highlight that the value of AI in planning is to turn observed traffic phenomena into knowledge for scenario design.

The remainder of the paper is organized as follows. Section 2 presents the state of art; Sect. 3 proposed methodological framework, from video acquisition and processing to microsimulation input generation. Sect. 4 introduces the study area and describes the analyzed traffic scenario. Section 5 discusses the results of the simulation-based assessment, comparing the current road configuration with the tested intervention hypothesis. Finally, Sect. 6 summarizes the main findings, outlines the planning implications, and discusses future developments toward a more comprehensive AI-supported mobility digital twin.

2 Related Work

The literature for this study can be positioned considering three components: AI-based video traffic monitoring, use of observed traffic data for transport simulation, and mobility digital twins for planning. To review these domains together is essential, because the

contribution here is not only video analytics and not only microsimulation and the real point is the methodological bridge between them.

2.1 Video-Based Traffic Monitoring and AI

Video-based traffic monitoring has gained increasing attention as advances in computer vision and deep learning have enabled more reliable extraction of traffic information from image streams. Recent review papers have highlighted the growing role of camera-based systems, fixed and aerial, in traffic surveillance, vehicle counting, trajectory reconstruction, and congestion analysis [1, 2]. The transition from manual interpretation to automated AI-enabled pipelines has improved a lot the scalability of traffic monitoring, especially in complex urban environments where many movements happen at the same time.

A substantial part of recent literature has focused on vehicle detection and tracking from video using deep-learning architectures. For example, [3] investigated road traffic monitoring from UAV images with deep learning networks, while [4] proposed a deep-learning-based image segmentation approach for traffic analysis from UAV streaming [5]. showed that UAV videos can extract key traffic parameters validated against on-board vehicle data, and [6] demonstrated the potential of drone-based large-scale traffic observation through the pNEUMA experiment. Altogether these studies confirm that AI-based video processing can support not only vehicle detection and counting, but also richer outputs like trajectories, lane usage, and movement patterns. Despite these advancements the major focus of literature is still mainly technical. Most contributions assess the accuracy of detection models, the robustness of tracking procedures, or the quality of traffic parameter extraction under specific imaging conditions. At the same time, less attention has been given to the transformation of video-derived observations into structured inputs for transport models and scenario-based planning. This issue is relevant when considering fixed municipal cameras, that are increasingly available in urban areas and may act as continuing sensing infrastructures for mobility management. In this respect, the challenge is not only to detect vehicles accurately, but also to organize video-derived information into traffic variables, such as directional flows and turning movements, suitable for simulation and decision support.

Beyond technical performance, the use of urban video streams raises also broader issues related to privacy, transparency, data governance, and responsible use. To employ fixed cameras as long-term traffic sensing devices, the design of the analytical pipeline should consider data minimization, operational explainability and aggregation procedures to support planning without unnecessary exposure of private information. These aspects are not in the core of transport engineering studies, but they are increasingly important in AI-enabled urban planning applications.

2.2 Video-Derived Data for Transport Simulation

Transport simulation has traditionally relied on observed traffic data for model calibration, demand estimation and validation. Relevant studies on traffic counts and O-D matrix estimation showed that observed flows are essential for updating travel demand representations and improving the predictive quality of transport models [7–9]. In this regard,

measured counts are not simple descriptive data, but core elements for reconstructing the interaction between transport demand and network supply.

At the operational level, microsimulation models are widely used to assess traffic performance under alternative management or infrastructure scenarios, but their validity is strongly influenced by proper calibration and validation. Comparative studies on car-following behaviour and simulation calibration have long emphasized the need to align model outputs with observed traffic conditions before using simulations for decisions [10, 11]. More recent works confirm that simulation-based assessment remains highly dependent on the quality, spatial coverage, and representativeness of the empirical traffic inputs used to feed the model.

Within digital-twin-oriented applications the integration of observed data into simulation models has become even more important [12]. presented a case study within Digital Twin Munich where loop-detector data were used for calibrating a microscopic traffic simulation [13, 14]. proposed an integrated approach for O-D matrix calibration using empirical traffic counts and a macro-simulation framework, highlighting how heterogeneous traffic data can be progressively embedded into simulation environments supporting a Digital Twin of Mobility. These studies demonstrate that transport simulation is moving away from isolated modelling exercises toward more data-connected architectures.

But a specific gap remains for video-derived data. While transport simulation routinely uses manual counts, loop detectors, radar sensors, or aggregated survey data, the direct operational use of traffic variables extracted from urban video streams is still limited. There is a lack of studies that address explicitly how AI-processed video data can be transformed into movement-based demand inputs for microsimulation. This gap is relevant for urban nodes where directional flows, route choices and localized conflicts must be represented with high spatial detail. The present work addresses this issue by using video-derived turning movements as model inputs for scenario-based microsimulation.

2.3 Mobility Digital Twins for Urban Planning

The concept of digital twin has progressively appeared in transport and planning literature, as a framework for integrating data, models and decision support. A recurrent distinction is pointed out between conventional models and digital twins: both aim to represent a physical system, but digital twins are expected to maintain a closer and more dynamic connection with the real-world through continuous and recurrent data updates [15]. In urban studies digital twins have been described as key components of smart-city strategies, able to support what-if analyses, performance monitoring and multiple scenario planning [16].

In the field of mobility, digital twins have been framed as virtual environments where transport infrastructures, demand patterns, traffic conditions and operational services can be jointly represented and evaluated [17]. provided one of the most systematic conceptualizations of the mobility digital twin, defining its architecture, case-study logic and future research directions. And other contributions have stressed the role of real-time or near-real-time data integration for enabling predictive analysis and simulation-based management. For example, [18] discussed the synergy between traffic data streams

and simulation for virtualizing motorway dynamics, while [19] addressed the empirical challenge of building and validating a large-scale traffic digital twin for Barcelona.

A further line of research concerns the urban-planning use of digital twins as decision-support environments and not only visualization platforms [20]. emphasized the importance of mobility and transport data for city digital twin modelling and exploitation, and [21] discussed the design of smart-city digital twins with 3D representation and what-if analysis capabilities. In this same perspective recent applications have shown how simulation-centred digital twins can support evaluation of urban interventions [22]. proposed a digital twin simulation framework for assessing street experiments in Acireale, while [23] highlighted the importance of integrating real-time communication, heterogeneous data, and transport models within the SAMOTHRACE smart mobility framework.

The literature suggests that mobility digital twins are evolving toward increasingly integrated ecosystems, where sensing technologies, transport models, and decision-support tools interact in a continuous loop. But one of the main unresolved issues is the transformation of heterogeneous observational data into model-ready information. In practice this means that the effectiveness of a mobility digital twin depends not only on the simulation engine itself, but also on the quality of the pipeline linking field data acquisition, traffic variable extraction, demand reconstruction, and scenario evaluation. In this context fixed urban cameras represent a potentially valuable but still under-used source of information. The present study contributes to this research direction by proposing a framework in which video-derived traffic flows are directly used to support microsimulation-based planning, so reinforcing the operational link between urban sensing and mobility digital twins.

3 Methodological Framework

The proposed methodology is structured as a multi-step framework aimed at linking urban video analytics with traffic microsimulation for planning-oriented applications. Figure 1 summarizes the proposed methodological framework, which consists of three main phases: (i) video acquisition from fixed traffic cameras and AI-based extraction of traffic information, (ii) transformation of the extracted observations into simulation input data and (iii) microsimulation-based scenario assessment. Following this research approach, the raw video streams are progressively converted into operational knowledge that can support the evaluation of traffic management and infrastructure modifications.

The rationale behind this framework is that the urban traffic cameras are treated as part of the existing sensing infrastructure of the city, thus providing a continuous and spatially detailed source of traffic observations. Their value for planning lies in the possibility of converting image-based observations into model-ready traffic variables. And in this respect the methodology is designed to bridge the gap between AI-based traffic monitoring and simulation-based decision support, within a perspective that is coherent with the progressive development of a Mobility Digital Twin.

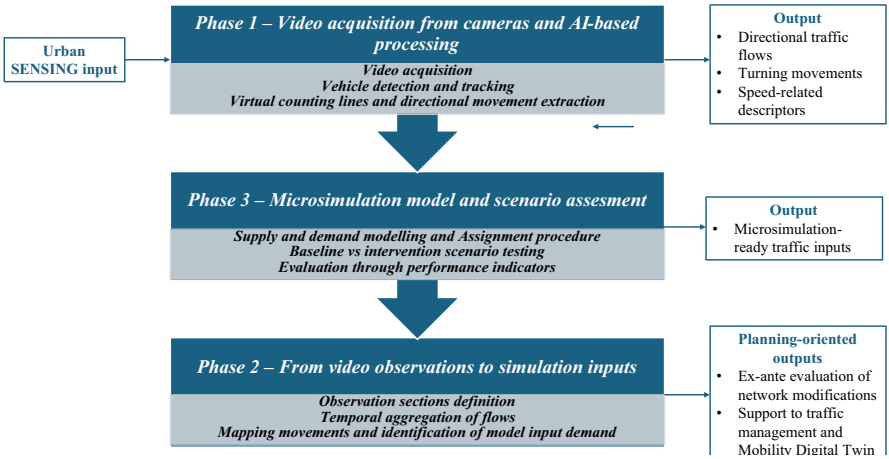

Fig. 1. Workflow of the proposed methodological framework

3.1 Video Acquisition from Fixed Cameras and Processing Pipeline

The first phase concerns the acquisition and processing of video streams collected from fixed urban cameras. Different from temporary survey devices, these cameras are considered like already available elements of the urban monitoring infrastructure, potentially suitable for recurrent or continuous observation of critical road nodes. In the specific case of Catania, this perspective is consistent with the broader UISH framework, within which existing municipal video-surveillance infrastructures are envisaged as part of a distributed observational backbone for future Digital Twin applications. The present case study should therefore be interpreted not only as a stand-alone local test, but also as a proof-of-concept for the progressive integration of AI-based video detection into a wider city-scale monitoring ecosystem. This makes them particularly relevant for applications in urban traffic management, control-room support, and simulation-based planning.

To extract traffic information from the recorded footage the methodology relies on an AI-based processing pipeline including vehicle detection, tracking, and movement counting. In line with recent video analytics approaches each frame is processed to identify vehicles and associate them across consecutive frames, so reconstructing their trajectories within the observation area. This step is essential to move beyond frame-by-frame counting and to interpret vehicle movements as continuous trajectories across the monitored junction or corridor. After reconstructing the vehicle trajectories, virtual counting lines and movement-specific zones are defined inside the video scene. These virtual elements act as digital observation sections and allow the system to detect crossing events and directional transitions. In this way, each tracked vehicle can be assigned to a specific movement pattern according to the sequence of lines or zones crossed during its path. This approach makes it possible to estimate turning flows, directional distributions, and, more generally, the traffic patterns at the observed node. The use of virtual counting sections is particularly advantageous in complex urban intersections, where multiple simultaneous manoeuvres must be observed without interfering with traffic operations. Compared with conventional manual counts, this solution enables a

more systematic reconstruction of vehicle movements and reduces the dependence on human presence on-site. In addition, when image resolution, perspective conditions, and geometric calibration are sufficiently robust, the same pipeline may also provide complementary descriptors like approximate speed-related information, lane usage and potentially non-compliant manoeuvres.

In our framework however the core output of the video processing phase is represented by directional movement flows, which constitute the most reliable and directly usable information for the simulation stage.

3.2 From Video Observations to Simulation Inputs

The second phase consists in converting video-derived observations into traffic inputs suitable for microsimulation. This step represents the methodological core contribution of our framework, because it transforms image-based information into planning-oriented variables for model calibration and scenario assessment. To this end, the monitored area is first schematized into observation sections corresponding to main entries, exits, and internal movement paths of the study network. Then, the directional traffic information extracted from the video is organized according to these sections and aggregated over selected time intervals. Temporal aggregation is necessary to convert individual vehicle trajectories into stable traffic flow variables that can be assigned within the simulation model. Moreover, the selection of the aggregation interval depends on objectives of the analysis and variability of traffic conditions, but it should remain consistent with the temporal resolution adopted in the simulation. After aggregation observed movements are translated into traffic demand inputs by associating each directional flow with the corresponding turning movement or travel path in the network model. In practice, the set of video-derived movements is used to reconstruct the local demand structure at the analyzed junction or corridor, ensuring coherence between empirical observation and simulated traffic patterns. This is especially relevant in urban contexts with multiple route alternatives, restricted manoeuvres, and localized congestion, where simple link counts may not reproduce actual operational conditions.

Compared with conventional manual counting campaigns the proposed approach offers two main advantages. First, it allows simultaneous observation of several movements within the same observed scene, improving completeness of the traffic dataset. Second, it provides a more scalable procedure for updating simulation inputs over time, enabling repeated calibrations or scenario checks as new video observations become available. Additionally, if speed estimates are sufficiently reliable, they may be used as complementary calibration information; however, in the present framework flow and movement data remain the primary simulation inputs, as they are the most robust outputs of the video-processing pipeline.

3.3 Microsimulation Model and Performance Indicators

The third phase is about the implementation of the microsimulation model and the definition of performance indicators used for scenario assessment. The model reproduces the geometric and operational characteristics of the analyzed road network, including lane configuration, turning connectors, permitted manoeuvres, priority rules, and conflict

areas at junctions. This represents the supply side of the system, and it is essential for capturing the local operating conditions, in order to shape traffic behaviour.

On the demand side the traffic flows derived from video observations are assigned to the corresponding paths and directional movements identified within the network. In this way the simulation environment reproduces the interaction between the reconstructed transport supply and the empirically observed demand pattern. Traffic dynamics are simulated through a car-following and lane-changing logic capable of representing local propagation of queues, the interaction among competing flows, and the resulting variation in operational performance under different configurations.

Once the base model is implemented alternative scenarios can be tested by modifying the network configuration or the movement structure associated with the analyzed intervention. This enables ex-ante evaluation of road-network changes before physical implementation, supporting planning decisions with a risk-free virtual environment. And in this logic microsimulation does not serve only as a descriptive tool, but as an operational support for understanding if a proposed intervention improves or worsens the functioning of the system.

The scenario analysis focuses on three main Key Performance Indicators (KPIs): Level of Service (LOS), travel time, and queue length. LOS is used to express the overall quality of traffic operations at nodes or along selected movements, synthesizing the operational conditions experienced by users. Travel time is adopted as a direct indicator of accessibility and network efficiency, since it captures the temporal cost associated with crossing the study area under each tested configuration. Finally, queue length is used to identify localized criticalities and spillback effects, especially in congested approaches or sections affected by bottleneck formation. All these indicators give a coherent basis for comparing the current state with the tested intervention scenario and for reading the potential impact of the proposed modification at both node and corridor level.

Therefore, our methodological framework combines urban video analytics and microsimulation within a unified planning-oriented workflow. Its added value lies in the possibility of transforming continuously available urban sensing data into simulation inputs that support scenario analysis, traffic management, and the progressive implementation of AI-enabled mobility digital twins.

4 Case Study

The proposed framework is applied to a real-case study located in the urban road network of Catania (Italy), a metropolitan city in eastern Sicily characterized by high motorization levels and recurrent congestion at major access corridors. In the last years the vehicular traffic in Catania has increased a lot and the city is now among those with the highest motorization rate in Europe. This fact makes the local traffic conditions particularly critical and the need for efficient planning tools even more urgent. Within this context the analyzed study area concerns the intersection between Via Caronda and Viale Odorico da Pordenone, positioned immediately downstream of the Tondo Gioeni node, which represents one of the most strategic connections to the inner ring-road system of the city (Fig. 2). This zone has been object of a deep rethinking of the road layout. In fact, the road configuration changed passing from an intersection with staggered levels to an at-grade

roundabout. But this roundabout presents unusual aspects because it has a geometric layout that does not reflect the classic and functional canons of a roundabout, due to some space limits which constrains the structural reconfiguration of the intersection. As already observed in other traffic studies developed for Catania, critical urban nodes in this area are strongly influenced by concentrated commuting flows and by the limited flexibility of the surrounding network under peak-hour conditions. The selected case study is particularly relevant because it concerns a critical access point to the ring road where local geometric constraints, route restrictions and heavy directional flows interact within a relatively compact urban space. the operational relevance of the site derives not only from its role as a traffic distribution toward different city sectors, but also from the fact that even localized modifications at this node may produce broader effects on nearby approaches and on the performance of the surrounding road system. For this reason, the area provides a suitable test bed for assessing how video-derived traffic information can support simulation-based evaluation of alternative traffic configurations.

Fig. 2. Study area - Via Caronda

4.1 Current Road Configuration

In the state of affairs in Fig. 3 the direct access from Via Caronda to Viale Odorico da Pordenone is closed. This point is an entry to the Catania ring road, a main urban orbital that connects different parts of the city. The present condition is the baseline scenario against which the intervention hypothesis is tested. From an operational point of view the existing configuration does not let vehicles coming from Via Caronda to merge directly into the ring-road system at this location. And so, the users must take alternative longer routes to get to where they need to go, with more travel time and more kilometres. This constraint is a reason why the reopening of this access has been considered as a possible intervention. But we must remember that the node already works under tight geometric

conditions. Therefore, any change in access regulation must be looked at not just for the direct accessibility gain for that specific movement, but also for the wider effect on road capacity and how the whole junction performs.

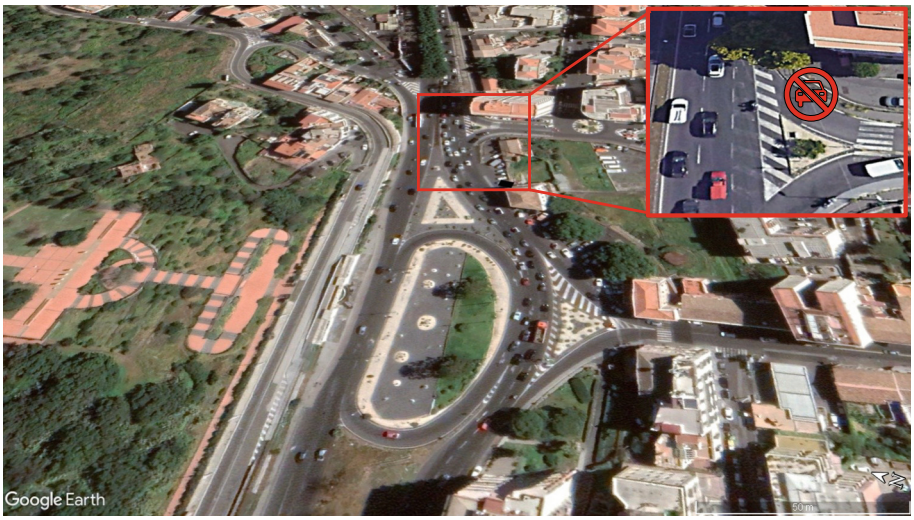

Fig. 3 Current state of via Caronda.

4.2 Tested Intervention Scenario

The analyzed scenario focuses on the hypothesis of reopening the direct access from Via Caronda to the ring road through Viale Odorico da Pordenone. Remember this is the point where traffic from Via Caronda tries to enter the main orbital of Catania. According to the examined design configuration this intervention would need a new channelizing island and would also suppress the third lane that now exists in the study section. Thus, the opening of this access changes the effective capacity of the approach. The current three-lane setup becomes a two-lane configuration in the direction of Ognina. This is central for the scenario assessment. Because it means that a possible gain in direct access for one movement comes together with a reduction of capacity for the main traffic stream. To put the new scenario inside the microsimulation model, the flow of the movement called manoeuvre g in the technical scheme was taken and redistributed as a new entering flow to the ring road. And this additional flow was split fifty-fifty between the two main directions: Ognina and Misterbianco. The demand from Via Caronda was assigned 50/50 to the two alternative paths.

The scenario was therefore designed to compare two conditions: the current state of affairs with the closed access from Via Caronda and three lanes available on the main approach, and the project hypothesis with the reopened access plus the geometric changes needed to make it happen. The comparison lets us see if the better directness for vehicles from Via Caronda is enough to pay for the loss of roadway capacity on the corridor. In

this sense the case study is good for simulation-based ex-ante evaluation. Because the expected effects are not obvious in one direction. They depend on the balance between the better accessibility and the worse traffic performance.

5 Results

5.1 Video-to-Flow Extraction Results

The first outcome of the framework concerns the extraction of traffic movements from the urban video streams and their transformation into directional flow inputs for the microsimulation model. The AI-based processing pipeline has analyzed the recorded video and has given in output the vehicle movements inside the monitored scene. The trajectories were reconstructed and each vehicle was associated to a specific directional path using virtual counting sections. In this way the raw video footage has been converted into structured traffic data usable for the planning analysis. The extracted information was organized according to the main movements of the study node and its connected approaches, ad shown in Fig. 4; and the resulting dataset was used to represent the directional structure of the traffic demand at the intersection system of Via Caronda, Tondo Gioeni, and Viale Odorico da Pordenone.

Fig. 4 Reconstruction of flow distribution

The flows were aggregated over the analysis period and put as input for the baseline microsimulation model, giving the empirical basis for the demand pattern of the scenario. The present work does not aim at a full technical validation of the video-processing chain; what we demonstrate here is the operational usefulness of video-derived traffic observations for generating simulation inputs. The case study shows that urban video can extract movement-based traffic data in complex nodes where many manoeuvres

happen at the same time in a limited space. This is important when the objective is not just monitoring the traffic but feeding a simulation environment with movement-specific demand information. The extracted flows are therefore the link between the observation part and the modelling part of the framework.

5.2 Scenario Assesment

To evaluate the intervention, we first reproduced in the microsimulation model the current state, that is the baseline condition with the access from Via Caronda closed and the three-lane configuration on the main approach. After that we implemented the project hypothesis, which consists in the reopening of the access together with the geometric modifications already described. The objective of the simulation was to put in light the sustainability of the intervention to quantify their impacts on worsening the traffic conditions. This is because it was already reasonable that opening a new entry point on a congested ring road could create additional traffic-related issues. The question to support planning decision are related to how much does the Level of Service decrease and how much the queues length increase.

All the evaluations presented in this paper refer to the peak hour condition. The simulation results give clear evidence. The reopening does not bring any overall improvement. On the contrary, the network performance gets significantly worse. The reduction from three lanes to two on the main approach creates a bottleneck that was not there before. The Level of Service distribution over the whole study area is reported in Fig. 5, where the comparison between the current state and the opening hypothesis is shown.

Fig. 5 Level of Service distribution over the whole study area

A detailed view of the Via Caronda intersection is provided in Fig. 6. From the LOS maps it is evident that several movements that in the current state have an acceptable or moderate Level of Service (LOS C or D) pass directly to LOS F in the opening scenario.

This is the case for the movements from Tondo Gioeni toward Ognina, from Tondo Gioeni toward Via Caronda, and from Viale Andrea Doria toward Ognina. And the same happens for the return movement from Viale Andrea Doria, which goes from LOS D to

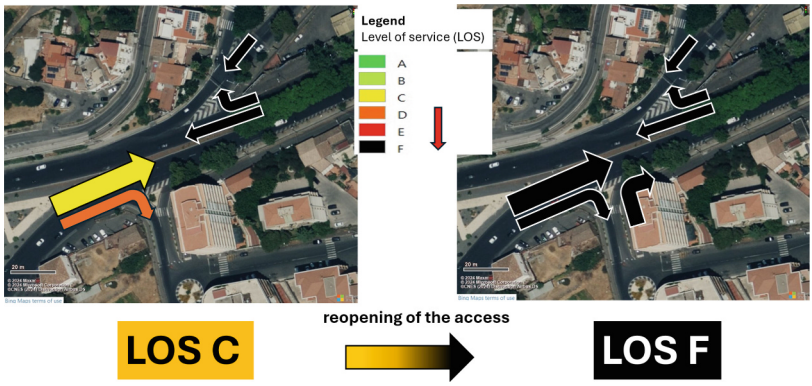

Fig. 6. A detailed view of the Via Caronda intersection

LOS F. The worsening is not only a matter of LOS classification. It has concrete effects on travel times and on the surrounding intersections. The travel time values for the two main directions are synthesized in Table 1.

Table 1. The travel time values

Direction	Current state: Via Caronda closed	Opening scenario
Ognina	1 min	3 min (+2 min)
Misterbianco	3 min	6 min (+3 min)

In the current state, during the peak hour, the average travel time for vehicles going toward Ognina is about 1 min. In the opening scenario this time becomes 3 min, with an increase of 2 min. For the direction toward Misterbianco the average travel time passes from 3 min in the current state to 6 min in the project hypothesis, with an increase of 3 min. So, the crossing times of the study area become practically the double. Moreover, the saturation created by the bottleneck does not remain confined to the Via Caronda node. The queue propagates and saturates also the following intersection along the ring road, creating a cascade effect that was not present in the baseline. The negative effects are not limited only to the peak hour. Even in off-peak conditions some movements show a degradation of service. The movement toward Via Caronda passes from LOS B to LOS C. The movements from Viale Andrea Doria toward Ognina and the return direction pass from LOS A to LOS C. This means that the intervention reduces the operational margin of the node even when the demand is not at its maximum. In conclusion, the scenario assessment demonstrates that the proposed reopening is not sustainable from an operational point of view. The local advantage of a more direct access for the vehicles coming from Via Caronda is largely compensated by the capacity loss on the ring road. The LOS drops from C or D to F on critical movements, the travel times double (from 1 to 3 min toward Ognina, from 3 to 6 min toward Misterbianco), and the congestion

propagates to the next intersection. The simulation has therefore quantified the trade-off and has given to the planning evaluation clear evidence: the intervention, even if it appears attractive for a specific user group, would produce systemic disbenefits that make it not recommendable.

5.3 Discussion

From a planning perspective the case study puts in evidence the importance of combining AI-supported traffic observation with simulation before doing modifications to critical urban nodes. The proposed framework consents to pass from raw traffic videos to planning-grade evidence. This allows public authorities to evaluate if an intervention that seems beneficial at a first look can instead create systemic disbenefits. In this sense the urban video analytics is an enabling layer for decision support and for digital twin applications in mobility planning.

A further aspect is about replicability. The workflow proposed in this paper could not be limited to the specific case of Via Caronda, but it can be extended to other urban intersections and corridors where fixed cameras are already present and where the local administration needs to assess the effects of access changes or lane reallocation. The main strength of the approach stays in the integration between sensing and modelling. Once the vehicle movements are extracted and organized into directional flows, the same logic works for different nodes and different scenarios. This supports recurring assessments over time, enriching the empirical basis of the simulation models. This replicability is especially relevant in the case of Catania, where the broader UISH framework already envisages the integration of existing municipal surveillance cameras into a Digital-Twin-oriented urban intelligence ecosystem. In this sense, the Via Caronda application can be read as an initial demonstrator of how AI-based video detection may evolve from a single case-study implementation into a more pervasive city-wide observation layer, capable of supporting traffic monitoring, simulation updating, and future decision-support services.

At the same time some limitations must be acknowledged. First the quality of the extracted traffic information depends on the visibility conditions of the monitored scene: camera angle, occlusions, lighting, image resolution. These factors can reduce the reliability of movement recognition, especially in congested conditions. Second the flow extraction is relatively robust but getting additional indicators like vehicle speeds needs more stringent geometric calibration and so must be treated with caution. And third the transferability of the framework depends on where fixed cameras are positioned and on the compatibility between what the camera sees and the movement structure that the simulation model needs to represent.

Finally, the use of urban video streams for planning requires attention to privacy and responsible use of data. In this framework the objective is not the identification of single road users. It is the extraction of aggregated traffic variables for model input and scenario assessment. The operational value of the approach is exactly this: converting video streams into anonymized movement-based traffic information. Information that can support simulation, control rooms, and future mobility digital twin implementations. And all this without relying on unnecessary data at personal level. The results of the scenario assessment are synthesized in Fig. 4, which shows the Level of Service distribution across the entire study area for both the current state and the opening hypothesis,

with a detailed focus on the Via Caronda intersection. The quantitative effects on travel times are reported in Table 1, where the doubling of the crossing times for the two main directions is clearly visible.

6 Conclusions

This paper presented an integrated framework for transforming urban video streams into microsimulation input data to support AI-enabled mobility planning. The framework combines vehicle detection, tracking, and directional movement extraction with a scenario-based microsimulation model. In this way it bridges the gap between traffic observation and transport simulation. The methodological contribution is the definition of an operational workflow that converts fixed-camera video data into movement-based traffic inputs. Inputs that are suitable for planning-oriented scenario assessment. The study gives a contribution to the research field at the intersection of urban video analytics, transport modelling, and mobility digital twins.

From the application side the case study on Via Caronda in Catania demonstrated that video-derived traffic flows can effectively support the ex-ante assessment of road-network modifications. The simulation put in light that the reopening of the direct access to the ring road, even if it gives a more direct route for a specific movement, reduces the effective capacity of the corridor due to the suppression of the third lane. The LOS on critical movements drops from C or D to F. The travel times double: from 1 to 3 min toward Ognina, from 3 to 6 min toward Misterbianco. And the queue propagates to the next intersection creating a cascade effect. These findings confirm the usefulness of the proposed framework for testing interventions before the implementation. And they help to identify systemic disbenefits that are not visible with a purely local or intuitive evaluation. The framework shows also the potential of fixed urban cameras as strategic data sources for traffic control rooms and simulation-supported planning. Their value is not only in the continuous observation. It is in the possibility to transform video streams into structured traffic knowledge that can update models, test scenarios, and support decisions inside complex urban systems. This is particularly relevant for cities that already have camera-based infrastructures and want to make stronger their analytical capabilities with AI-enabled tools.

Future research will specifically address the scaling-up of the proposed framework within the UISH ecosystem for the city of Catania. In this perspective, the processing of video streams from the broader network of municipal surveillance cameras already installed across the city may enable the creation of a pervasive observational layer capable of supporting more continuous traffic-flow reconstruction, broader simulation coverage, and progressively updated Digital Twin functionalities. Further developments will also investigate the integration of additional indicators, such as speed estimation and speed profiles, whenever geometric calibration and video quality allow robust extraction, as well as more continuous and quasi-real-time data feeds for recurrent model updates. The aim is to support recurrent model updates and a more dynamic interaction between monitoring systems and simulation. In this perspective the proposed framework is a first step toward a more comprehensive and operational AI-supported mobility digital twin for urban planning and traffic management.

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From Point Events to Continuous Surfaces: A Framework for Multi-scale Spatial Analysis

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Abstract. Existing approaches for analysing point-based data either model stochastic intensity or operate on fixed representations, limiting the ability to explicitly examine how relationships vary across space. This study presents a methodological framework that transforms point-event data into a continuous, mass-preserving spatial surface, enabling flexible, user-defined multi-scale analysis of spatial processes. The framework is demonstrated using unmanaged waste sites across three sub-Saharan cities. Results highlight distinct scale-dependent mechanisms across cities: in Lagos, population density structures city-scale patterns while accessibility shapes local accumulation; in Freetown, accessibility dominates at the city scale but local patterns reflect economic gradients; and in Nairobi, urban morphology governs city-scale patterns while informality drives local variation. By linking discrete events to continuous representations, the framework provides a flexible and generalisable approach for analysing point-based phenomena in systems where understanding spatial heterogeneity is critical for interpretation.

Keywords: Point processes · Exposure surface modelling · Random Forest · Urban analytics · Log-Gaussian Cox Process

1 Introduction

Many spatial phenomena are observed as discrete events or point locations, yet are shaped by continuous processes operating across space [21]. Such events are common across ecology, epidemiology, urban systems, and climate-related hazards, often reflecting the interaction of overlapping spatial dynamics [2]. Two broad classes of methods commonly used to analyse these processes are: local spatial regression approaches, such as geographically weighted regression (GWR) [4,6,8], and spatial point-process models (PPM), which provide a probabilistic framework for analysing event occurrence [2,16].

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Local spatial regression methods, including GWR and its extensions, are widely used to investigate spatially varying predictor–outcome relationships. [6,8]. These models assume that a sufficiently coherent response surface exists over which local patterns can be meaningfully specified. Whilst this assumption may hold for some phenomena (i.e. disease spread, species presence, agricultural yield), it is problematic for phenomena observed as spatially fragmented point patterns (i.e. crime events, waste site presence). Extensions such as Multiscale GWR (MGWR), and spatial variants of Random Forest, improve flexibility but remain reliant on the assumption that the response can be represented as a sufficiently dense or continuous surface for local inference [6].

Spatial point-process models offer a complementary perspective by modelling event patterns directly. Gibbs processes capture interaction between nearby events, while Cox processes model spatially varying intensity through latent stochastic fields. Log-Gaussian Cox Processes (LGCPs), in particular, are widely used to represent clustered event patterns and account for spatial dependence [2,16]. These models provide a rigorous framework for estimating event intensity and identifying process scales; however, they lack user-defined scale-setting, limiting analysis of heterogeneity across spatial scales. The primary inferential target of these models is stochastic intensity rather than an interpretable response surface for downstream analysis. In complex settings, they can become computationally demanding and are often restricted to additive formulations, limiting their ability to capture highly non-linear and locally heterogeneous relationships [2,7].

In settings where point events are spatially discontinuous or clustered, and drivers vary across space and scale, current methods do not provide a continuous, interpretable surface for explanatory analysis. In these approaches, the scale of inference is typically dictated by implicit bandwidth optimisation or covariance structure, rather than aligned with the spatial support of the phenomenon [6,13]. This limits the incorporation of domain-specific scale knowledge and constrains analysis to a single scale. As a result, researchers lack a flexible framework to construct response surfaces that preserve the original event pattern while supporting analysis of broad trends and local heterogeneity.

This study introduces an analyst-controlled, deterministic, mass-preserving, and scale-explicit event surface that links discrete events to the continuous processes that shape them. Rather than replacing point-process models, the framework provides an interpretable response surface through which domain knowledge can be directly incorporated, supporting analysis of spatial heterogeneity while remaining faithful to the original event pattern. As an example of a downstream analysis, we demonstrate the utility of this framework by exploring the drivers of unmanaged waste sites. Random Forest models are applied at a global and local scale to identify city-scale drivers and local variation. To situate these results within established spatial modelling paradigms, we compare the predictors identified by the framework with those derived from a traditional LGCP intensity surface.

2 The Study

Across sub-Saharan Africa (SSA), rapid urbanization has caused waste generation to outpace formal management capacity [19,26]. Consequently, the region now records the lowest formal collection rates and some of the highest volumes of unmanaged waste globally. This has resulted in cascading impacts on public health, local ecosystems, and climate systems [12,24]. Whilst waste sites are typically represented by polygons or point locations, their emergence and persistence is shaped by continuous, and interacting, spatial gradients in population density, accessibility, neighbourhood morphology, and socio-economic conditions. These drivers interact through complex, non-linear dependencies that vary geographically, producing heterogeneous patterns within a single metropolitan area. Analysing such phenomena requires methods capable of linking discrete event data to the continuous urban processes that generate them. Urban waste presents an ideal case for evaluating the framework, as it reflects the interaction of multiple spatial gradients operating across scales. By exploring the drivers of waste at different scales, this framework demonstrates how it can be used on spatial point-event data to generate meaningful insights and uncover (layered) patterns.

2.1 Data Used for Study

The framework was implemented using mapped waste sites across three urban centres: Lagos, Freetown, and Nairobi. These cities were selected for their contrasting built morphologies, infrastructure coverage, and stages of urbanisation, enabling assessment across diverse contexts. Waste sites were represented as spatial point locations with associated footprint extents derived from manual mapping. Five predictor groups were considered for each city, selected based on existing literature and known drivers of uncontrolled waste deposition.

The groups of predictors considered in this study are: (i) demographic measures (population density and U-18 population share), capturing population pressure and household structure associated with waste generation [9]; (ii) economic proxies (relative wealth index and night-time lights), closely linked with goods manufacturing and consumption [15]; (iii) settlement informality (slum probability), associated with poor service access and separation from urban infrastructure [1,3,15]; (iv) accessibility (distance to tertiary & secondary roads and an accessibility index), capturing network constraints on service provision [17,23]; and (v) urban morphology (building footprint and spacing, orientation dispersion, distance to open space, Clark–Evans R, and a built-environment index), reflecting city structure and configuration [15,17]. Predictors were harmonised and interpolated onto a common 30 m grid across each city.

3 Methodology

Figure 1 summarises the proposed framework, in which discrete waste-site locations are transformed into a continuous, mass-preserving surface for downstream

analysis. Random Forest (RF) models are then applied to examine drivers of waste presence, with global models identifying city-scale patterns and local models capturing neighbourhood-level variation. LGCP models provide a complementary comparison by assessing spatial dependence and process scale. The surface is constructed through five steps that preserve relative site importance, ensure bounded influence, and maintain comparability across the urban area.

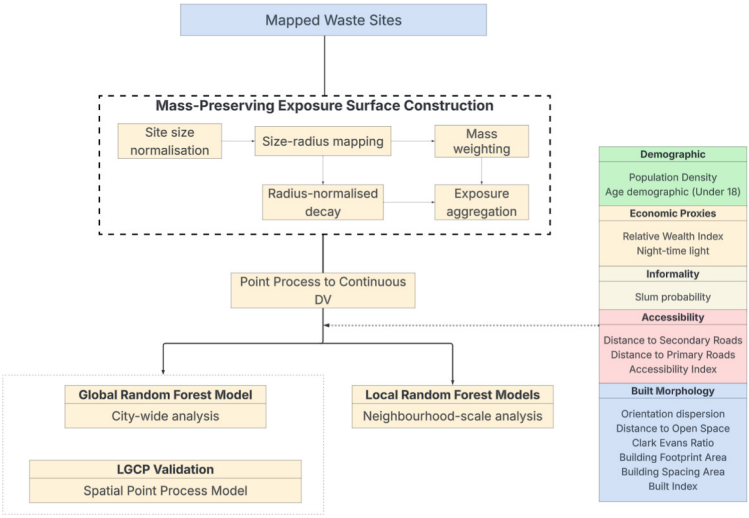


Fig. 1. Framework for generating a continuous surface from point-process data

Site Size Normalisation

Mapped events can vary substantially in their spatial extent or magnitude (e.g., footprint area, intensity). Without adjustment, larger events can disproportionately influence the resulting exposure surface and obscure meaningful spatial variation. To preserve relative differences in event magnitude while limiting the influence of extreme outliers, each event j was assigned a bounded size score $s_j \in [0, 1]$ derived from its footprint area A_j. Site areas were log-transformed to reduce right-skew, then Winsorised by replacing values below and above the 5th and 95th percentiles of the log-area distribution, respectively. Let

$$\ell_j = \ln(A_j), \tag{1}$$

where A_j is the footprint area of event j, and let L_5 and L_{95} denote the 5th and 95th percentiles of the set $\{\ell_j\}$. The Winsorised log-area, $\ell_j^{(w)}$, was defined as

$$\ell_j^{(w)} = \begin{cases} L_5, & \text{if } \ell_j < L_5, \\ \ell_j, & \text{if } L_5 \le \ell_j \le L_{95}, \\ L_{95}, & \text{if } \ell_j > L_{95}. \end{cases} \tag{2}$$

The normalised size score was then computed as

$$s_j = \frac{\ell_j^{(w)} - L_5}{L_{95} - L_5}, \tag{3}$$

which ensures $s_j \in [0, 1]$.

This transformation preserves the relative ordering of site sizes while limiting the influence of extreme values on the resulting event surface.

Radius Mapping Based on Site Size

Spatial phenomena often exhibit multi-scalar influence, with the drivers and impacts of point-represented events extending beyond their immediate location and attenuating with distance, consistent with Tobler's first law [8,21]. The spatial extent of this influence varies with site characteristics and local context. Empirical studies describe impacts ranging from highly localised effects, such as odour, poor air quality, and immediate health risks [11,20], to broader regional-scale influences linked to environmental conditions [25]. Collectively, this literature suggests that contributing factors and impacts operate within a plausible influence zone in the order of 100–800 m [15,22].

Guided by these findings, a sensitivity analysis was conducted to identify plausible bounds of site influence. Candidate radius mappings were evaluated separately for each city using a fixed lower bound of 75 m and upper bounds between 200 m and 400 m. The evaluation assessed whether the resulting exposure surfaces provided sufficient spatial support for downstream analysis while preserving local structure. Candidate settings were compared based on surface coverage, site overlap, and the stability of waste–predictor relationships under regression diagnostics. Results indicated that:

- Influence distances below 75 m produced minimal variation in regression diagnostics, indicating highly localised effects for smaller sites;
- Increasing distances beyond 75 m led to systematic increases in surface coverage and site overlap, consistent with local-level interactions; and
- Beyond 400 m, surfaces became overly smooth and less locally interpretable, with unstable diagnostics and divergence from established waste–predictor relationships.

Each site, j, was assigned an effective radius of influence, r_j, representing the spatial extent that contributes to site presence and size. Radii were mapped from normalised size scores, s_j, as:

$$r_j = R_{\min} + (R_{\max} - R_{\min})\, s_j^{\gamma}, \tag{4}$$

where s_j denotes the scaled size of site j, $R_{\min} = 75\,\text{m}$ (approximately three grid cells), $R_{\max} \in [200, 400]\,\text{m}$, and $\gamma = 1$ specifies a linear mapping (alternative γ values allow non-linear scaling if different size–influence relationships are desired). This imposes a monotonic relationship between site size and spatial influence, such that larger sites affect wider surrounding areas while maintaining bounded, comparable influence across the urban footprint.

Quantity (Mass) Weighting
While the radius controls spatial extent, a separate mass term governs each event's total contribution to the surface. If $\beta = 1$, site contribution scales linearly with site area. However, given substantial variation in site sizes, very large sites, often formal landfills or sanctioned disposal areas, may not relate to the predictors in the same way as smaller, uncontrolled sites. To account for this, a sublinear scaling exponent β was introduced so that larger sites contribute more mass, but with diminishing influence relative to size. The exponent was defined by anchoring the relative contribution of large sites, such that those at the 95th percentile contribute a fixed multiple R of the mass of a median-sized site:

$$\beta = \frac{\ln(R)}{\ln\left(A_{95}/A_{50}\right)}, \tag{5}$$

where $R = 3$ was selected to provide moderate weighting of larger sites without allowing them to dominate the exposure surface. This choice was supported by sensitivity analysis, which indicated that stronger scaling led to reduced interpretability and increased dominance of a small number of large sites. The resulting mass weight for each site was then computed as:

$$q_j = A_j^{\beta}. \tag{6}$$

This formulation preserves a monotonic relationship between site size and contribution while ensuring that the event field reflects a balanced combination of localised and neighbourhood-scale influences. Mass-weighting is flexible, and alternative values of β (including $\beta = 1$ for linear scaling) may be adopted depending on the application context and underlying data characteristics.

Radius-Normalised Distance Decay
Spatial influence is assumed to decay smoothly with distance, reflecting the diminishing relevance of an event's effects with increasing separation [21]. A radius-normalised exponential decay kernel was adopted to ensure continuous attenuation while remaining interpretable and consistent across sites of different sizes. This provides a simple, monotonic, and parameter-light formulation, avoiding strong assumptions about spatial form while maintaining consistency across heterogeneous urban settings. The radius-normalised exponential kernel selected for the study is defined as:

$$w\left(d_{pj}; r_j\right) = \exp\left(-\frac{d_{pj}}{r_j}\right), \tag{7}$$

where $w(\cdot)$ denotes the contribution weight, d_{pj} is the distance from grid point p to site j, and r_j is the radius of influence. This ensures larger sites influence over longer distances, while smaller sites decay more rapidly. To define an effective spatial support, the kernel was truncated using a small threshold (ε), with contributions below this level treated as negligible. This yields finite support, ensuring computational tractability while preserving continuous decay.

Exposure Surface Construction
The final event surface was constructed by aggregating the kernel-weighted contributions, of all sites, at each grid point. For grid location, p, exposure was:

$$\mathrm{DV}(p) = \sum_{j:\, d_{pj} \le \tau_j} q_j \, \exp\left(-\frac{d_{pj}}{r_j}\right), \tag{8}$$

where q_j is the site mass, r_j is the site-specific radius of influence, and τ_j denotes the limit of the spatial support beyond which influence is assumed to be negligible ($\varepsilon = 0.05$).

A hexagonal tessellation was used as the finite-element representation of the exposure surface to support spatial aggregation and local analysis. Hex sizes of 80–100 m were selected to stabilise local exposure estimates while remaining comparable to the lower bound of influence ($R_{\min}$) and well below the upper bound ($R_{\max}$). This ensured that each cell aggregates multiple 30 m grid points, reducing noise while preserving local variation.

Parameter Selection
The surface is constructed through a parameterised aggregation of event-level contributions, allowing adaptation to different phenomena, spatial scales, and modelling objectives. Key components are controlled through user-defined parameters:

1. **Spatial influence bounds** ($R_{\min}, R_{\max}$): define the lower and upper limits of event influence.
2. **Radius–size mapping exponent** (γ): controls how the radius of influence r_j scales with normalised event size s_j.
3. **Mass weighting factor** (R, β): governs the relative contribution of larger versus smaller events; here, β is defined such that upper-percentile events contribute a fixed multiple R of a median event.
4. **Distance decay function** $w(d_{pj}; r_j)$: specifies how influence attenuates with distance, implemented as a radius-normalised exponential decay.
5. **Minimum influence threshold** (ε): defines the cutoff below which contributions are negligible.
6. **Spatial aggregation scheme** (e.g., hexagon size): determines the resolution and structure of analysis units.

These parameters enable application-specific tuning within a consistent framework. For this study, values were selected based on prior literature, sensitivity analysis, and the spatial characteristics of waste. Table 1 summarises the parameters used for each city.

This aggregation captures cumulative influence from single large sites, multiple smaller sites, or overlapping influence zones. The resulting surface is a mathematical representation of waste influence across the city and is used as the dependent variable (DV) in subsequent global and local Random Forest analyses. Figure 2 illustrates the constructed surface for a ward within a local government area (LGA) in Lagos.

Table 1. Parameter settings used for exposure surface construction across cities.

City	$R_{\min}$	$R_{\max}$	Decay rate	β	Hex-grid size
Lagos	75	250	0.8	0.57	100
Freetown	75	300	0.8	0.40	80
Nairobi	75	350	0.8	0.42	80

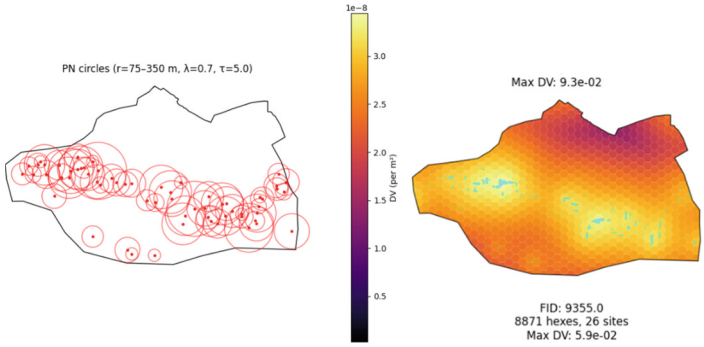


Fig. 2. Surface for mapped waste sites in Sabo-Oniba (ward), Ojo (LGA), Lagos. Red circles show site radii (75–350 m), illustrating bounded influence (left); the corresponding event surface is shown on the right

3.1 Global Model

Following construction of the continuous, non-sparse event surface, relationships between the response variable and spatial predictors can be analysed directly. The parameterised surface enables analysis across scales. Here, we examine both city-wide and local relationships to assess how drivers of waste deposition vary across the urban landscape. A global Random Forest (RF) model is first used to identify predictors explaining variation in waste presence at the city scale, providing a baseline for assessing spatial heterogeneity.

To ensure computational efficiency while preserving the full range of DV values, the global RF was trained on a stratified and spatially balanced sample of approximately 20,000 grid points per city. Sampling followed two principles. First, dependent-variable stratification ensured representation across DV levels by including a subset of zero-exposure cells alongside samples drawn from each decile of the positive DV distribution. Second, spatial balancing was applied to mitigate the effects of spatial autocorrelation. Grid points were partitioned into spatial blocks using k-means clustering in projected (UTM) coordinate space, with these blocks serving as sampling strata and cross-validation folds. This limited localised overfitting and improved the robustness of variable-importance estimates.

Blocked cross-validation was used to assess model performance (R^2, MAE), with Moran's I computed on test residuals as a spatial robustness check. Fol-

lowing validation, RF was refit on the sampled dataset (20,000 points). Permutation importance was then computed from this fitted model, with the mean importance and associated standard deviation (SD) derived from repeated permutations. RF models were implemented using 600 decision trees, a maximum tree depth of 20, and a minimum node split of 5 observations. These parameters were selected to balance three competing objectives: sufficient model flexibility to capture non-linear relationships and interactions; controlled tree depth to limit overfitting in complex spatial settings; and stable estimation of variable importance across cross-validation folds.

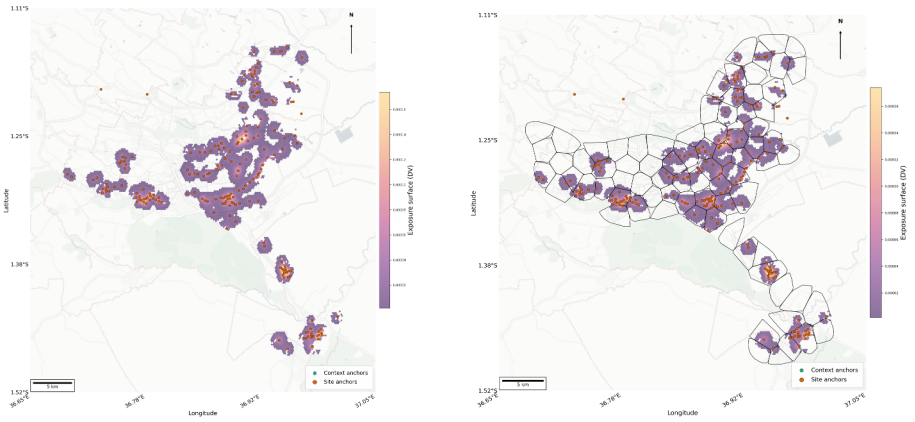
3.2 Localised RF Modelling

To characterise spatial heterogeneity in the drivers of waste, a region-stratified RF framework was implemented in which separate RF models were fitted within spatially contiguous sub-regions of each city. Unlike the global RF, which estimates an average relationship across the entire urban domain, this approach allows predictor importance to vary spatially, thereby capturing non-stationarity in the relationships between waste presence and urban characteristics.

Spatial Partitioning of the Urban Domain
The derived event surface was partitioned into K spatial regions using k-means clustering applied to projected UTM coordinates of hexagon centroids. This produced a set of non-overlapping, spatially contiguous regions that collectively covered the full surface. Following partitioning, regions were ranked by total DV value (exposure mass), defined as the sum of the exposure hexagons within each region. To focus local modelling on areas that either contain waste or that contribute to waste sites, regions with the highest total DV value were retained for subsequent analysis. An elbow and cumulative-share diagnostic was used to assess whether the selected number of regions captured a substantial fraction of total mass, providing a principled basis for the choice of K regions. Figure 3 illustrates the continuous waste surface derived from mapped waste sites and its partitioning into spatial regions used for local Random Forest analysis.

For each region, an independent RF model was fitted using all assigned grid cells. Locality is defined by region membership: each cell belongs to one region, and each region yields a single RF model. Predictors were standardised within regions using region-specific scalers prior to fitting, ensuring numerical stability for permutation importance while allowing adaptation to local predictor distributions. RF parameters were fixed across regions to enable comparison of relative importance patterns. Permutation importance was computed for each model using repeated feature shuffling on the training data. As models are fitted on distinct spatial subsets and independently standardised, importance magnitudes are interpreted within regions rather than as globally comparable effects.

Spatial heterogeneity in predictor relevance was quantified by aggregating permutation importance across regions. For each predictor, the coefficient of variation (CV) of importance scores was computed. Low CV indicates spatially stable influence, while high CV reflects strong spatial differentiation. This



(a) Continuous waste exposure surface. (b) Spatial regions for local RF analysis.

Fig. 3. Waste exposure in Nairobi: (a) continuous exposure surface from mapped sites; (b) k-means partitioning into regions capturing local intensity and extent

regional RF framework provides a structured representation of spatial heterogeneity in waste drivers, complementing the global RF by showing how local importance and stability compare with city-scale influence.

3.3 Log-Gaussian Cox Process for Spatial Comparison

LGCP models were used to characterise the underlying spatial point process governing event locations. LGCP models intensity as:

$$\Lambda(\mathbf{p}) = \exp\left(\mathbf{X}(\mathbf{p})^\top \boldsymbol{\beta} + Z(\mathbf{p})\right),$$

where $\mathbf{X}(\mathbf{p})$ are covariates, $\boldsymbol{\beta}$ are fixed effects, and $Z(\mathbf{p})$ is a Gaussian process capturing residual spatial dependence, parameterised by variance σ^2 and range ϕ. Parameters were estimated using Bayesian Inference in R-INLA [18].

While Random Forest models operate on the DV surface, LGCP models analyse event locations directly, explicitly accounting for spatial dependence. LGCP therefore provides a complementary, process-based perspective. Comparing LGCP covariate effects with RF-derived predictor importance allows assessment of whether identified relationships align with the underlying spatial structure.

4 Results

This section presents results from the global RF, local RF, and LGCP analyses for each city. Global RF results summarise dominant predictors at the city scale, while local RF models characterise spatial heterogeneity in predictor importance.

LGCP results provide an independent, point-process perspective by explicitly modelling spatial dependence, enabling comparison with RF-derived patterns. In the LGCP, coefficient sign indicates the direction of association with waste occurrence (positive: increased likelihood; negative: decreased likelihood), while magnitude reflects the strength of this relationship on the log-intensity scale.

4.1 Global and Local RF Modelling Results for Lagos

Tables 2a to 3 present the Global RF model, Local RF model, and LGCP results for Lagos. The global RF model identifies population density, accessibility, night-time lights (NTL), and relative wealth index (RWI) as the strongest city-scale predictors of waste exposure (Table 2a). These predictors exhibit low variability across cross-validation folds, indicating stable global importance. Results from the LGCP model corroborate these findings, with the same predictors showing statistically robust effects (Table 3), providing independent confirmation that the RF-derived patterns align with the underlying spatial process.

Local RF models provide additional insight, revealing that distance to tertiary and secondary roads exhibits both high local importance and substantial spatial heterogeneity across the city. Population density, despite being the dominant global predictor, displays the highest coefficient of variation locally, indicating marked spatial variability in its local influence. Built morphology predictors, including footprint area and spacing, exhibit moderate global importance but heterogeneous local behaviour (Table 2b).

Table 2. RF predictor importance for Lagos: (a) Global and (b) Local models.

(a) Global Random Forest

Predictor	Mean Imp.	SD	Rank
Population Density	1.249	0.027	1
Accessibility Index	0.482	0.011	2
Night-Time Lights	0.377	0.009	3
Relative Wealth Index	0.224	0.007	4
Footprint (Mean)	0.192	0.005	5
Dist. to Secondary Roads	0.164	0.004	6
Under-18 Population	0.138	0.011	7
Dist. to Tertiary Roads	0.135	0.003	8
Footprint Spacing	0.112	0.004	9
Slum Likelihood	0.056	0.002	10
Built Environment Index	0.033	0.001	11
Dist. to Open Space	0.030	0.001	12
Orientation Dispersion	0.025	0.000	13
Clark–Evans R	0.019	0.001	14

(b) Local Random Forest

Predictor	Mean Imp.	SD	CV
Population Density	0.119	0.455	3.822
Dist. to Open Space	0.052	0.127	2.451
Slum Likelihood	0.052	0.108	2.086
Built Environment Index	0.075	0.139	1.861
Under-18 Population	0.020	0.036	1.773
Dist. to Tertiary Roads	0.425	0.751	1.766
Orientation Dispersion	0.029	0.045	1.526
Footprint Spacing	0.044	0.061	1.404
Footprint (Mean)	0.118	0.166	1.401
Clark–Evans R	0.025	0.033	1.339
Dist. to Secondary Roads	0.459	0.534	1.163
Night-Time Lights	0.530	0.513	0.967
Accessibility Index	0.558	0.507	0.909
Relative Wealth Index	0.559	0.474	0.847

Table 3. LGCP covariate effects for Lagos arranged by absolute coefficient value.

Predictor	Coef.	SE	CI	Sig.
Footprint (Mean)	−1.800	0.198	[−2.19, −1.41]	TRUE
Accessibility Index	−1.015	0.127	[−1.26, −0.77]	TRUE
Under-18 Population	−0.783	0.060	[−0.90, −0.66]	TRUE
Night-Time Lights	−0.729	0.090	[−0.91, −0.55]	TRUE
Relative Wealth Index	0.432	0.100	[0.24, 0.63]	TRUE
Slum Likelihood	0.381	0.063	[0.26, 0.50]	TRUE
Dist. to Tertiary Roads	−0.351	0.080	[−0.51, −0.19]	TRUE
Built Environment Index	−0.331	0.057	[−0.44, −0.22]	TRUE
Footprint Spacing	−0.326	0.048	[−0.42, −0.23]	TRUE
Dist. to Secondary Roads	−0.269	0.163	[−0.59, 0.05]	FALSE
Population Density	0.241	0.041	[0.16, 0.32]	TRUE
Clark–Evans R	0.077	0.026	[0.03, 0.13]	TRUE
Orientation Dispersion	0.024	0.031	[−0.04, 0.08]	FALSE

4.2 Global and Local RF Modelling Results for Freetown

Tables 4a–5 present the Global RF, Local RF, and LGCP results for Freetown. The global RF model identifies accessibility, road connectivity (secondary and tertiary roads), and built morphology as the dominant city-scale predictors of waste exposure. Economic proxies, NTL and RWI, also exhibit strong influence (Table 4a). LGCP results broadly corroborate these findings, with distance to secondary and tertiary roads, NTL, and RWI exhibiting statistically robust effects (Table 5).

Local RF models indicate that road connectivity remains important at a local scale but exhibits spatial heterogeneity across the city. In contrast, NTL and RWI retain relatively stable local importance (Table 4b). Together, the results indicate that waste exposure in Freetown is structured by fragmented urban morphology, with road accessibility and economic gradients shaping the spatial distribution of waste presence.

4.3 Global and Local RF Modelling Results for Nairobi

Tables 6a–7 present the Global RF, Local RF, and LGCP results for Nairobi. The global RF model identifies distance to secondary roads, RWI, accessibility, and BEI as the dominant city-scale predictors of waste presence (Table 6a). LGCP results identify a consistent set of structural drivers, with built morphology (footprint spacing, footprint size, and BEI), alongside road proximity and RWI, emerging as significant covariates (Table 7).

Local RF models indicate substantial heterogeneity, particularly for built morphology predictors, including BEI, footprint size, and spacing. Road connectivity and accessibility remain locally important, whilst RWI exhibits com-

Table 4. RF predictor importance for Freetown: (a) Global and (b) Local models.

(a) Global Random Forest

Predictor	Mean Imp.	SD	Rank
Dist. to Secondary Roads	7.161	0.109	1
Accessibility Index	1.628	0.030	2
Relative Wealth Index	0.416	0.010	3
Footprint Spacing	0.377	0.007	4
Dist. to Tertiary Roads	0.295	0.005	5
Night-Time Lights	0.232	0.005	6
Built Environment Index	0.151	0.009	7
Dist. to Open Space	0.088	0.002	8
Under-18 Population	0.076	0.002	9
Footprint (Mean)	0.071	0.001	10
Slum Likelihood	0.040	0.001	11
Clark–Evans R	0.029	0.001	12
Orientation Dispersion	0.019	0.000	13
Population Density	0.013	0.000	14

(b) Local Random Forest

Predictor	Mean Imp.	SD	CV
Under-18 Population	0.133	0.341	2.558
Population Density	0.000	0.000	2.462
Clark–Evans R	0.061	0.150	2.452
Orientation Dispersion	0.052	0.123	2.390
Built Environment Index	0.110	0.246	2.243
Dist. to Open Space	0.043	0.092	2.127
Footprint Spacing	0.104	0.195	1.877
Dist. to Secondary Roads	0.211	0.384	1.816
Dist. to Tertiary Roads	0.120	0.216	1.806
Footprint (Mean)	0.122	0.201	1.641
Accessibility Index	0.113	0.158	1.392
Night-Time Lights	0.417	0.548	1.313
Slum Likelihood	0.032	0.042	1.302
Relative Wealth Index	0.364	0.441	1.213

Table 5. LGCP covariate effects for Freetown arranged by absolute coefficient value.

Predictor	Coef.	SE	CI	Sig.
Dist. to Sec. Roads	−1.379	0.284	[−1.94, −0.82]	TRUE
Relative Wealth Index	0.713	0.185	[0.35, 1.08]	TRUE
Footprint Spacing	−0.623	0.158	[−0.93, −0.31]	TRUE
Night-Time Lights	−0.592	0.131	[−0.85, −0.34]	TRUE
Dist. to Tert. Roads	0.561	0.217	[0.14, 0.99]	TRUE
Dist. to Open Space	−0.466	0.112	[−0.68, −0.25]	TRUE
Under-18 Population	−0.263	0.080	[−0.42, −0.11]	TRUE
Footprint (Mean)	−0.211	0.079	[−0.37, −0.06]	TRUE
Population Density	0.145	0.137	[−0.12, 0.41]	FALSE
Accessibility Index	0.134	0.268	[−0.39, 0.66]	FALSE
Slum Likelihood	0.080	0.054	[−0.03, 0.19]	FALSE
Orientation Dispersion	−0.077	0.053	[−0.18, 0.03]	FALSE
Clark–Evans R	−0.059	0.085	[−0.23, 0.11]	FALSE
Built Env. Index	0.027	0.106	[−0.18, 0.23]	FALSE

paratively stable influence across local areas (Table 6b). Slum likelihood also increases in local importance relative to the global model. Together, the results indicate that waste exposure in Nairobi is structured by interacting accessibility, economic, and built morphology gradients, with strong spatial variation in local-scale influence.

Table 6. RF predictor importance for Nairobi: (a) Global and (b) Local models.

(a) Global Random Forest			
Predictor	Mean Imp.	SD	Rank
Dist. to Secondary Roads	0.560	0.014	1
Relative Wealth Index	0.459	0.010	2
Accessibility Index	0.329	0.008	3
Built Environment Index	0.320	0.010	4
Footprint Spacing	0.215	0.002	5
Population Density	0.205	0.004	6
Dist. to Tertiary Roads	0.138	0.003	7
Night-Time Lights	0.072	0.002	8
Footprint (Mean)	0.033	0.001	9
Slum Likelihood	0.021	0.000	10
Under-18 Population	0.019	0.000	11
Clark–Evans R	0.017	0.000	12
Orientation Dispersion	0.014	0.000	13
Dist. to Open Space	0.012	0.000	14

(b) Local Random Forest			
Predictor	Mean Imp.	SD	CV
Built Environment Index	0.151	0.378	2.506
Under-18 Population	0.034	0.078	2.284
Population Density	0.142	0.311	2.190
Footprint (Mean)	0.062	0.122	1.974
Slum Likelihood	0.047	0.092	1.947
Orientation Dispersion	0.020	0.038	1.895
Footprint Spacing	0.081	0.129	1.604
Night-Time Lights	0.136	0.213	1.559
Accessibility Index	0.268	0.416	1.552
Dist. to Open Space	0.009	0.013	1.389
Dist. to Tertiary Roads	0.258	0.340	1.319
Dist. to Secondary Roads	0.226	0.293	1.293
Relative Wealth Index	0.316	0.381	1.208
Clark–Evans R	0.021	0.025	1.170

Table 7. LGCP covariate effects for Nairobi arranged by absolute coefficient value.

Predictor	Coef.	SE	CI	Sig.
Footprint Spacing	−1.477	0.306	[−2.08, −0.88]	TRUE
Footprint (Mean)	−0.894	0.462	[−1.80, 0.01]	FALSE
Dist. to Open Space	−0.752	0.123	[−0.99, −0.51]	TRUE
Built Env. Index	0.634	0.103	[0.43, 0.84]	TRUE
Dist. to Sec. Roads	0.475	0.079	[0.32, 0.63]	TRUE
Night-Time Lights	−0.396	0.140	[−0.67, −0.12]	TRUE
Relative Wealth Index	−0.374	0.090	[−0.55, −0.20]	TRUE
Slum Likelihood	−0.287	0.102	[−0.49, −0.09]	TRUE
Under-18 Population	−0.267	0.077	[−0.42, −0.11]	TRUE
Accessibility Index	−0.209	0.142	[−0.49, 0.07]	FALSE
Dist. to Tert. Roads	−0.180	0.113	[−0.40, 0.04]	FALSE
Orientation Dispersion	−0.046	0.075	[−0.19, 0.10]	FALSE
Clark–Evans R	−0.040	0.114	[−0.26, 0.18]	FALSE
Population Density	−0.015	0.062	[−0.14, 0.11]	FALSE

5 Discussion

Results between the global RF and LGCP models display close alignment in the dominant domains associated with waste across cities. In Lagos, both models consistently prioritise economic conditions and accessibility-related factors as primary drivers, highlighting the combined influence of wealth gradients, night-time activity, and access to basic infrastructure. In Freetown, accessibil-

ity emerges as the dominant mechanism, with road connectivity and associated income proxies jointly shaping waste presence. Nairobi exhibits a more balanced configuration, in which built-form characteristics, secondary road connectivity, and economic indicators jointly govern waste presence. Across all cities, this convergence at the domain level demonstrates that the RF-derived exposure surface captures meaningful spatial processes, with LGCP results providing independent confirmation of the same underlying mechanisms. The predictor-level discrepancy in results between Global RF and LGCP may be attributed to both approaches characterizing spatial relationships in different ways. RF variable importance provides a descriptive ranking of predictor relevance based on contribution to predictive accuracy, but does not indicate the direction, magnitude, or functional form of associations. By contrast, LGCP explicitly models the intensity of the point process and estimates directional covariate effects alongside residual spatial dependence through mathematically optimised spatial structures. Furthermore, the LGCP operates on the observed point pattern itself, whereas the RF models are fitted to a user-informed, deterministic surface designed to represent the spatial influence of the studied phenomena. The framework proposed here is not intended to reproduce LGCP results exactly, but rather to provide a complementary perspective against which broader spatial patterns can be compared.

Global RF and LGCP models provide a first-order characterisation of waste exposure patterns, but their aggregated nature obscures locally distinct mechanisms within heterogeneous urban systems. This is particularly relevant in cities with fragmented land use, uneven infrastructure provision, and mixed socio-economic conditions. In such contexts, city-scale drivers associated with waste presence differ from the predictors and interactions operating at a sub-city scale.

Figure 4 illustrates how local RF models extend city-scale insights by revealing shifts in the relative importance of predictor domains within urban sub-regions. In Lagos, local RF results show a marked re-weighting of drivers, with economic and accessibility indicators increasing in importance relative to the global model, while population density becomes substantially less influential. This suggests that city-wide demographic pressure masks more localised constraints linked to infrastructure access and economic conditions. In Freetown, divergence between global and local RF results is more pronounced. While accessibility remains important at both scales, local models indicate a more even balance between urban structure, demographic pressure, and accessibility, alongside a strengthened role for economic proxies. This pattern highlights strong within-city heterogeneity that is not apparent in global summaries. Nairobi exhibits the greatest consistency between global and local RF results, indicating comparatively stable drivers across scales. The primary local-level deviation is an increased importance of informality, suggesting that slum probability acts as a locally intensified modifier rather than a dominant city-wide driver. Figure 5 provides mapped examples linking the Global and Local RF results to spatial context across Lagos, Freetown, and Nairobi.

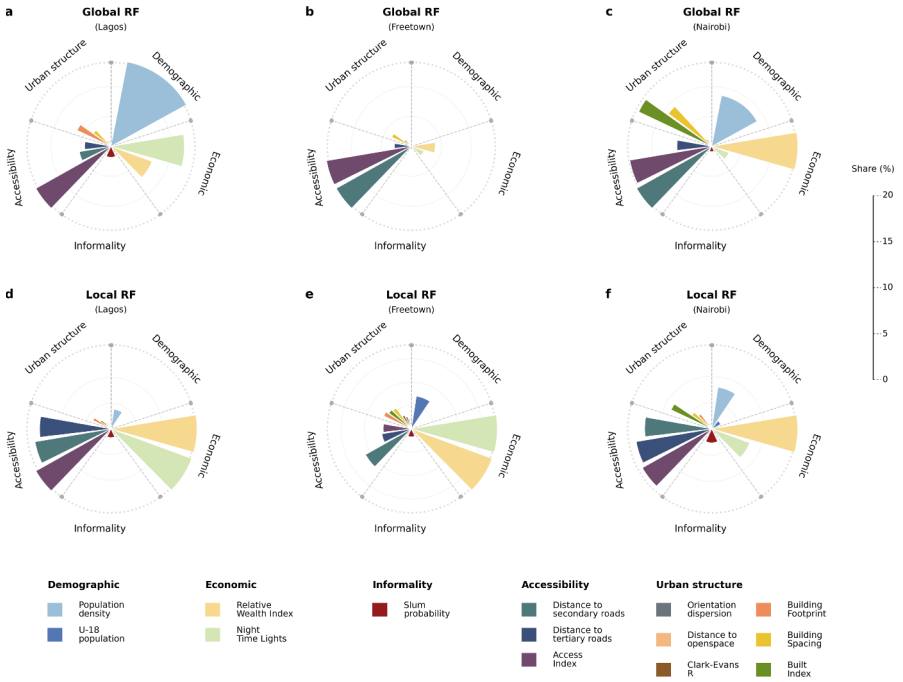


Fig. 4. Figures a-c present the relative predictor share at a city-scale for Lagos, Freetown, and Nairobi, respectively. Figures d-f present the relative predictor importance share at a local-level for the same cities

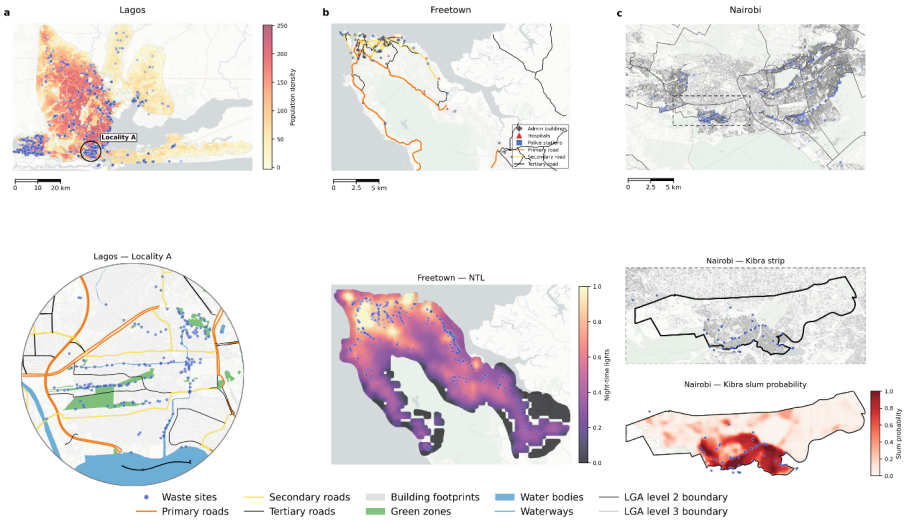


Fig. 5. Examples of the city-scale and local-level drivers of waste that were predicted by Global and Local RF models

Lagos, Freetown, and Nairobi represent contrasting urban configurations: rapid urban expansion, severe infrastructure deficit, and moderate infrastructure development, respectively. In Lagos (column a), rapid population growth and urban expansion (5.7%) [14] have outpaced infrastructure provision, resulting in population density acting as a city-wide envelope within which waste sites emerge. Simultaneously, secondary and tertiary road access concentrates waste within disconnected peripheral areas, consistent with the importance of accessibility in the Local RF model (Fig. 4). In Freetown (column b), which exhibits the highest infrastructure deficit among all cities ($\leq$46% of the population in severe or extreme access constraints) [3], road infrastructure and services are concentrated within the urban core and remain limited in peri-urban areas. Consequently, accessibility governs waste presence at the city scale, while economic inequality shapes waste accumulation across peri-urban and lower-income areas. Nairobi (column c) represents an intermediate system, where demographic, economic, accessibility, and infrastructure pressures jointly structure waste exposure. Although urban structure displays a broad city-scale association with waste, local clustering closely aligns with areas of high slum probability, such as Kibra ward, reinforcing the increased local importance of informality in systems where infrastructure provision has not fully kept pace with urban growth.

As demonstrated in this case study, the drivers of point-based phenomena are inherently scale-dependent, with distinct relationships emerging at different spatial extents. This behaviour is not unique to urban systems. Evidence from ecology and epidemiology shows that processes governing spatial distributions vary across scales, with different drivers becoming dominant under different spatial supports. For example, biotic factors have been shown to dominate pathogen spread at local scales ($\sim 10^2$–$10^3\,\mathrm{km}^2$), while climatic and demographic drivers become significant only at broader regional scales ($> 10^4\,\mathrm{km}^2$) [5]. Similarly, invasive species distributions are often shaped by climate at large scales, but by infrastructure and human activity at local scales [10]. More broadly, spatial epidemiological studies demonstrate how reliance on global trends can obscure heterogeneous transmission dynamics and locally specific drivers. These findings highlight the importance of frameworks that explicitly incorporate spatial variation into analysis. Within this context, the proposed framework allows domain knowledge to guide the generation of a continuous, mass-preserving response surface. The resulting surface can then be interrogated at user-defined resolutions, supporting the identification of predictors and mechanisms operating across spatial scales.

6 Conclusion

This study introduces a framework for analysing point-based phenomena by transforming discrete event locations into a continuous, mass-preserving influence surface. The results demonstrate that the drivers of waste are strongly scale-dependent, with global models capturing dominant patterns while local analyses reveal substantial heterogeneity within urban systems. By enabling analysis

at user-defined spatial resolutions, the framework provides a flexible means of exploring how relationships vary across space while preserving the spatial structure of the original data. Beyond waste, this approach offers a generalisable and computationally practical framework for analysing point-based phenomena in complex systems, where understanding spatial heterogeneity is critical for interpretation and targeted intervention.

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