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

LNCS 16762

Computational Science and Its Applications – ICCSA 2026 Workshops

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

5 Part V



Springer

Lecture Notes in Computer Science **16762**

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ISSN 0302-9743 ISSN 1611-3349 (electronic)
Lecture Notes in Computer Science
ISBN 978-3-032-30523-7 ISBN 978-3-032-30524-4 (eBook)
https://doi.org/10.1007/978-3-032-30524-4

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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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The Specific Characteristics of Surface Heat Islands in Semi-Arid Environments. Implications for Urban and Landscape Planning

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Abstract. Urban thermal patterns are shaped by a combination of land-cover configuration, surface energy exchanges and regional climatic drivers. Although the classical Surface Urban Heat Island (SUHI) paradigm describes urban areas as warmer than their surrounding rural environments, recent studies, conducted in arid and semi-arid regions, have reported the occurrence of daytime cooling effects within urban areas, commonly referred to as the Surface Urban Cool Island (SUCI) phenomenon.

This study examines summer Land Surface Temperature (LST) dynamics in the municipality of Lecce (Southern Italy), a Mediterranean city, characterized by hot, dry summers and peri-urban agricultural landscapes under seasonal water stress. LST was retrieved from Landsat 8/9 TIRS imagery (June-August 2024, cloud cover $< 10\%$), using the Single Channel Algorithm applied to Band 10. To establish a rural thermal reference, a spatial filtering was applied within a buffer of 5–10 km from the urban centroid. Corine Land Cover data were used to exclude anthropogenic surface and water bodies, as well as to identify thermally anomalous areas. Thermal anomalies (ΔT) were then calculated relative to the filtered rural reference.

Results reveal an inversion of the classical Surface Urban Heat Island (SUHI) pattern during late-morning satellite acquisition ($\approx$11:30 local time). The historic urban core shows negative thermal anomalies (down to -4.87 °C) compared to the surrounding peri-urban agricultural matrices. Thermal hotspots were primarily concentrated in non-irrigated croplands, bare soils, olive groves affected by water stress and industrial areas. These findings indicate that, under summer semi-arid conditions, peri-urban soils act as thermally dominant sensible heat sources, whereas urban morphology and material properties induce a transient daytime SUCI effect.

This study integrates urban climatology and soil degradation perspectives within a unified surface energy balance framework, highlighting the climatic dependency of urban thermal regimes in Mediterranean transitional environments.

Keywords: Urban Heat and Cool Island · Land Surface Temperature · Landsat images · Planning

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 3–20, 2026.
https://doi.org/10.1007/978-3-032-30524-4_1

1 Introduction

1.1 The Heat Island Issue

Urbanization represents one of the most pervasive anthropogenic transformations of the Earth's surface, profoundly altering land-atmosphere energy exchanges [1]. Among its most documented climatic impacts is the Urban Heat Island (UHI) phenomenon, defined as the thermal contrast between urban areas and their rural surroundings [2]. Traditionally, UHI has been investigated in terms of canopy air temperature [3], whereas the advent of thermal remote sensing has enabled the assessment of the Surface Urban Heat Island (SUHI) through Land Surface Temperature (LST) measurements [4–6].

LST acts as a primary indicator of the surface energy balance [7]. Urban expansion has drastically modified land cover [8], replacing natural landscapes with impervious surfaces, characterized by high thermal mass and lower albedo compared to rural agricultural or forested areas [2]. This alters both the hydrological cycle and the distribution of incident solar radiation [9]. Focusing on climatic impacts, soil sealing causes the rapid discharge of runoff during precipitation events, thereby reducing evapotranspiration [9]. Simultaneously, construction materials, featuring high heat capacity, combined with compact urban geometry, trap incoming radiation within urban canyons [10, 11]. This elevates the LST without significant latent heat dissipation [4, 12].

Thermal remote sensing has proven fundamental in the systematic, multi-scale monitoring of surface thermal anomalies [4, 13, 14]. Recently, the availability of satellite platforms equipped with Thermal Infrared (TIR) sensors, such as Landsat 8 and 9, MODIS, ASTER, Sentinel-3, and ECOSTRESS, has advanced SUHI research [15, 16]. The choice of sensors entails a methodological trade-off: although instruments like Sentinel-3 or ECOSTRESS provide high temporal resolution, which is ideal for studying diurnal and nocturnal cycles [17], the TIRS sensors aboard the Landsat constellation remain among the most suitable for intra-urban spatial analyses [18–21]. Despite being limited by a 16-day revisit time, their 100 m spatial resolution, resampled to 30 m, allows for precise mapping of the interactions between urban morphology and temperature [22]. For LST retrieval, the Single Channel Algorithm (SCA) has been extensively validated for Landsat 8 TIRS data, proving optimal when applied to Band 10 due to its greater radiometric stability [23, 24].

1.2 Urban Heat, Soil Degradation and Shared Energetic Drivers

Parallel to UHI research, an extensive literature has addressed soil degradation processes, both broadly [25] and specifically within Mediterranean and semi-arid environments [18, 26], highlighting their direct impacts on desertification [27, 28]. Erosion, loss of vegetative cover, and intensive agricultural practices, particularly deep plowing and soil compaction, alter soil properties under already critical climatic conditions [29].

These intensive practices deplete Soil Organic Carbon (SOC) [25, 30], which in turn alters soil properties. This depletion reduces heat capacity, bringing the thermal inertia of dehydrated agricultural soil closer to that of construction materials [31] and diminishing water retention [32]. These physical changes increase the dominance of sensible heat fluxes during dry seasons, consequently raising surface temperatures [27, 33].

Research rarely addresses UHI and soil degradation in an integrated manner, although these processes share common physical drivers and impacts, such as reduced evaporative cooling, increased surface exposure, and altered radiative properties. Under summer semi-arid conditions, non-irrigated agricultural soils can reach surface temperatures exceeding those of adjacent urban centers, particularly during morning and afternoon observations [34, 35]. This dynamic challenges the classical paradigm that views urban cores as systematically warmer than rural areas, an issue warranting further investigation to which this paper aims to provide an initial contribution.

1.3 Urban Cool Island and Climatic Dependency of Thermal Gradients

Recent studies conducted in arid and desert environments have documented a diurnal reversal of the conventional UHI signal, introducing the concept of the Urban Cool Island (UCI) [6, 14, 34, 35]. In such contexts, barren or sparsely vegetated rural surfaces undergo rapid radiative heating due to low thermal inertia and severely limited evapotranspiration [6, 18, 35–37]. Conversely, compact urban grids frequently record lower daytime LSTs. Vertical shading within urban canyons, the high thermal mass of construction materials, and localized irrigated vegetation all drive this temporary cooling effect [6, 19, 31, 34, 38, 39].

Analyzing over 100 cities in arid and semi-arid climates globally, Liu et al. (2024) [14] demonstrated that the daytime UCI phenomenon is a frequent occurrence, observed in approximately 50% of the sampled locations. The literature offers several examples of this anomaly: Gago et al. (2020) [40] analyzed Landsat-derived LST for the city of Seville (Spain) over a three-decade timeframe, revealing that urban areas remain cooler than surrounding bare soils and agricultural lands during dry summer periods. Abedrabboh et al. (2025) [6] documented a similar phenomenon in Smara (Morocco), recording a daytime UCI of up to 9 °C, largely driven by the strong albedo contrast between the dark desert lands and the urban core characterized by light-colored surfaces. Further supporting this, Siddiqui et al. (2025) [34] observed a daytime UCI of 3.5–4.6 °C in Erbil (Iraq), attributing the thermal dampening to urban density and water bodies contrasting with the arid outskirts.

1.4 Research Gap and Study Objective

Mediterranean climates, classified as Csa under the Köppen system, feature hot, dry summers and marked seasonal water deficits. During the summer, peri-urban agricultural landscapes, dominated by non-irrigated crops or bare soils, act thermally like semi-arid systems. Under these conditions, rural matrices exhibit a low evaporative fraction, high sensible heat flux dominance and rapid diurnal heating.

Concurrently, historic urban cores, characterized by a low Sky View Factor (SVF), shade and thermally insulate the urban grid during the morning. This delays surface temperature peaks, generating a temporary daytime cool island effect. Despite this emerging evidence, Mediterranean cities remain noticeably underrepresented in studies tracking the diurnal transition from UHI to UCI. This gap is particularly concerning given the accelerating regional trends of soil drying and climate change.

Therefore, this study aims to:

1. quantify high spatial resolution summer LST patterns within the municipality of Lecce (Southern Italy);
2. establish a robust rural thermal baseline using rigorous land-cover spatial filtering;
3. assess the occurrence, spatial extent and intensity of the daytime UCI effect;
4. examine the physical relationship between peri-urban thermal hotspots and localized soil degradation processes.

By linking urban climatology with land degradation research, this work refines the conceptual understanding of climate-dependent urban thermal regimes. It provides empirical evidence to reinterpret summer Mediterranean dynamics within a semi-arid energetic framework.

2 Materials and Methods

The investigation focuses on the municipality of Lecce (Southern Italy, see Fig. 1), situated in the Salento peninsula. The climate is typically Mediterranean (Köppen classification: Csa; source: https://koeppen-geiger.vu-wien.ac.at/), with hot, dry summers and mild, wetter winters.

The urban fabric is characterized by a compact historic center with narrow streets and high height-to-width (H/W) ratios, surrounded by peri-urban agricultural landscapes dominated by non-irrigated arable lands and olive groves.

The summer of 2024 was selected for this analysis due to its persistent high solar irradiance and cumulative precipitation deficit. These meteorological conditions strongly amplify surface thermal contrasts [41, 42].

To assess the dynamics of both the Surface Urban Heat Island (SUHI) and the Surface Urban Cool Island (SUCI), Land Surface Temperature (LST) was retrieved using Thermal Infrared (TIR) sensors. Although several consolidated algorithms exist for LST retrieval, such as the Radiative Transfer Equation (RTE) and the Split-Window Algorithm (SWA) [24], the Single Channel Algorithm (SCA) was selected [23].

For intra-urban analyses, involving high morphological heterogeneity, literature favors Landsat TIRS data resampled to a 30 m spatial resolution over coarser sensors like MODIS (1 km) [19], despite the higher temporal frequency of the latter. Choosing Landsat represents a compromise between spatial resolution (30 m for multispectral, 100 m for TIR resampled to 30 m), temporal revisit time (16 days per single satellite) and radiometric accuracy (12-bit, scaled to 16-bit in distributed products) [43, 44].

In this study, LST dynamics were investigated using data acquired by the TIRS sensors onboard Landsat 8 and TIRS-2 onboard Landsat 9. These sensors are widely utilized and validated for urban thermal mapping [20, 22–24, 45]. For the Lecce case study, summer scenes between June 1, 2024 and September 1, 2024, were acquired, strictly filtering for cloud cover below 10% (9 scenes in total). This specific temporal window was defined based on a meteorological analysis using data provided by the regional environmental agency ARPA portal (source: http://www.webgis.arpa.puglia.it/meteo/).

This period exhibited a severe radiative load (average seasonal solar irradiance of 283.30 W/m2) combined with a cumulative rainfall deficit. Under these specific conditions, both heat island phenomena and soil water stress become highly pronounced.

A critical factor, for correctly interpreting the data, is the Landsat satellite overpass time, which occurs at approximately 09:30 UTC (11:30 local time). This late-morning window captures the active phase of surface thermal accumulation and the specific shadowing dynamics of the urban geometry, playing a decisive role in defining the observed spatial patterns.

LST data for the Lecce municipality were derived from the Landsat Collection 2 Level-2 Surface Temperature (L2SP) product, provided by the USGS (source: https://earthexplorer.usgs.gov/). Relying on this Level-2 product eliminates the uncertainties typically associated with manual atmospheric corrections required for Level-1 data. The L2SP algorithm implements the SCA on Band 10, correcting atmospheric effects by integrating the Radiative Transfer Equation (RTE). It utilizes atmospheric profiles extracted from the NASA Earth Observing System for Instrument Teams (GEOS-IT) to accurately calculate atmospheric transmittance, upwelling radiance and downwelling radiance. Furthermore, surface emissivity (ε) is incorporated via the ASTER Global Emissivity Dataset (GED). Excluding Band 11 is due to documented residual calibration issues, primarily stray light artifacts [44].

Final LST values (in degrees Celsius) were obtained by applying the Collection 2 scale factors to the pre-processed pixel thermal values (DN_{ST}):

$$LST(\circ C) = [(DN_{ST} \times M_T) + A_T] - 273.15 \quad (1)$$

Here, DN_{ST} represents the pre-processed pixel Digital Number, while M_T and A_T define the multiplicative scale factor and additive scale factor, respectively, extracted from the _MTL.txt metadata file accompanying each image [45].

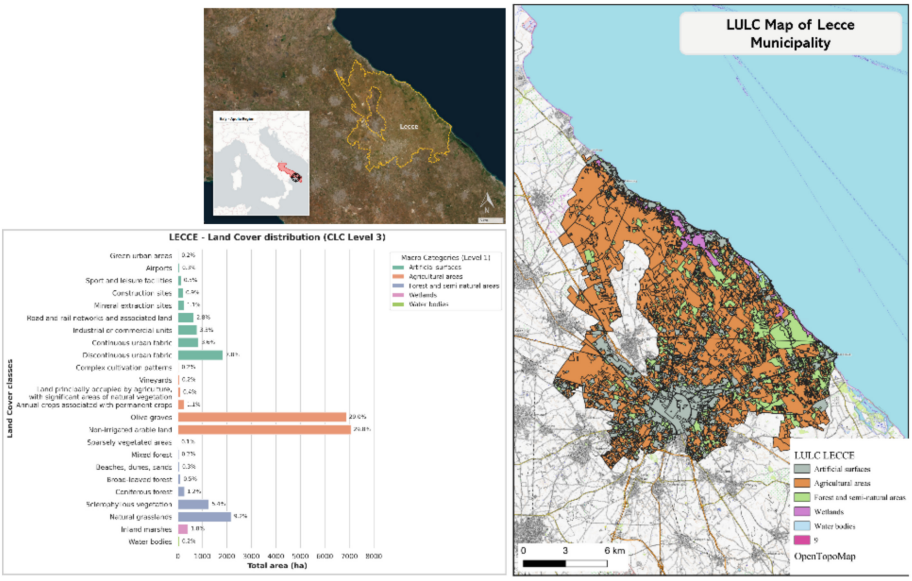


Fig. 1. The study area (Lecce, Southern Italy) and its land cover characterization based on the Corine Land Cover (CLC) nomenclature. The horizontal bars represent the total area (in hectares) occupied by each CLC Level 3 class, while the colors indicate the corresponding CLC Level 1 macro-categories.

3 Results

Although the methodological framework included a dual temporal scale (specifically, the analysis of individual daily acquisitions and the generation of a map representing the mean seasonal thermal anomaly), the processing from August 14, 2024, was selected to demonstrate the single-acquisition analysis. On this date, the study area recorded maximum air temperatures of 38.3 °C, a peak solar irradiance of 801.2 W/m2 and weak wind conditions mean wind speed: 1.1 m/s), following 23 consecutive days without precipitation.

The processed acquisitions reveal a spatial thermal inversion: contrary to the conventional Surface Urban Heat Island (SUHI) paradigm, the dense urban core maintained lower surface temperatures compared to the peri-urban and rural matrix, where the highest LST values were observed (see Fig. 2).

This trend is consistent with the analysis of diurnal LST dynamics for the city of Lecce, during the June - August period from 2018 to 2024 across six daily time intervals [46]. This phenomenon, found in other Mediterranean cities, is explained by the energy balance resulting from the rural characterization of Lecce: peri-urban soils, predominantly characterized by sparse vegetation, simple arable land in non-irrigated areas or sparse olive groves, present low thermal inertia and high exposure to direct radiation.

The frequency histogram provides an overview of the surface thermal regime of the surveyed area. The retrieved LST values span an overall range between approximately 34 °C and 55 °C.

The distribution exhibited a predominantly unimodal and slightly left-skewed behavior. The main peak occurred between 50 °C and 53 °C, indicating that these temperature ranges represent the dominant thermal condition within the landscape. The lower-temperature tail of the distribution represented a minority fraction of total pixels and spatially corresponded to coastal areas, wetlands, woodlands and the compact urban core. Conversely, the central portion of the distribution, encompassing most of the pixels, coincided with the peri-urban and rural matrix. The high frequency of elevated LST values reflects the summer physical conditions of exposed rural surfaces, including limited shading, direct solar exposure, low soil moisture availability and the widespread presence of bare soil.

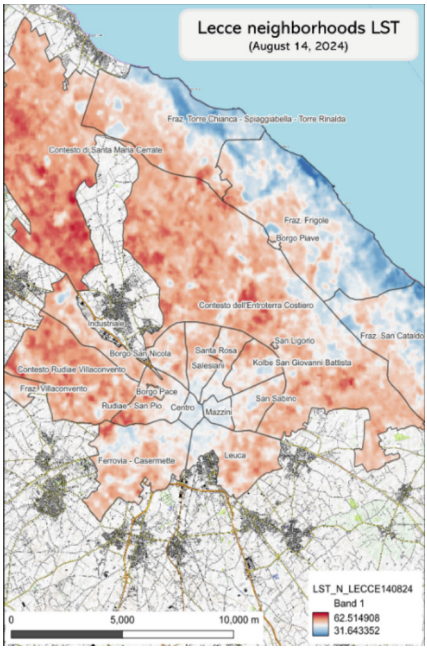


Fig. 2. Retrieved Land Surface Temperature (LST) for the municipality of Lecce (Landsat 8/9 acquisition, August 14, 2024; https://earthexplorer.usgs.gov/)

Quantifying the relative thermal anomaly (ΔT) required the definition of a rural thermal reference. For the spatial filtering procedure, an annular buffer between 5 and 10 km from the urban centroid was isolated, as this distance was considered sufficient to minimize the direct thermal influence of the urban core [47].

Utilizing Land Use Land Cover (LULC) vector data provided by the SIT Puglia portal (see Fig. 1, https://pugliacon.regione.puglia.it/web/sit-puglia-sit), the extraction was limited to vegetated classes (i.e., "Forest and semi-natural areas", "Wetlands" and "Agricultural areas"). A preliminary comparative analysis (see Fig. 3) revealed that specific agricultural classes ("non-irrigated arable land", "vineyards" and "olive groves") and semi-natural areas ("natural grasslands") recorded LST values exceeding the mean

(50.43 °C). Particular attention must be drawn to olive groves, which, alongside non-irrigated arable lands, constitute the most extensive land cover in the Lecce territory (accounting for 29% and 29.8%, respectively). The elevated LST values observed in these areas, despite their classification as vegetation cover, may be related to specific surface and canopy thermal dynamics. In olive groves, the satellite thermal signal represents a mixed radiometric response resulting from the combined contribution of the tree canopy and the exposed soil between rows. Under severe summer water stress conditions, potentially exacerbated by the effects of *Xylella fastidiosa*, the thermal contribution of bare and desiccated soil may become increasingly relevant within the emitted radiance signal. In the Lecce area, this interpretation is further supported by previous studies, as reported in [46], which analyzed summer soil moisture conditions between 2017 and 2022, reporting values frequently below 0.10 m^3/m^3, substantially lower than the average soil moisture levels typically observed across Italy (approximately 0.30 - 0.35 m^3/m^3). Consequently, these areas may behave as localized sources of sensible heat during daytime conditions.

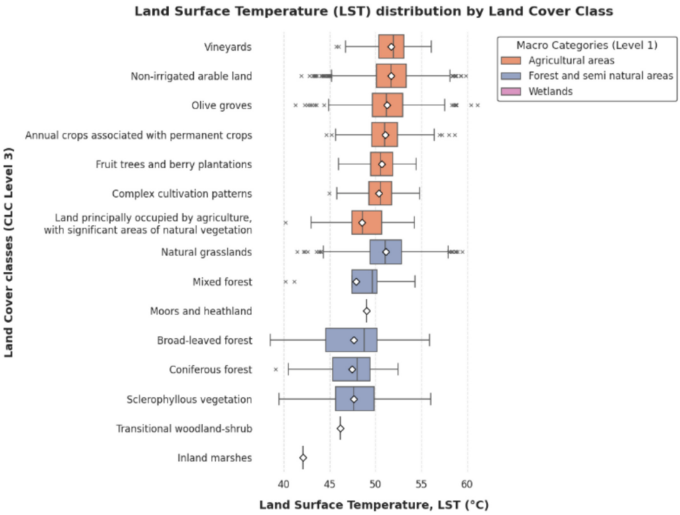


Fig. 3. Evaluation of vegetation cover (agriculture, forests and wetlands) for the rural baseline definition, highlighting the exclusion of agricultural surfaces with significant thermal anomalies.

The methodology adopted to define the rural reference value follows the approach described in [47] and consists of subtracting the mean LST value, calculated across a set of sampling points (pins) representative of non-urban areas, from each pixel within the study area. Each pin strictly satisfies the following spatial criteria:

1. it is the centroid of a union of contiguous Corine Land Cover (CLC) polygons belonging to the Level 1 macro-classes “Agricultural areas” or “Forest and semi-natural areas” or “Wetlands”;
2. it falls within the previously defined annular buffer;
3. it is located at a minimum distance of 350 m from the CLC “Artificial surfaces” class.

To isolate the rural thermal signal as accurately as possible, artificial surfaces and water bodies located within the annular buffer were explicitly excluded.

The LST spatial mean was calculated using a total of 3108 sample pins, obtaining a rural reference value LSTrif = 51.44 °C (median: 51.48 °C; SD: 2.59 °C; NMAD: 2.33 °C).

The thermal anomaly map was finally generated according to Eq. (2) [47, 48]:

$$\Delta T_{(x,y)} = LST_{(x,y)} - \overline{LST}_{rif} \tag{2}$$

where $\Delta T_{(x,y)}$ represents the thermal anomaly associated with the pixel located at coordinates (x,y).

The interpretation of thermal anomalies also considered the expected quality and uncertainty of the Landsat Collection 2 Level-2 Surface Temperature product. Landsat 8 TIRS and Landsat 9 TIRS-2 acquire thermal infrared data at a native spatial resolution of 100 m, subsequently resampled to 30 m in the distributed products and are characterized by high radiometric sensitivity. The sensors exhibit Noise Equivalent Delta Temperature (NE Δ T) values generally below 0.4 K and typically close to 0.1 K at 300 K under nominal operating conditions [23]. In addition, the operational USGS LST retrieval chain integrates atmospheric correction and ASTER GED emissivity information, leading to expected LST uncertainties generally on the order of 1–2 °C under clear-sky conditions [45]. Consequently, thermal anomalies substantially exceeding this uncertainty range can be interpreted as physically meaningful spatial signals rather than retrieval noise or instrumental artifacts.

Mapping the thermal anomaly (see Fig. 4) allowed the identification of two main thermal regimes:

- $\Delta T > 0$ defines hotspots areas, where the surface energy balance appears dominated by radiative absorption and reduced evaporative dissipation. This class includes peri-urban areas with bare soil/arable land in non-irrigated areas, olive groves, abandoned settlements and industrial zones (see Fig. 5).
- $\Delta T < 0$ indicates cool spot areas, where surface temperatures remain below the rural thermal reference. This class includes the dense historic center, urban green spaces (see Fig. 5), woodlands and wetlands.

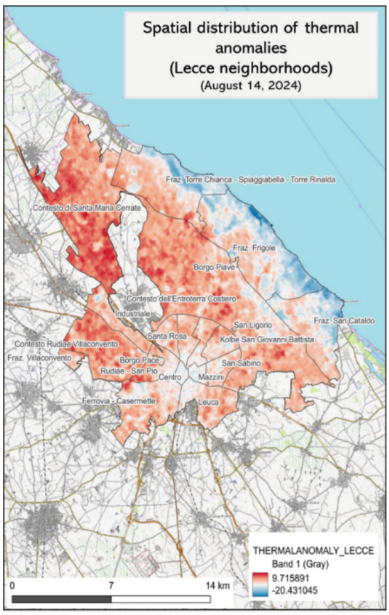


Fig. 4. Relative thermal anomaly map (ΔT) for the municipality of Lecce

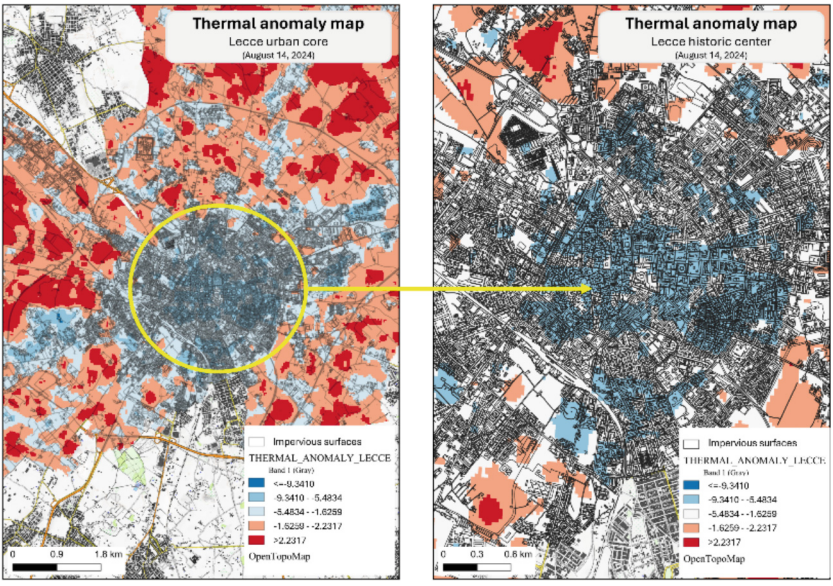


Fig. 5. Characterization of the Surface Urban Cool Island (SUCI) phenomenon, highlighting the negative thermal gradient associated with shaded impervious surfaces in the historic center and arboreal vegetation compared to the peri-urban agricultural context.

An interpretation of the cooling patterns observed within the urban core may be attributed to the combined effect of building shadows and urban geometry, characterized by high building height-to-street width ratios and reduced Sky View Factor (SVF) values [50, 51]. During the morning hours, this configuration maximizes street shading and prevents air mixing within urban canyons. Furthermore, the "Lecce Stone" (Miocene calcarenite rock) and the light-colored paving materials contribute to relatively high thermal inertia and medium-to-high albedo conditions. As a result, a fraction of incoming solar radiation is reflected, while surface heating occurs more gradually than in the surrounding rural environments. At the Landsat overpass time (approximately 11:30 local time), the city remains within its thermal accumulation phase and has not yet reached the afternoon thermal emission peak. Conversely, the surrounding peri-urban areas, characterized by lower thermal capacity and reduced soil moisture availability, tend to heat more rapidly under intense solar forcing.

This interpretation is consistent with the findings reported in [46], where the analysis of LST dynamics across different Local Climate Zones (LCZs) and six daily temporal intervals revealed a characteristic bell-shaped thermal curve. Minimum LST values were observed during the nighttime and early morning periods (23:00–03:00 and 03:00–06:00), whereas maximum temperatures occurred between 11:00 and 14:00. During this peak thermal interval, the compact urban core (classified as LCZ 2) exhibited lower LST values compared to peri-urban zones classified as LCZ 6 and LCZ 8. However, the study did not specifically investigate the thermal behavior of non-urban rural surfaces such as olive groves, bare soils, and wetlands.

Densely vegetated areas, including woodlands, irrigated urban parks and wetlands, are distinctly differentiated from both urban and semi-arid agricultural environments, representing actual climate mitigation zones (Fig. 6). In these areas, the climate mitigation mechanism is governed by the distribution of net radiation in favor of the latent heat flux. Vegetation dissipates the incident radiation through evapotranspiration: thermal energy is not stored in the soil or reflected; rather, it is absorbed to allow the state change from liquid to vapor. This process removes sensible heat from the environment, keeping the surface temperature close to air temperature and ensuring a fundamental ecosystem service of local thermoregulation.

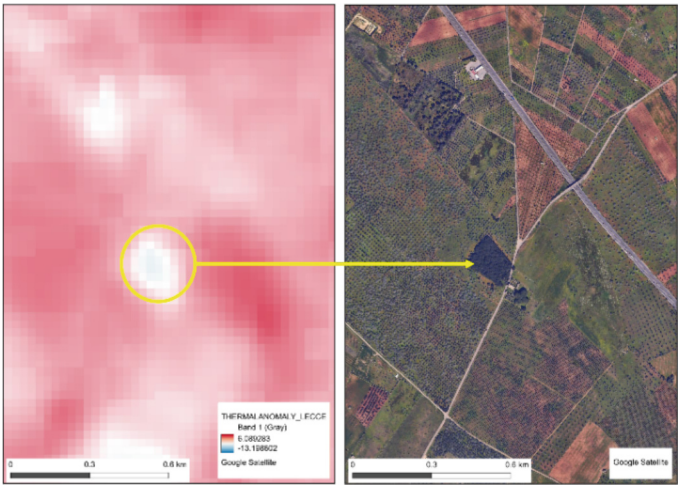


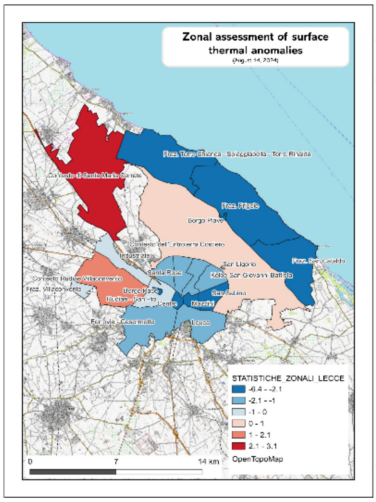
Fig. 6. Thermal heterogeneity of vegetation cover. Note how the olive grove, characterized by inter-row bare soil and direct exposure, acts as a Hotspot ($\Delta T > 0$), whereas the dense tree cover generates a cool spot ($\Delta T < 0$)

The thermodynamic drivers governing both the SUHI effect and the thermal anomalies associated with degraded agricultural soils are linked to similar radiative and hydrological imbalances. The transition from healthy vegetated surfaces to impervious urban materials or degraded semi-arid soils may significantly reduce evaporative cooling capacity by suppressing evapotranspiration processes. Under these conditions, a larger fraction of incoming radiative energy is converted into sensible heat fluxes rather than latent heat [15, 50, 52].

In urban environments, replacing natural surfaces with mineral materials generally increases heat storage capacity and modifies the optical and thermophysical properties of the surface. The relatively high thermal inertia of urban materials contributes to delayed heat release and plays a major role in sustaining the nocturnal SUHI effect [9].

Similarly, degraded rural environments characterized by bare soils, sparse vegetation and chronic summer water deficits may undergo rapid daytime surface heating due to low soil moisture availability and reduced thermal buffering capacity. In the Lecce context, these conditions appear particularly evident in agricultural areas affected by prolonged drought stress and vegetation degradation processes, including those associated with *Xylella fastidiosa*. These findings suggest that the degradation of vegetative cover may significantly amplify local microclimatic thermal extremes under semi-arid summer conditions.

Applying zonal statistics to the neighborhoods and hamlets of the city of Lecce enabled the quantification of the average thermal anomaly for each territorial unit (see Fig. 7).



District	ΔT(°C) Mean	ΔT(°C) Median	ΔT(°C) Std. Dev.	ΔT(°C) Min
Fraz. Frigole	-6.39	-6.18	4.50	-20.66
Centro	-5.81	-5.78	0.82	-9.11
Fraz. San Cataldo	-5.45	-4.89	4.19	-18.40
Mazzini	-5.44	-5.68	1.56	-8.37
Fraz. Torre Chianca - Spiaggiabella - Torre Rinalda	-3.88	-2.62	5.16	-17.57
Borgo Piave	-3.12	-3.17	0.86	-4.74
Borgo Pace	-2.34	-2.37	1.41	-5.81
San Sabino	-2.12	-2.18	2.34	-8.06
Salesiani	-2.08	-2.51	2.64	-8.21
San Ligorio	-2.03	-2.05	0.93	-3.50
Kolbe San Giovanni Battista	-1.77	-2.10	2.96	-9.58
Ferrovia - Casermette	-1.57	-1.72	2.82	-9.49
Leuca	-1.47	-1.61	2.78	-7.91
Santa Rosa	-1.40	-1.26	2.42	-8.04
Borgo San Nicola	-1.07	-1.31	2.13	-7.31
Fraz. Villaconvento	-0.86	-0.97	2.40	-7.12
Rudiae - San Pio	-0.80	-1.43	3.35	-6.72
Industriale	-0.64	-0.57	2.43	-11.11
Contesto dell'Entroterra Costiero	0.62	0.86	2.75	-11.96
Contesto Rudiae Villaconvento	2.10	2.31	2.29	-7.18
Contesto di Santa Maria Cerrate	3.15	3.30	2.51	-6.97

Fig. 7. Quantification of the thermal regime at the neighborhood scale: mapping of the average anomaly calculated via zonal statistics, highlighting the heterogeneity between the urban core, coastal hamlets and peri-urban areas.

Tabular data analysis reveals two macro-clusters with opposite thermal behaviour:

1. Urban and natural cool spots (with negative thermal anomaly). These two types of territorial fabric share negative anomaly values but differ in physical cooling drivers:
   a. dense urban core: historic and commercial neighbourhoods show marked negative anomalies, with the historic center (ΔT_{mean} = -5.81 °C; ΔT_{median} = -5.78 °C; ΔT_{SD} = 0.82 °C) and the Mazzini neighbourhood (ΔT_{mean} = -5.44 °C; ΔT_{median} = -5.68 °C; ΔT_{SD} = 1.56 °C) being among the coolest areas overall. This evidence confirms the hypothesis of shading and the thermal inertia of materials as the dominant mitigating factors during the morning satellite acquisition hours.
   b. Coastal districts and wetlands: the lowest value was recorded in the district of Frigole (ΔT_{mean} = -6.39 °C; ΔT_{median} = -6.18 °C; ΔT_{SD} = 4.50 °C), followed by San Cataldo (ΔT_{mean} = -5.45 °C; ΔT_{median} = -4.89 °C; ΔT_{SD} = 4.19 °C) and the hamlet of Torre Chianca (ΔT_{mean} = -3.88 °C; ΔT_{median} = -2.62 °C; ΔT_{SD} = 5.16 °C). The low thermal regime is attributable to the presence of natural surfaces with high evaporative capacity (reservoirs, wooded areas of the Rauccio Park and the Le Cesine wetland) as well as the mitigating effect of the sea, given the areas' proximity to the coastline.
2. Peri-urban hotspots (with positive thermal anomaly). The highest surface temperature values are found in the Santa Maria Cerrate rural area (ΔT_{mean} = + 3.15 °C; ΔT_{median} = + 3.30 °C; ΔT_{SD} = 2.51 °C), Rudiae-Villaconvento (ΔT_{mean} = + 2.10 °C; ΔT_{median} = + 2.31 °C; ΔT_{SD} = 2.29 °C) and in the coastal hinterland area (ΔT_{mean} = + 0.62 °C; ΔT_{median} = + 0.86 °C; ΔT_{SD} = 2.75 °C). These areas confirm the thermal vulnerability of peri-urban surfaces characterized by bare soils, sparse vegetation under water stress, or large, unshaded, sealed areas, where the surface energy balance is heavily skewed toward sensible heat fluxes.

In temperate regions, urban areas are typically surrounded by densely vegetated rural landscapes. In this scenario, the city appears warmer than the countryside both day and night due to the lower evaporative cooling capacity of impervious surfaces compared to the rural environment.

Conversely, in strictly arid regions where urban grids border barren land, a diurnal gradient reversal is common. The city acts as an 'urban oasis,' maintaining localized humidity and lower surface temperatures through irrigated green spaces and geometric shading. Rapid nocturnal cooling of rock, however, contrasts with the thermal retention of urban concrete, driving a nighttime SUHI.

4 Discussion

The LST analysis in the Lecce municipal area, during the summer of 2024, highlights a thermal behaviour deviating from the classic SUHI paradigm. Processing the Landsat images, acquired at 11:30 local time, displays an inversion of the urban-rural thermal gradient: the compact urban core is, on average, cooler than the surrounding peri-urban agricultural matrix.

The average rural reference LST, calculated by applying spatial filtering to land cover classes and excluding thermally anomalous surfaces, is 51.44 °C, with peaks reaching 59.78 °C. The historic center and the most compact urban neighbourhoods show lower LSTs compared to the average rural LST, up to approximately -5.8 °C.

A morning SUCI, dominated by sensible heat flux, is therefore demonstrated for the area under study, functioning as a semi-arid area, although it is not classified as a semi-arid climate with traditional climate indices [32].

Beyond standard urban climate assessments, this finding holds implications for agricultural landscape management. The empirical evidence suggests that the desertification risk identified for this area [53] is driven more by localized soil overheating than by broad meteorological climate indices.

This data is crucial for agricultural land management because the organic matter contained in soil exposed directly to intense summer solar radiation (and consequently overheated, as demonstrated in the case study) is mineralized and leads to the depletion of soil fertility.

The spatial organization of the thermal regime, described by the map of thermal anomalies detected (ΔT), is divided into two main configurations:

– *Urban and natural cool spots ($\Delta T < 0$).* This behavior is attributable to urban morphology and material properties. Although the spatial average for the entire Lecce urban area indicates an open fabric (mean SVF of 0.96 and AR of 0.08 due to extensive green spaces and expanding peripheral zones [49]), the specific microclimate of the historic core follows a completely different dynamic. The Lecce historic fabric, comparable to the "compact midrise" Local Climate Zone, is characterized by narrow streets and locally high height-to-width (H/W) ratios. This specific micro-geometry creates mutual shading and lowers the local SVF, preventing daytime convective mixing. This factor, combined with the high thermal inertia and the local stone albedo, drives the daytime cooling effect.

– *Peri-urban and rural hotspots ($\Delta T > 0$).* Positive anomalies are concentrated mainly in the peri-urban and rural matrix, in areas characterized by bare soil, non-irrigated crops and sparse olive groves. In these contexts, numerous synergistic factors combine, all converging towards soil warming:

  - these soils generally exhibit a low albedo, increasing shortwave radiation absorption. Coupled with sparse vegetation cover, the exposed topsoil absorbs direct solar radiation, driving intense and rapid surface heating. Not even olive groves show a significant effect on this phenomenon in the Landsat thermal signal, which is evidently dominated by the bare soil temperature;
  - reduced soil moisture severely limits evapotranspiration and, therefore, prevents latent heat extraction.

The overall effect is a rapid accumulation of radiative energy across these exposed peri-urban and agricultural surfaces, which helps explain the elevated LST values observed in the Landsat acquisitions. Under late-morning summer conditions, these environments may therefore behave as dominant daytime heat sources relative to the compact urban core. At the very least, the results provide experimental evidence of a daytime SUCI effect, highlighting a substantial deviation from the classical SUHI paradigm traditionally associated with Mediterranean cities.

These findings suggest that urban thermal regimes in Mediterranean transitional environments cannot be interpreted exclusively through the conventional SUHI framework, but should instead be examined within a broader surface energy balance perspective that also incorporates processes related to land degradation, soil moisture depletion and semi-aridification of peri-urban agricultural landscapes.

From a territorial planning perspective, this evidence highlights the importance of considering urban and rural systems as strongly interconnected components of a single environmental and climatic framework, rather than as separate sectors analyzed independently. In the case of the Apulia region, this assumption has particularly relevant implications for the Regional Territorial Landscape Plan (PPTR) [54]. In particular, the present results:

1. provide empirical support for innovative territorial governance frameworks, such as the "*Patto Città-Campagna"* and the development of local ecological networks, reinforcing the need for integrated urban–rural planning strategies;
2. demonstrate how satellite-derived thermal analysis can offer an operational methodology for guiding climate-sensitive green infrastructure planning across multiple spatial scales, including urban, peri-urban and rural environments.

5 Conclusion

The empirical evidence presented in this study indicates that peri-urban agriculture plays a key role in the surface energy balance of the urban system. Although the present analysis focuses on the specific case of Lecce, the observed thermal dynamics may show potential transferability to other Mediterranean (Csa) urban environments characterized by compact settlements surrounded by semi-arid agricultural landscapes vulnerable to

land degradation processes. Under these conditions, sustainable soil management, the preservation of vegetative cover and the protection of wetlands and forested areas represent fundamental components for local thermoregulation. From a territorial planning perspective, these findings highlight the strategic importance of integrating peri-urban agricultural regeneration within broader climate adaptation policies. In particular, reducing bare soil exposure and restoring vegetative cover may contribute significantly to mitigating summer thermal stress and strengthening climate resilience in Mediterranean urban regions.

Acknowledgments. This study was funded by PRIN_EO4DES Earth Observation for Desertification, Italian University Ministry.

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

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Mapping the Photovoltaic Landscape of Puglia Using Open Energy Data

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Abstract. The urgent need to address climate change, reduce the environmental impact of oil extraction, and respond to rising energy costs is accelerating the transition toward sustainable energy systems. Italy, like many other European countries, offers favorable conditions for the development of renewable energy, and photovoltaic infrastructure is being increasingly promoted in response to these challenges. In this context, the growing installation of solar power plants plays a central role in the transition to sustainable energy systems. However, comprehensive planning strategies specifically aimed at defining optimal locations for photovoltaic installations and monitoring the sustainability of their spatial distribution are still limited. This study integrates solar power plant datasets provided by the Gestore Servizi Energetici and World Resources Institute with geographical information system tools to evaluate the spatial distribution and characteristics of solar power plants in the Puglia region (Southern Italy). Thus, after creating a dedicated geographical database in the QGIS environment, spatial data analyses were performed to assess the distribution of solar power plants at both provincial and regional levels. The analysis provides insights into the concentration of solar infrastructure and identifies areas with higher renewable energy development. The results reveal a high spatial variability in the distribution of photovoltaic installations in Puglia, reflecting differences in land availability, solar energy potential, and infrastructure availability. There are in total more than 110,307 solar power plants installed, with an overall mean value of 32.88 kW and 12 kW for low-tension and 850 kW for medium-high tension levels, with more than 98% of power plants being small-scale installations (<200 kW).

1 Introduction

The growing demand for sustainable energy sources has accelerated the global transition to renewable energy systems [1]. Among them, solar photovoltaic technology has now become one of the most widely used renewable energy solutions due to its ability to generate electricity without producing greenhouse gases and its adaptability to a wide range of spatial scales, from small rooftops to large-scale solar power plants [2–4]. Thus, their geographical distribution has expanded significantly over the past two decades, as governments around the world promote this kind of renewable energy to mitigate climate change and reduce dependence on fossil fuels [5, 6].

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 21–34, 2026.
https://doi.org/10.1007/978-3-032-30524-4_2

At the same time, this expansion is not without consequences. Large-scale photovoltaic installations often require substantial land areas, potentially altering existing land use and land cover (LULC) patterns [7]. In many cases, agricultural land or natural ecosystems are converted to energy production sites, raising important questions about sustainability and spatial planning [8]. Renewable energy infrastructure is therefore considered a key element in monitoring land conversion processes. Therefore, mapping and analyzing the spatial distribution of solar power plants can provide valuable information on LULC changes and their impact on the environment [9].

Recent developments in geospatial technologies have significantly improved the ability to monitor LULC at regional and global scales. Remote sensing techniques, including Geographic Information Systems (GIS), can help researchers and policymakers respond to LULC changes with greater precision in landscape models [10, 11]. Satellite missions such as Landsat and Sentinel provide continuous observations to support large-scale environmental monitoring and spatial planning [12, 13]. At the same time, the availability of geospatial energy datasets has improved considerably, allowing researchers and policymakers to better understand the distribution and capacity of renewable energy infrastructure [14, 15].

The Puglia region in southern Italy is a particular case study. Because of the high solar radiation and favorable climate, the region has experienced a massive expansion of photovoltaic installations on both domestic and commercial scales [16]. However, integrating renewable energy data from different sources remains challenging due to differences in structure, completeness, and accuracy [17, 18].

To address these issues, this study integrates and analyzes datasets on photovoltaic energy production using World Resources Institute (WRI) and Gestore Servizi Energetici (GSE) geospatial datasets. WRI is a massive geodatabase portal with both spatial and structured datasets containing information on all types of energy resources, including Wind, Biomass, Thermoelectric, and a few others. The method combines spatial processing and logical validation procedures to improve the accuracy and structural consistency of renewable energy datasets from two different sources. The main objectives of this study were: (i) creation and harmonization of a dataset for optical installations in the Puglia region; (ii) integration of external data on solar energy production from the national energy database; (iii) identify and correct inconsistencies in geographic information and features; (iv) develop an iterative approach based on GIS to maintain reliable spatial information databases for renewable energy sources.

The main contribution of the study is the creation of a harmonized, multi-source geographic database of photovoltaic installations in the Puglia region, which would be the most comprehensive open, database-based geographic database of photovoltaic infrastructure at the regional level in southern Italy. Unlike existing national registries that treat low-voltage or large-scale power plants separately, the proposed system systematically integrates both GSE table records and WRI geographic data at all capacity levels. The resulting geographic database, together with a GIS-based analytical workflow, provides a reproducible method for spatial monitoring of renewable energy, which can be extended to other regions and energy sources.

2 Datasets and Methodology

The overall workflow adopted in this study, reported in Fig. 1, was structured as a sequence of interconnected steps aimed at ensuring both data consistency and spatial reliability. The process began with the collection of photovoltaic datasets from GSE and WRI, which were first examined independently to identify differences in structure, level of detail, and completeness. This preliminary phase was essential to highlight inconsistencies that could affect subsequent analyses. Following data acquisition, a harmonization step was carried out. Attribute fields were standardized, units of measurement were aligned, and naming conventions were made consistent across the datasets. Particular attention was given to removing duplicate entries and resolving conflicting records, which are common when integrating data from heterogeneous sources.

The next stage involved spatial processing within the QGIS environment. All datasets were projected into a common coordinate reference system (EPSG:32633) to ensure geometric consistency. Spatial validation procedures were then applied, including the verification of plant locations against administrative boundaries and the correction of evident positional errors. Once the database was cleaned and aligned, the datasets were merged into a single geospatial framework. This unified database allowed for both descriptive and spatial analyses, including the classification of installations by capacity and the evaluation of their distribution at provincial and regional scales.

Finally, the workflow included a validation and quality control phase. Logical checks were performed to ensure coherence between attributes (e.g., capacity values and plant classification), while spatial consistency was re-evaluated to confirm the reliability of the final dataset. This iterative approach made it possible to refine the database progressively, improving its suitability for further analysis and interpretation.

Integrating this database with solar radiation models and grid infrastructure data will optimize future decisions on the deployment of photovoltaic plants. Ultimately, this approach will accelerate the regional energy transition in a spatially sustainable manner.

2.1 Study Area

This study was conducted in the Puglia region (Fig. 2), located in southern Italy, on the Adriatic and Ionian coasts. Covering an area of approximately 19,500 km^2, the region boasts a Mediterranean climate and abundant sunshine, making it one of the most suitable regions for the development of solar energy in Europe. The Puglia region has seen a rapid expansion of renewable energy infrastructure, especially solar power plants, in the last decade. This rapid development has led to new types of LULC, such as the conversion of agricultural land to solar power plants or the installation of rooftop solar systems in urban areas on a domestic and commercial scale. Since solar power plants are not evenly distributed across municipalities and regions, an integrated spatial framework is needed to process large-scale datasets and provide a consistent spatial view across administrative areas.

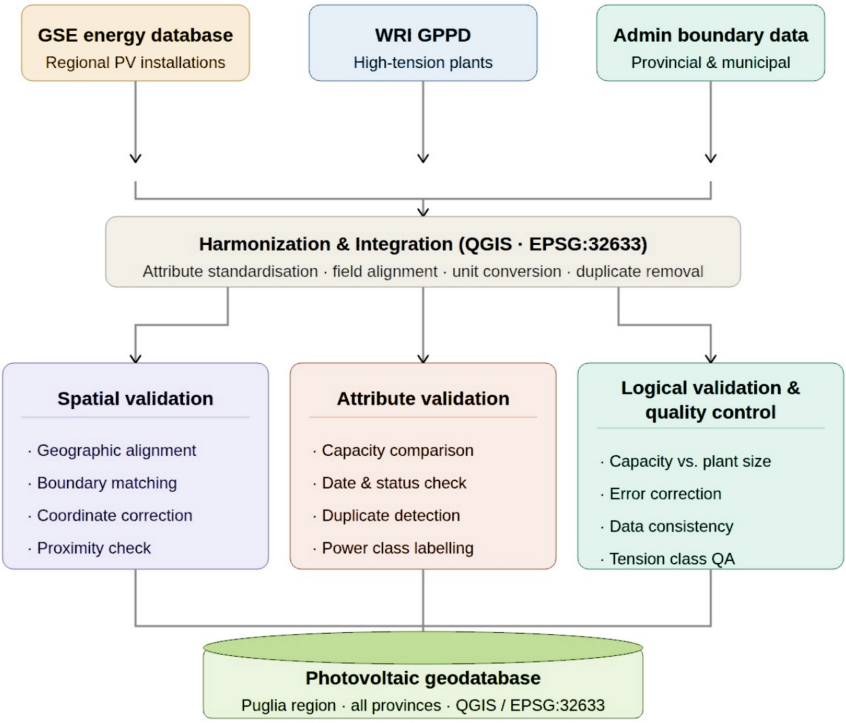

Fig. 1. Workflow of the study

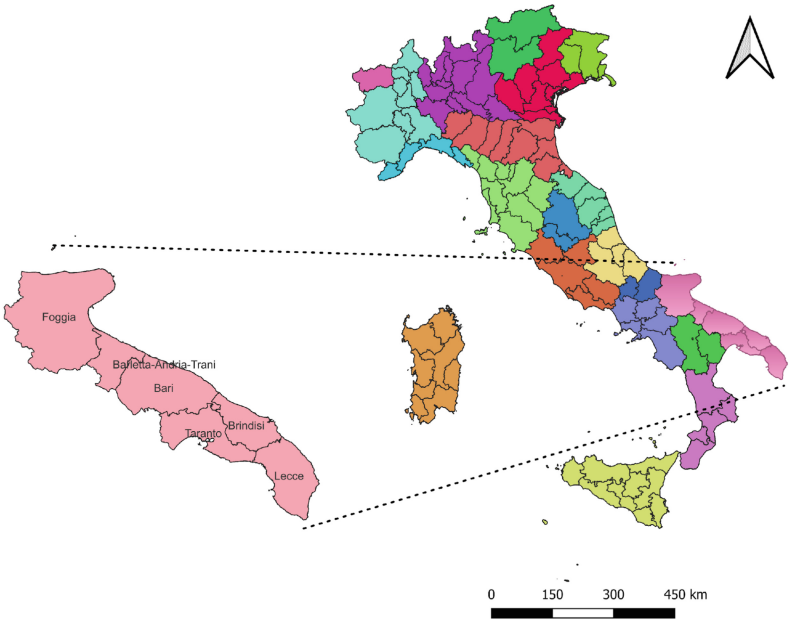

Fig. 2. Study area of the Puglia region, Italy

2.2 Data Sources

Three data sources are used for this study to integrate and harmonize the required data, which is a necessary step to perform spatial, logical, and attribute validation and quality assurance to create a photovoltaic geodatabase: i) GSE; ii) WRI; and iv) administrative boundary layer. They are described in the subsequent paragraphs.

2.2.1 GSE Energy Database

The main dataset used in this study includes tabular and structured data on solar power plants located in the administrative region of Puglia. This dataset contains spatial and descriptive information on solar power plants in the region. The website provides easy access to a GIS web database called Atlaimpianti, which is a key resource for implementing renewable energy projects in Italy. The consultation documents show renewable energy projects, from solar to wind and biomass. The platform provides analysts with tools to categorize real estate needs based on geographic boundaries (region, state, or city), energy sources, and business financing options. In addition to providing metrics such as workload and status of power plants through an interactive map, the portal facilitates the export of large amounts of data, allowing users to extract structured and raw data into spreadsheets for easier integration into analysis.

2.2.2 WRI Infrastructure Dataset

More information on solar power plants can be found on the WRI infrastructure portal (Fig. 3).

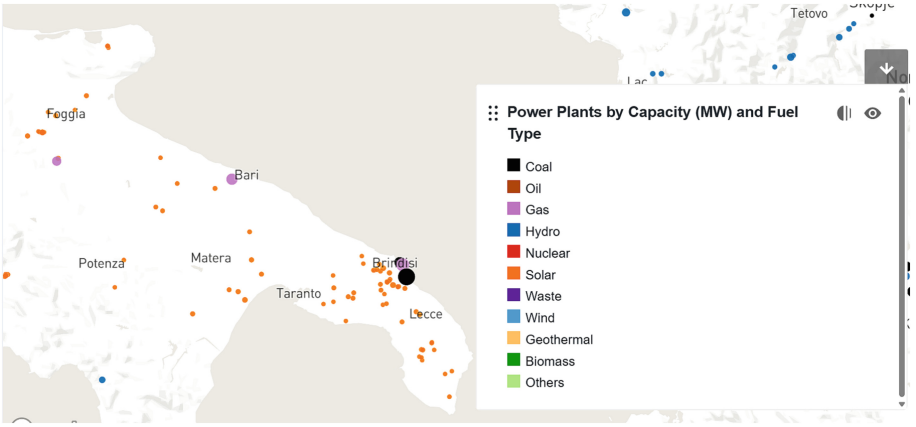

Fig. 3. WRI Global Power Plant database (GPPD) portal showing large-scale photovoltaic installations in the Puglia Region

WRI offers country-level datasets on power plants and transmission infrastructure. However, its coverage of photovoltaic systems is limited, as it mainly includes high-tension installations, while low- and medium-tension systems are not represented. Coordinates for these facilities can be retrieved through the WRI Global Power Plant Database (GPPD) portal, where geographic information is accessible via interactive visualization.

The WRI database includes several related attributes per plant, including installation capacity in megawatts, power plant type, commissioning year, and operating company. Although this makes it a valuable resource for analyzing large-scale energy infrastructure, some limitations need to be considered. In particular, while the integration of the WRI GPPD helps compensate for missing coordinate information in national datasets, it introduces constraints for detailed spatial analysis. The database represents installations as point geometries rather than spatial polygons, which limits the accurate assessment of LULC impacts.

In practice, in the Italian context, this database only includes utility-scale installations, effectively excluding micro and small decentralized plants below approximately 1 MW, which constitute approximately 90% of the physical infrastructure in the region. Therefore, local WRI data should be accurately linked to aggregated national data (e.g., GSE) to avoid overall underestimation of infrastructure.

2.2.3 Administrative Boundary Data

Administrative boundary data at both municipal and provincial levels were used to support the spatial validation of photovoltaic installations. These layers made it possible to verify the positional accuracy of power plant locations and to correctly assign each installation to its corresponding administrative unit. In addition, boundary data were used to identify and correct potential mismatches between recorded coordinates and actual territorial divisions. This step was particularly relevant for high-capacity installations derived from the Terna dataset, where occasional spatial inaccuracies have been

observed. By cross-checking plant locations against administrative boundaries, it was possible to improve the overall reliability of the geospatial dataset.

2.3 GIS Environment and Data Processing

All spatial processing and database management tasks are performed using the open-source software QGIS. The overall GIS workflow consists of a series of sequential steps, each designed to improve the consistency and reliability of the integrated dataset. The process began with preliminary data collection and initial processing, followed by database alignment and reconstruction through the integration of GSE and WRI datasets. Since the WRI database does not include micro-scale installations, particular attention was given to ensuring that smaller systems from national sources were properly incorporated. Subsequent steps focused on spatial validation and coordinate correction. These procedures were necessary to address positional inaccuracies and to ensure that all installations were correctly located within the study area. Finally, logical validation and quality control checks were applied to verify the consistency between spatial features and their associated attributes. All datasets were projected into the EPSG:32633 coordinate reference system (UTM Zone 33N) in order to maintain a consistent spatial framework across the entire analysis.

2.4 Database Alignment and Attribute Standardization

Datasets derived from different sources often present structure variations, naming conventions, and data formats. To address these issues, a series of attribute standardization procedures was implemented to harmonize the integrated database. This process included the alignment of field names across attribute tables, the normalization of text fields to avoid inconsistencies related to case sensitivity or formatting, and the conversion of numerical values, particularly installation capacity, into consistent units. In addition, duplicate and redundant records were identified and removed.

Once standardized, the dataset was further refined through spatial and logical verification. This included cross-checking the relationship between installation capacity and site characteristics, as well as identifying missing or inconsistent entries.

These steps resulted in a coherent and structured geodatabase, suitable for spatial analysis and visualization (Fig. 4). Overall, the applied procedures significantly improved data reliability and ensured that the photovoltaic system was represented as accurately as possible.

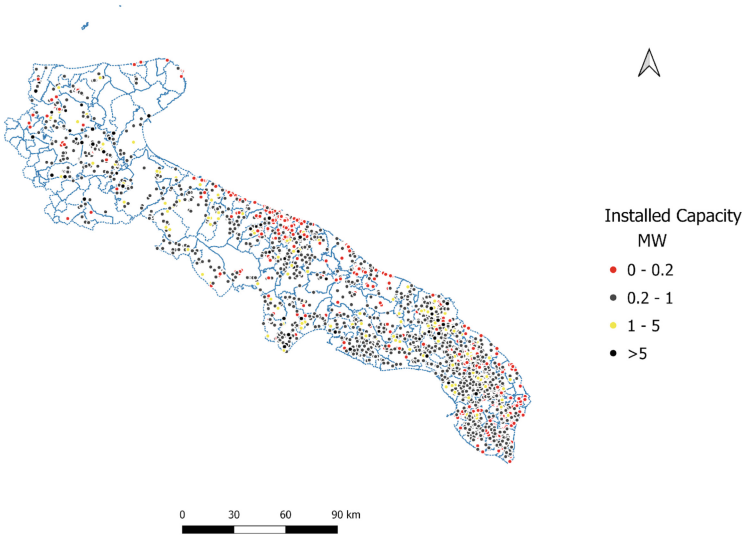

Fig. 4. Spatial Map with PV installation in the Puglia Region

3 Results and Discussion

3.1 Summary of Photovoltaic Infrastructure Data

The integrated geospatial database includes a total of 110,307 photovoltaic installations across the Puglia region, obtained through the combined use of GSE and WRI datasets. After processing and validation within the QGIS environment, the dataset provides a detailed picture of the regional photovoltaic landscape, highlighting its rapid and widespread expansion. The total installed capacity reaches approximately 3,626.96 MW, confirming the central role of solar energy in the regional energy system. On average, individual installations have a capacity of about 0.032 MW (32.8 kW), although this value masks a high degree of variability.

Indeed, installation sizes range from very small systems, close to zero capacity, to large-scale plants exceeding 42.7 MW. High-tension (AAT-AT) systems show an average capacity of around 10.75 MW, further emphasizing the coexistence of very different scales of production (Table 1 and Table 2). Taken together, these figures suggest a clearly heterogeneous structure. The photovoltaic system in Puglia does not rely on a single model but rather on a combination of decentralized rooftop installations and larger, centralized solar plants (Tables 1 and 2). This "hybrid configuration" represents a defining characteristic of the regional energy system.

Table 1. Low and Medium Tension PV Statistics

Metric	Value
Total Number of Installations	110,307

(*continued*)

Table 1. (*continued*)

Metric	Value
Total Installed Capacity	3,207.7 MW
Overall Mean Capacity	0.029 MW
Mean Capacity (Low Tension < 0.2 MW)	~0.012 MW
Mean Capacity (Medium Tension 0.2–5 MW)	~0.850 MW
Minimum Capacity	0.001 MW (1 kW)

Table 2. High Tension (AAT-AT) PV Statistics

Metric	Value
Number of Plants	46
Total Capacity	515.2 MW
Average Capacity	11.20 MW
Median Capacity	8 MW
Minimum Capacity	5.0 MW
Maximum Capacity	42.7 MW

3.2 Distribution of Photovoltaic and Electrical Installations

To better understand the nature of photovoltaic development, the installations have been divided into four power categories based on installed capacity. According to the dataset provided by GSE, small systems (less than 0.2 MW) are the most numerous. The distribution of installations across different power capacities is given in Table 3.

Table 3. Classification of PV sizes in the Puglia Region based on GSE Power Classes (Source: GSE Open Data, 2024).

Classification Size	Power Threshold	GSE Power Classes	n° Plants	Percentage of Total (%)
Micro (Low Tension)	<0.2 MW	Classes A to I	108,100	98.0%
Small (Medium Tension)	0.2 MW–1.0 MW	Classes L to M	1,655	1.5%
Medium (Medium Tension)	1.0 MW–5.0 MW	Class N	442	0.4%
Large (High Tension)	> 5.0 MW	Class O	110	0.1%
Total			110,307	100%

Micro-scale systems (<0.2 MW) overwhelmingly dominate in terms of number, accounting for approximately 108,100 installations, or 98% of the total. These systems are typically associated with rooftop installations in residential and small commercial settings. Despite their large number, their contribution to total installed capacity remains

relatively limited. The intermediate categories, small (0.2–1 MW) and medium (1–5 MW) installations, together represent only about 2% of all systems. However, their role in energy production is much more significant. With a combined capacity exceeding 1,900 MW, these installations account for more than half of the total regional output. Their average size, around 0.85 MW, reflects their importance as a backbone of the regional electricity system. Large-scale plants (>5 MW) are comparatively rare, with only around 110 installations recorded (0.1% of the total). Even so, their contribution is far from negligible. These facilities provide more than 11% of the total installed capacity, with some individual plants reaching up to 42.7 MW, such as the facility located in Cellino San Marco (Brindisi province). These larger systems are generally ground-mounted and tend to be located in agricultural or peri-urban areas, where land availability and infrastructure conditions are more favorable.

Overall, this distribution shows a clear trend, with a large number of small and medium-sized systems and few large-scale solar power plants constituting the renewable energy landscape in the region. This hybrid architecture, combining distributed rooftop generation with centralized solar stations, is a defining structural characteristic of the Puglia PV landscape and has important implications for grid management, land-use planning, and future capacity expansion strategies.

3.3 Spatial Distribution of Photovoltaic Power

The spatial analysis of photovoltaic power plants shows a varied distribution of solar power installations in the Puglia region. It reveals that all six provinces have substantial heterogeneity in both the number of installations and installed capacity, reflecting the combined influence of solar irradiance, available land, population density, and local policy implementation. The provincial distribution of solar energy is given in Table 4, with full statistics confirmed against GSE data.

The province of Lecce is the most powerful, with 33436 solar power systems and a total installed capacity of 883 MW, representing 24.3% of regional installations. This dominance is due to the favorable climate, abundant solar radiation, and the availability of land suitable for the development of the Salento peninsula, as well as a historically supportive environment for the deployment of distributed renewable energy systems. The province of Bari, with over 34868 systems and a total installed capacity of 752.5 MW, indicates a large number of distributed and large-scale solar power systems, with 20.7% of the total. Despite having the largest amount of solar systems, it reflects the province's dense urban and peri-urban fabric and widespread adoption of small rooftop systems; its per-unit average capacity is comparatively lower, indicative of a predominantly micro-scale deployment pattern.

At the same time, Foggia contributed 737 MW, indicating a moderate but strong development of solar energy, with 20.3% of the regional total having 10495 installations. Despite having fewer installations than Lecce or Bari, Foggia's high average plant size reflects a concentration of large-scale utility systems in the Capitanata plain, where land availability and grid connectivity favor utility-scale development. When high-tension (AT/AAT) installations from the WRI dataset are incorporated, Foggia contributes 98.3 MW from six utility-scale plants alone, including the 40.0 MW Vega Apulia facility. The province of Brindisi comes next with the production of 562.7 MW of

solar energy, contributing 15.5% of the regional total with 11153 solar installations. This reflects the concentration of large commercial and utility-scale plants in this province. In terms of high-tension infrastructure specifically, Brindisi is the regional leader with 19 AT/AAT plants, aggregating 192.9 MW, including the region's largest installation, which is the Cellino San Marco facility producing 42.7 MW of energy.

Next is the Province of Taranto, which constitutes 14,563 installations with 473.8 MW of solar production capacity (13.1% of the regional total) and seven utility-scale solar plants contributing 91.4 MW at the AT/AAT level. The last in terms of solar energy production is the Province of Barletta-Andria-Trani (BAT), which, as the most recently established provincial authority, it has the smallest PV footprint with 5,792 installations and 217.9 MW, accounting for 6.0% of regional capacity.

Regarding high-tension (AT/AAT level) infrastructure specifically, the WRI dataset identifies 46 utility-scale installations ($\geq$ 5 MW) in the Puglia region with a combined installed capacity of 515.2 MW, a mean of 11.20 MW per plant, and a median of 8.0 MW. These plants are consistent with the GSE-derived HT category total of 419.2 MW, with the difference attributable to boundary classification and dataset vintage. Despite representing only 0.04% of the total site count, high-tension installations contribute approximately 11.6–14.2% of the total regional installed capacity, underscoring their strategic importance in the regional energy mix. The provincial distribution of these high-tension facilities is presented in Tables 5 and 6.

Table 4. Distribution of Solar PV installations and related energy production capacity per province in the Puglia Region (Source: GSE Open Data, 2024).

Province	Total n° of Plants	Total Capacity (MW)
Bari	34,868	752.5
Lecce	33,436	883.0
Taranto	14,563	473.8
Brindisi	11,153	562.7
Foggia	10,495	737.0
Barletta-Andria-Trani	5,792	217.9
Total Puglia Region	110,307	3,626.9

In summary, the province of Lecce remains the region with the highest number of installations and total installed capacity, reflecting the dominance of distributed PV systems. However, in terms of high-transmission power, the provinces of Brindisi and Foggia emerge as the leading energy hubs, contributing mostly from AAT-AT level installations alone. Bari presents the largest raw installation count driven by distributed micro-scale systems, whereas BAT and Taranto occupy intermediate positions. This spatial differentiation between provinces reflects a fundamental duality in the regional PV landscape: a distributed model of small-scale adoption in densely populated coastal and suburban areas, contrasted with a centralized model in the more sparsely populated agricultural interior.

Table 5. Descriptive statistics of high-tension (AT/AAT) PV installations in Puglia (Source: WRI Global Power Plant Database).

Metric	Value
Number of Plants	46
Total Installed Capacity	515.2 MW
Mean Capacity	11.20 MW
Median Capacity	8.0 MW
Minimum Capacity	5.0 MW
Maximum Capacity	42.7 MW (Cellino San Marco, Brindisi)

Table 6. Provincial distribution of high-tension (AT/AAT) PV installations in Puglia (Source: WRI Global Power Plant Database).

Province	No. of Plants	Total Capacity (MW)	Grid Connection	Largest Plant (MW)
Brindisi	19	192.9	AT/AAT	42.7 (Cellino San Marco)
Bari	11	105.0	AT/AAT	24.0 (Monte di Eboli)
Taranto	7	91.4	AT/AAT	29.3 (Giga)
Foggia	6	98.3	AT/AAT	40.0 (Vega Apulia)
Lecce	3	27.6	AT/AAT	11.0 (Lecce A)
BAT	0	0.0	—	—
Total	46	515.2		

Land use patterns show that the development of solar energy is strongly influenced by land availability, infrastructure availability, and regional energy regulations. The largest solar power installations are located in agricultural and rural areas, where there is sufficient land to support this development. It is acknowledged that this study does not include an independent validation step based on fieldwork or external reference imagery. The internal consistency checks used, including cross-validation between GSE tabular data and WRI spatial records, logical attribute verification, and administrative boundary refinement, serve as a form of indirect validation but cannot fully replace external reference data. This limitation is inherent to the nature of the open datasets used and is highlighted as a direction for future work. Future studies should include high-resolution satellite imagery (e.g., Sentinel-2 or VHR data) to verify feature locations and assess the physical footprint of recorded features, especially for large features, where spatial accuracy is important for assessing land-use impacts.

4 Conclusion

The Puglia region has a highly advanced photovoltaic system, with 110307 installations and an installed capacity of over 3626 MW. This confirms its leading position in solar energy production in Italy. Its distribution varies; Lecce and Bari have the highest concentration and capacity, while areas like Foggia and Brindisi have a much lower distribution but produce a significant amount because of their high-tension, large-scale plants. This reflects regional differences in infrastructure development with variability in each province. The high concentration of small installations, combined with a low number of highly efficient solar power plants, reflects a hybrid energy model that combines decentralized and centralized production. However, the increasing presence of large photovoltaic plants in agricultural areas raises new conflicts regarding land use and the need for sustainable solar power planning. Overall, the development of photovoltaics in Puglia is an essential driver of the regional energy transition and a key factor influencing land use dynamics. Future strategies should help integrate sustainable solar energy systems into the built environment, minimizing the use of fertile land and ensuring a balance between the development of renewable energy sources and the protection of natural resources.

The GIS-based methodology applied in this study by integrating spatial validation, attribute standardization, coordinate correction, and logical quality control, proved effective in resolving the inconsistencies inherent in merging national administrative data (GSE) with a global infrastructure dataset (WRI). The resulting geodatabase provides a reliable and analytically tractable representation of the regional PV landscape. The increasing penetration of utility-scale solar plants into agricultural and perirural areas raises important challenges regarding land-use competition, soil sealing, and coexistence with agrivoltaics. Future research should extend this framework to integrate temporal monitoring of land-cover change using remote sensing data (e.g., Sentinel-2), enabling quantitative assessment of the landscape transformation associated with PV expansion. The integration of this database with solar radiance models and data on grid infrastructure could further help optimize future decisions on the deployment of photovoltaic plants and accelerate the regional energy transition in a spatially sustainable manner.

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Coastal Hazards Along the Ionian Arc of Apulia (Southern Italy)

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Abstract. This study investigates coastal hazards along the Ionian arc coast of the Apulia region (Southern Italy). As the study area was previously classified as a medium-risk sector in a regional-scale assessment, a detailed hazard analysis was conducted to identify the main driving factors and the most affected areas. The shoreline evolution between 1992 and 2023 reveals an overall stable coastal configuration, characterized by alternating phases of progradation and retreat and a slight net shoreline advance. Despite this general stability, the coastal system remains vulnerable to extreme wave storms, sea-level rise, and both riverine and pluvial flooding. In recent years, sea level has increased, with the highest annual mean value recorded in 2023. Estimated wave run-up values indicate a potential risk of temporary flooding on low-lying beaches and dune areas, while riverine and pluvial flooding events have also been documented in recent decades. Overall, coastal risk in the study area is primarily related to the interaction between extreme water levels, low coastal elevations, and the condition of natural and anthropogenic coastal features, highlighting the need to integrate regional-scale assessments with detailed local analyses. Due to the importance of flooding, these processes will be further studied using 2-D numerical models to simulate hydrodynamic and morphodynamic behavior.

Keywords: Coastal Risk · Shoreline evolution · Sea storms · Sea Level · Riverine flood · Pluvial flood

1 Introduction

The increasing pressure of the effects of climate change on coastal areas, combined with the growing exploitation and development of these zones [1], makes it necessary to constantly update the investigations of littoral areas, especially those with the highest risk. In the most vulnerable areas, large-scale assessments

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 35–47, 2026.
https://doi.org/10.1007/978-3-032-30524-4_3

may be insufficient to accurately identify the most at-risk coastal stretches and to determine, site by site, the predominant hazard factors [2].

Coastal areas along the Mediterranean Sea are particularly vulnerable to ongoing environmental changes, and numerous studies have focused on the various processes and features that characterize these coasts [3,4]. Regional-scale coastal risk assessment along Apulian coastal areas conducted using the Modified EUrosion Model (Mod.E.M.) identified several hotspot areas [5]. Following this approach, the coastline of the Municipality of Castellaneta was classified as presenting a medium level of risk, in contrast to adjacent coastal stretches, along the Ionian sector of the region, which were categorized as low risk. The methodology adopted was based on indicators calculated on the municipal scale, designed to effectively represent the vulnerability and exposure of the coastal zone.

In light of the model results, the Castellaneta coast was subsequently subjected to further in-depth analyses to thoroughly assess both the critical situations that have already occurred and those that may potentially develop in the future. In this study, key factors influencing the assigned risk classification—namely sea level, wave run-up on the emerged beach, shoreline evolution, and flooding events—were analyzed in detail to identify the most vulnerable coastal sectors and the main sources of criticality.

2 Materials and Methods

2.1 Case Study

The coastal area of Castellaneta Marina is located along the Ionian side of the Apulian coast (Gulf of Taranto) and falls within the littoral cell which begins at the multi-sector pier of the Port of Taranto and ends in Basilicata (Sub-Unit 7.3) [5]. This littoral cell is characterized by an extensive sandy beach with a nearly continuous dune system behind it, except near residential settlements. The coastal strip of Castellaneta is characterized by a coastline that extends continuously for about 9 km from the mouth of the Lato River to the boundary with the Municipality of Ginosa (Riva dei Tessali settlement) (Fig. 1). The sandy beach is relatively wide with a gently slope, and is bordered by partially vegetated dunes. Several orders of dune ridges parallel to the coast are present along the entire shoreline, reaching elevations of up to 15 m above sea level. The mouth of the Lato River, which marks the boundary between the Municipality of Palagiano and Castellaneta, remains in a natural state. From the mouth of the Lato River to the beginning of the Castellaneta Marina settlement, the dunes develop almost continuously, interrupted only by a few beach access paths. East of the Castellaneta settlement and westward to the boundary with the Municipality of Ginosa, the dune ridge appears heavily degraded. The total area of the beach within the Municipality of Castellaneta, measured as the area between the 2017 shoreline and anthropogenic structures or the foot of the dune ridge where present, was estimated to be approximately 0.61 km^2 (referred to 2017). The sediments on the emerged beach are classified as medium sand (diameter

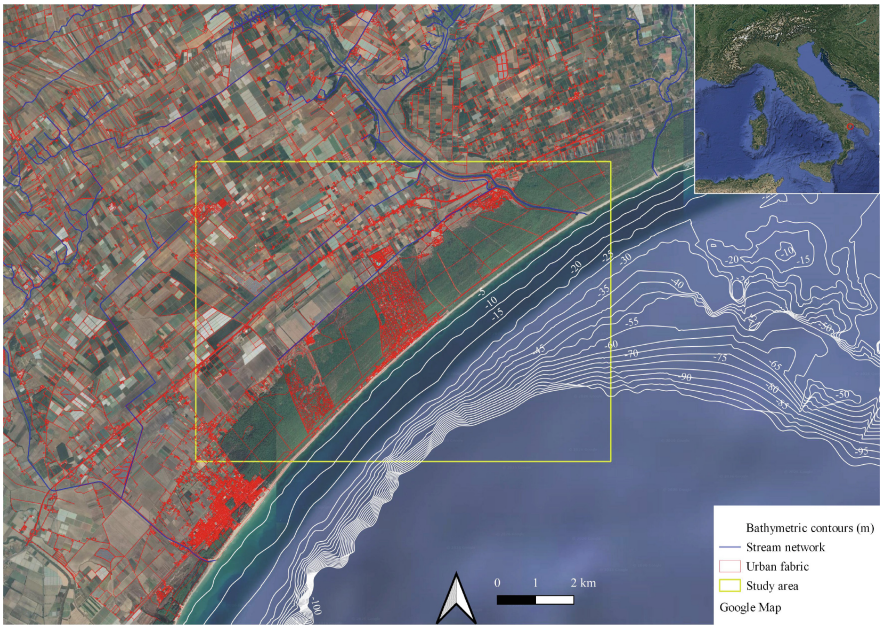

Fig. 1. Study area with stream network (blue lines), bathymetric contours (white lines) and urban fabric (red polygons). (Color figure online)

between 0.25 and 0.5 mm) according to the Udden–Wentworth scale, and quartz is the main mineralogical component (70% of the total).

Rainfall in Castellaneta Marina is typically moderate and seasonal, with most precipitation occurring in autumn and winter and relatively dry summers, consistent with the Mediterranean climate [6]. The hydraulic framework of the area is particularly complex due to the presence of several watercourses, as well as extensive land reclamation and drainage works. In the late 19th century, a railway line was constructed along the coastal belt and, since the 1950 s, numerous concentrated tourist settlements have been developed. These human interventions, together with the construction of numerous reservoirs along the watercourses that flow into the Ionian Sea, have led to a sediment deficit since the 1960s, resulting in widespread erosion phenomena along the Basilicata Ionian coast [7].

Despite the anthropogenic interventions described above, as shown by the diachronic analysis of shoreline positions recorded between 1992 and 2008, the Apulian coastline from Taranto to Ginosa could be considered substantially stable, with some stretches showing a slight progradation trend.

Much of the Castellaneta Marina area is subject to geomorphological constraints, classified as geomorphological hazard areas (low risk-PG1) under the Hydrogeological Plan (PAI) [8], supported by the presence of dune ridges. Moreover, some areas along the Lato River and at its mouth are affected by river

flooding phenomena and fall within areas classified under the PAI as high and medium hydraulic hazard zones.

According to the CNAT – Nature Charter, the municipal coastal area hosts several habitats classified under the European CORINE Biotopes system, ranging from sparsely vegetated sandy shores to more structured dune systems, including native Aleppo pine forests on fossil dunes, many of which have been partially degraded due to human development [9].

Due to the combined occurrence of coastal erosion processes, hydraulic hazard, low elevations above sea level (which contribute to site vulnerability), and the presence of natural areas and residential settlements (constituting the exposure), the Mod.E.M. method classifies the resulting risk level as medium [5]. Specifically, to analyze in detail the hazard indicators affecting the study area, the components attributable to meteo-marine forcing, riverine and pluvial flooding, as well as the evolutionary coastal processes and their temporal variations, have been investigated here.

2.2 Data Sources and Methods

The predisposition of the coast to erosion and/or flood in the Mod.E.M.approach was based on the morphological, geological, hydraulic, and sediment characteristics of the study area, as well as the oscillation of sea level and wave energy approaching the coast [5]. In order to achieve a higher level of characterization, including spatial resolution, these elements were examined in detail by analyzing the evolutionary processes, sea-level fluctuations, wave run-up on the emerged beach, and hydraulic risk phenomena.

To reconstruct the evolution of the sandy shoreline in the examined area, the shoreline positions extracted from aerial and satellite imagery taken at different times were analyzed (1992, 2005, 2019, 2023). The shorelines were digitized and superimposed for comparison. Shoreline evolution was analyzed using DSAS (Digital Shoreline Analysis System), an ArcGIS extension developed by the United States Geological Survey (USGS) [10]. DSAS is based on the tracing of transects, with user-defined length and spacing, perpendicular to a baseline. In this case, 90 transects spaced approximately 10 m apart were drawn from north to south. For each transect, the NSM (Net Shoreline Movement) parameter was calculated, representing the distance between the oldest and most recent shoreline, and the EPR (End Point Rate), representing the annual rate of advance or retreat. The use of EPR values allows for comparison of evolutionary processes without being influenced by different observation period lengths. A high-resolution DTM acquired in 2017 allowed the estimation of the beach slope.

Statistical characterization of meteomarine forcings involved analysis of wave and sea-level events off the investigated area.

Extreme storm event analysis was performed using the ERA5 wave dataset at the grid point located at 40.0°N, 17.5°E, produced by the Copernicus Climate Change Service (C3S) of the European Centre for Medium-Range Weather Forecasts (ECMWF). The ERA5 dataset provides, among the more than 200 overall variables, hourly time series of ocean waves on a 0.5° grid [11].

The wave events were then subjected to an analysis of extremes, after employing the POT (Peaks Over Treshold) method in order to consider only the maximum value of significant wave height (peak value) occurring within a single storm event that exceeds the value of a predetermined threshold [12]. The extreme events determined were described by means of the Weibull probability distribution function. In particular, storm events have been analysed with the aim of evaluating their extreme values associated with return periods between 10 and 100 years.

The study of sea-level oscillations in the study area was carried out using data acquired from the Taranto tide gauge station (National Tide Gauge Network managed by ISPRA – Italian Institute for Environmental Protection and Research) [13]. The observed sea level data consist of the sum of contributions from the local mean sea level, the astronomical tide, and the meteorological tide. The annual mean sea level was calculated from the observed data using the Doodson filter [14]. Correcting the observed level with respect to the mean sea level of the reference year makes it possible to remove the influence of the local mean sea level— which varies depending on the reference site—thus allowing a comparison among the results obtained at different stations and, moreover, disregarding the interannual variability of the mean annual sea level.

The probability distribution of extreme events for both the observed level and the corrected level was estimated using a Generalized Pareto Distribution (GPD) applied to two truncated series consisting of the five highest values recorded each year, extracted from the two historical time series [15].

The coastal inundation hazard was assessed using an estimate run-up analysis based on the simplified method proposed by Stockdon [16]:

$$R_{u2\%} = 1.1(0.35\beta_f(H_0L_0)^{0.5} + [H_0L_0(0.563\beta_f^2 + 0.004)]^{0.5}/2) \quad (1)$$

where $R_{u2\%}$ is the run-up level exceeded by two percent of the incoming waves; H_0 is the wave height in deep water; L_0 is the wave length in deep water and β_f is the foreshore slope.

The Stockdon equation estimates wave run-up, defined as the maximum vertical extent of wave uprush on a beach or structure above the Still Water Level (SWL), including also wave setup and requires offshore wave characteristics, so use of this formula is very convenient for cases of application to large areas and where bathymetric data are not available. The probability distribution of extreme events for wave height was estimated using a Weibull Distribution applied to values exceeding a threshold value, extracted from the ERA5 daraset [12]. For each TR return period, run-up values were calculated, allowing the identification of 4 hazard classes (P1 to P4, with increasing hazard level), based on a quartile division of the identified individual samples. The sum of observed sea level and wave run up provides the total storm surge.

Moreover, a targeted search with flood-related keywords has been carried out in local online newspapers following a consolidated approach [17], leading to the detection of other flood events related to extreme rainfall events that caused both river and pluvial flood events [18,19].

3 Results

3.1 Shoreline Evolution Analysis

The diachronic analysis of shoreline positions from 1992 to 2023 shows that the examined coastal stretch is characterized by a variable evolutionary trend depending on the analyzed period (Fig. 2).

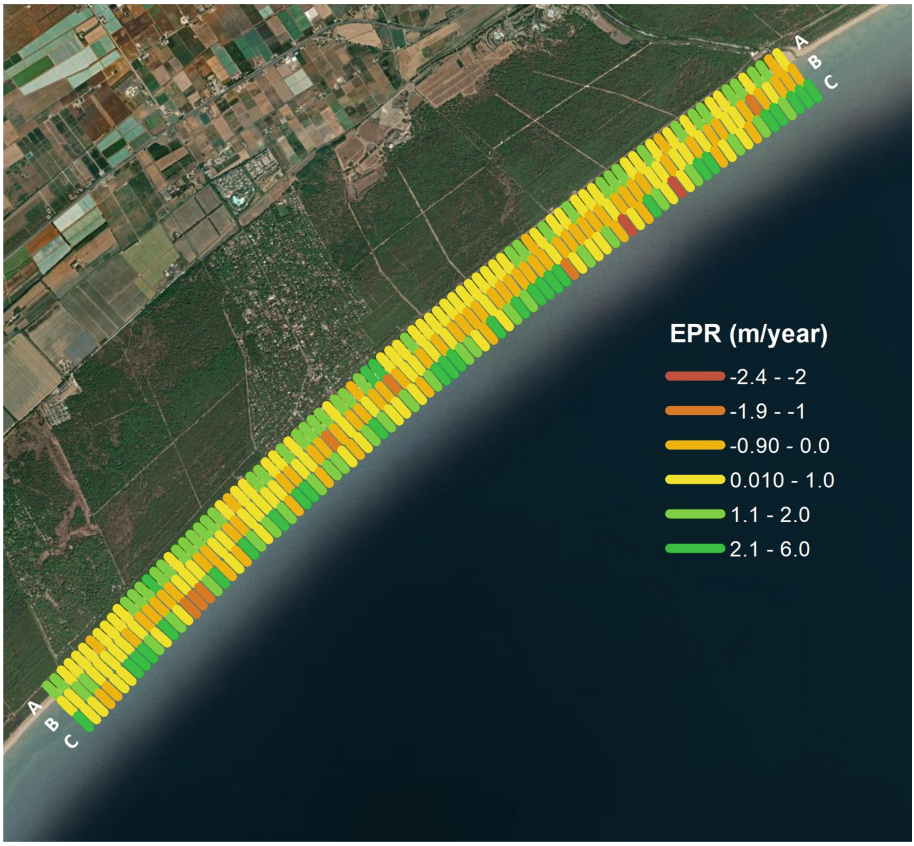

Fig. 2. End Point Rate (EPR) in m/year calculated along 90 transects for three time intervals: A) 1992–2005, B) 2005–2019, and C) 2019–2023.

Between 1992 and 2005, a general positive trend was observed along the entire municipal coastline. Later, in the period 2005–2019, a severe retreat affected approximately 2.8 km of coastline between the mouth of the Lato River and the settlement of Castellaneta Marina, while progradation phenomena were observed along 1.3 km of shoreline, mainly west of the Castellaneta Marina settlement and Riva dei Tessali. The remaining portion of the coast (approximately 50% of the total) remained substantially stable. For the period 2019–2023, based on

satellite imagery retrieved from Google Earth (acquired on 17/09/2023), the EPR analysis shows significant shoreline dynamism, with extensive stretches advancing at rates exceeding 2 m/year.

Overall, despite the alternating phases of retreat and advancement, the analyzed coastal stretch remained largely stable throughout the 1992–2023 period, showing a slight net progradation.

It should be emphasized that the shoreline evolution analyses are based on aerial imagery that captures specific moments in time. Since continuous shoreline monitoring data are not available for the examined stretch, it cannot be excluded that greater advances or retreats occurred during the 1992–2023 period than those reported herein.

3.2 Sea Level Variations

After 2007, a sudden increase in mean sea level was observed in the Mediterranean Sea [20,21], and tide gauges along the Adriatic and Ionian coasts recorded a similar increase, resulting in numerous coastal flooding events. Due to these events, with the aim of checking the current mean levels and extreme events, sea level time series acquired by the nearest tide gauge.

Figure 3 shows the sea level observations collected by the Taranto tide gauge during the period 1999–2024. The variation range is approximately 70 cm: levels vary on average between +0.2 m and −0.50 m. With reference to the hourly dataset, the maximum value of +0.51 m was recorded on 13/11/2019 at 14:00, while the minimum value of −0.71 m was recorded on 10-02-2005 at 21:20.

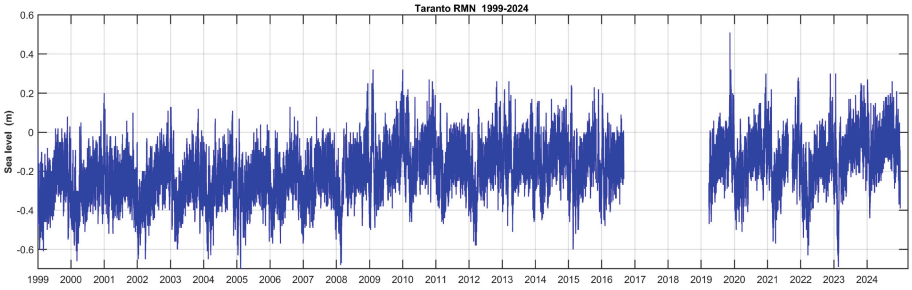

Fig. 3. Sea level recorded by Taranto tide gauge in the period 1999–2024 (hourly dataset).

A strong seasonal variation in mean sea level can be observed, with a marked decrease during the first months of the year. The analysis of annual mean levels at the Taranto station shows a general increase starting from 2008, with differences between 2007 and 2009 on the order of ten centimeters. In 2011, levels decreased to values close to those prior to 2009, followed by a new increase in 2012. It is also observed that in 2023 the highest annual mean sea-level value

was recorded (−0.072 m), with a further increase of approximately 7 cm compared to the previous year. The hourly sea level data was analyzed with the aim of evaluating their extreme values associated with RT between 5 and 100 years. With reference to the results reported in Table 1, it can be observed that the estimated sea levels vary between 0.22 m (5-year return period) and 0.50 m (one-hundred-year return period) through the 50-year value of 0.45 m.

Table 1. Extreme analysis of hourly sea level (observed and corrected with reference to the mean annual level) - GPD distribution.

	RT (years)	Sea level observed (m)	Sea level corrected (m)
	100	0.50	0.78
Years of observation: 22	50	0.45	0.74
Observed max: 0.51 m	10	0.30	0.60
	5	0.22	0.49

3.3 Run-Up Estimation

The wave events were analyzed with the aim of evaluating their extreme values associated with RT between 5 and 100 years. With reference to the results reported in Table 2, it can be observed that the significant wave heights of the sea states coming from the sector 120°- 210° N vary between 4.9 m (10-year return period) and 5.96 m (100-year return period) through the 50-year value of 5.7 m.

Table 2. Extreme analysis of offshore wave heights (sector 120°-210°N) (Weibull distribution).

Sector 120°-210°N	RT (years)	$H_s(m)$
	100	5.96
Threshold: 2. 5 m	50	5.67
Years of observation: 75	10	4.95
Observed max: 5.1 m	5	4.6

Run-up estimation was made using the Stockdon's formula with reference to the extreme values estimated for the offshore wave heights, with associated return periods. For each RT, run-up values were calculated, which allowed the identification of 4 run-up classes (P1 to P4, with increasing level), based on a quartile division of the individual identified samples.

The run-up analysis indicates that the highest values occur in the sector between the mouth of the Lato River and the Castellaneta Marina settlement, due to the steeper slope of the beach, as reported in Fig. 4. The highest level refers to run-up values greater than 1.3 m estimated for a return time of 50-years.



Fig. 4. Run-up estimation for return time RT = 50 years. Run-up classes are based on a quartile division of the individual identified samples. The highest level refers to run-up values greater than 1.1 m.

3.4 Hydraulic Hazard Analysis

The Municipality of Castellaneta is also affected by other types of flood hazards. According to the local flood risk management plan (Fig. 5), the municipal area is interested from river flood prone areas due to the presence of the Lato river, a stream with a catchment of approximately 670 km^2 [22]. The areas surrounding the Lato river have been interested in different flood events, such as those that occurred in October 1966, September 2003, December 2013 and January 2017, which caused relevant damage to infrastructure and rural areas.

The targeted search for flood-related keywords carried out in the local online newspaper has revealed several flooding events. In particular, we mention the events of 2024, 24 July, and 4 August that caused pluvial flooding and road closure of some underpasses of Castellaneta Marina, where the water reached a considerable depth of 0.5 m (Fig. 5). The importance of such events for the city of Castellaneta Marina is motivated by the occurrence of short-duration intense

raifall events, which generally occur in the summer months, when there is a peak of tourists and then a greater risk to people [23].

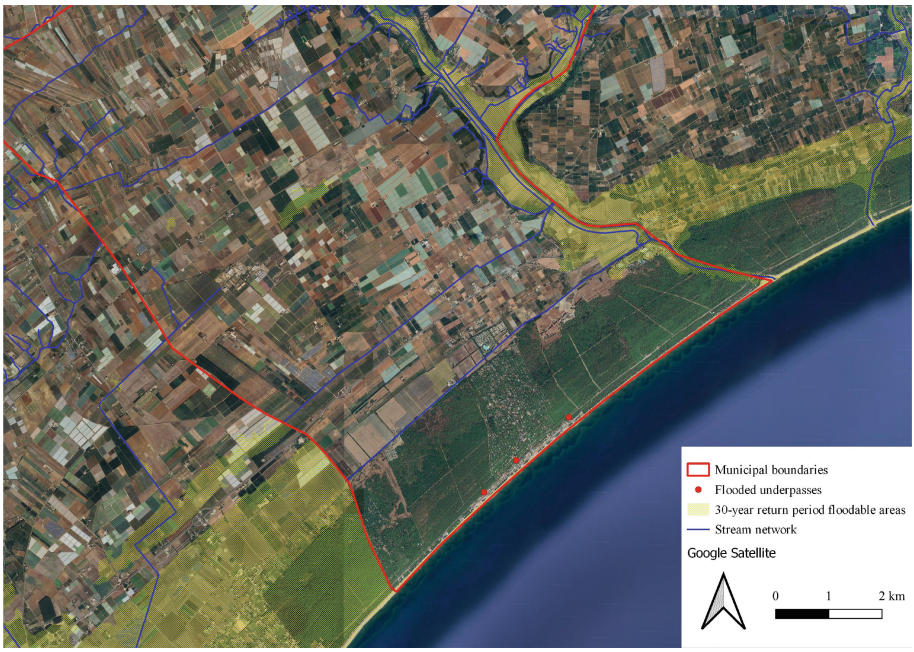

Fig. 5. Floodable area for return time RT = 30 years according to River Basin Plans - PAI (yellow-hatched area). Flooded underpasses after intense rainfall events (red dots). (Color figure online)

4 Discussion and Conclusions

The results of this study provide a clearer understanding of the coastal risk classification for the area examined. This classification comes from a regional-scale assessment using the Mod.E.M. approach. The detailed investigation shows that the coastal system generally has a stable shoreline. However, vulnerability arises mainly from hydrodynamic forces and local landform conditions.

The analysis of shoreline evolution reveals that the coast has gone through cycles of accretion and retreat over the past 30 years. Yet, the overall balance from 1992 to 2023 indicates a mostly stable shoreline configuration with slight advancement. Localized shoreline retreat, especially in the period 2005–2019 between the mouth of the Lato River and Castellaneta Marina, may be related to changes in sediment supply and longshore transport, influenced by dominant wave directions from the S-SSE sector and several severe storms after 2008 in the Ionian Sea [24].

Despite the general stability, the climatic analysis points out the possible exposure of the coastal zone to extreme weather events. Statistical analysis of wave events indicates that significant wave heights could reach nearly 6 m with return periods of 100 years. When these offshore wave conditions reach the nearshore zone, the resulting run-up values exceed 1.1 m in various areas along the coast. This suggests a risk of temporary flooding on low-lying beaches and dune regions.

The sea level analysis further underscores the need to consider long-term changes in mean sea level when assessing coastal vulnerability. Data from the Taranto tide gauge show a general increase in mean sea level since 2008, which is consistent with trends observed throughout the Mediterranean basin [15,25,26]. Specifically, the trend in the annual mean level confirms that the sea level is rising. This suggests that future coastal flooding events may become more frequent and intense, especially when extreme sea levels coincide with storm-induced wave run-up.

The combination of these factors suggests that the current coastal risk is not primarily based on large-scale erosion trends. Instead, it relies on the possible interaction between total water levels, low coastal elevations, and the existence of natural and human-made features. Areas with degraded dune ridges or urbanized coastal zones may be the most vulnerable. The loss of natural dune protection increases the risk of storm impacts in inland areas [27].

Within this framework, it is quite relevant to remark how flood risk management in coastal areas is a complex topic, which requires an in depth analysis of local dynamics arising from the interaction of water with the built environment and people.

In general, the findings highlight the need to integrate regional risk assessments with specific site analyses. Although broad models can identify critical areas, detailed studies of shoreline trends, wave conditions, sea-level changes, and flooding events are essential to understand local processes that affect coastal risk. Given the relevance of flooding phenomena, these processes will be further investigated using 2-D numerical modelling to simulate hydrodynamic and morphodynamic processes.

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A Multi-source Geospatial Framework for Assessing Coastal Risks and Cascading Processes into the COASTLINE Project

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Abstract. After the Second World War, the coastal areas have been subjected to a wide range of hazards, including human activities, geomorphological changes, and hydrodynamic forcing, which have molded their shapes and generated non-linear risk patterns. Nevertheless, most of the existing approaches assess hazards individually and do not explore the consequences of their interaction. To go beyond these constraints, this work introduces a novel geospatial pipeline for assessing risks in coastal environments, including cascading processes through the integration of heterogeneous data sources. The proposed framework is based on the integration of multi-source data (satellite observations, UAV surveys, in situ, and geophysical datasets), which are incorporated in a structured data fusion process, along with the evaluation of hazard dependency and propagation. This methodology is tested on three case studies in order to derive spatial indicators of hazard intensity and risk amplification. The results show that this approach allows for improving the detection of critical areas, elements at risk, exposure, and vulnerability. In contrast to conventional methods, this approach provides a more comprehensive representation of coastal zones. Additionally, the methodology is designed to be scalable and transferable, supporting the planning of adaptation and mitigation strategies.

Keywords: Cascading processes · probability analysis · risk analysis · vulnerability

1 Introduction

Coastal areas are widely acknowledged as among the most dynamic and vulnerable environments on Earth [1, 2]. In recent decades, there has been an increased number of threats from climate change, sea level rise, extreme weather conditions, and increasing anthropogenic impact on coasts [3, 4]. As a result, a gradual increase in the frequency of various coastal hazards, such as erosion, flooding, and deterioration of the coast, has been observed [5, 6]. The threat of coastal erosion is particularly acute, since it impacts the majority of sandy coasts, with an even greater threat posed by future sea level rise [7–9].

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 48–59, 2026.
https://doi.org/10.1007/978-3-032-30524-4_4

Coastal risk understanding has evolved considerably over the last decade, shifting from a mono-hazard perspective to a multi-hazard and systemic risk approach [10, 11]. Hazard processes are considered to be interdependent and are able to initiate cascade effects within the environment and socio-economic systems. Cascade effect can be defined as a chain of processes triggered by the first process and leading to a compounding of the impact through interaction of different processes in space and time [12, 13]. This approach appears highly relevant for coastal environments, where geomorphological, hydrodynamic, and human processes often create a non-linear pattern in the development of coastal risks [14, 15].

Even though great achievements have been made in the field of multi-risk or disaster risk assessment, there are still some challenges remaining when applying these methods to assess risks in coastal areas. First of all, most of the methods currently used don't fully utilize the capabilities of multi-scale and heterogeneous geospatial data. Secondly, the concept of cascade effects is rarely represented explicitly, including its temporal dimension, and finally, there is still a gap between the existing approaches to risk assessment and operational tools that could support decision-making in the field [14]. Though some frameworks have already been suggested describing the hazard interdependence, dynamic vulnerability, and probabilistic chains of events [13]. Nevertheless, practical application of these concepts for the analysis of coastal risk appears to be insufficiently developed at this point [16, 17].

However, research on coastal erosion and the functioning of coastal ecosystems has shown that primary risks, such as the increase in sea level, may cause a number of secondary effects, such as habitat loss, fragmentation of the coastal system, and disruption of its ecological processes [8]. These phenomena exemplify the fact that coastal risk is a cascading phenomenon, where physical changes in shoreline morphology translate into ecological and socio-economic processes, eventually affecting the resilience of coastal territories [18]. With technological advancements in Earth observation systems, monitoring of coastal processes has considerably increased. Remote sensing observations from satellites, UAV surveys, and GIS-supported techniques are some of the modern methods of monitoring coastline and coastal hazards, producing high-resolution multitemporal datasets [19–21]. Although integrating all these information sources in order to produce a risk assessment framework is quite challenging, especially considering the existence of cascading processes and multi-risk events.

It should be noted that in this context, this paper presents an innovative methodology framework for supporting coastal risk assessment, using geospatial multi-source datasets and analysis of cascading processes. In particular, the approach uses information from remote sensing systems and UAV surveys together with other geophysical and environmental data for assessing risks, exposures, and vulnerabilities to a particular hazard. Moreover, the approach uses a theoretical approach for representing cascading effects, which makes it possible to identify connections among different coastal processes and analyze the impact on important assets in line with cascading risk models [14].

The objective of this paper is to establish and illustrate the utility of an operational methodology that will improve the effectiveness of coastal risk assessment through the use of multiple and diverse data sources in a geospatial environment, taking into consideration the cumulative effects of coastal risks, and offering useful information

that will aid in risk-based decision making. The methodology employed is versatile and scalable enough for application in different coastal scenarios and valuable in both scientific inquiry and risk management [4, 16].

2 Methodology

The methodology has been developed within the COASTLINE project as an operational framework for coastal risk assessment, specifically designed to integrate multi-source geospatial data and analyze cascading processes. The approach builds upon established risk assessment paradigms, in which risk is conceptualized as a function of hazard, exposure, and vulnerability, while extending these models by explicitly considering hazard interdependencies and dynamic system responses [14, 17, 21]. Within this framework, coastal risk is interpreted as the result of interacting processes evolving in space and time, rather than as the outcome of isolated hazard events. This perspective is consistent with multi-risk approaches, which highlight the importance of hazard interdependencies and the role of cascading effects in amplifying overall impacts [10, 11]. Cascading processes are therefore treated as a central component of the methodology. They are defined as sequences of interconnected events triggered by an initial hazard, characterized by feedback mechanisms and cumulative impacts [13, 14].

The framework is structured as a modular and scalable workflow composed of six main analytical components:

(i) reference context definition;
(ii) multi-source data integration;
(iii) hazard characterization;
(iv) exposure and vulnerability assessment;
(v) cascading process analysis;
(vi) spatial risk evaluation and mapping;

These components are implemented within a geospatial environment, enabling the integration of heterogeneous datasets and the production of spatially explicit outputs to support decision-making. The overall workflow is illustrated in Fig. 1.

2.1 Reference Context

The methodology has been defined as a framework for coastal risk assessment, intended for application in different Mediterranean coastal environments. The first step, referred to as reference context definition, represents a key phase to ensure coherence and comparability among the collected multi-source data. This step includes:

i) the definition of the spatial reference system;
ii) the delineation of the analysis domain, and
iii) the specification of the temporal framework.

To ensure spatial consistency and interoperability, all datasets should be processed in the same geodetic reference system (e.g., WGS84 or equivalent projected coordinate systems). In parallel, to account for coastal processes across different spatial scales,

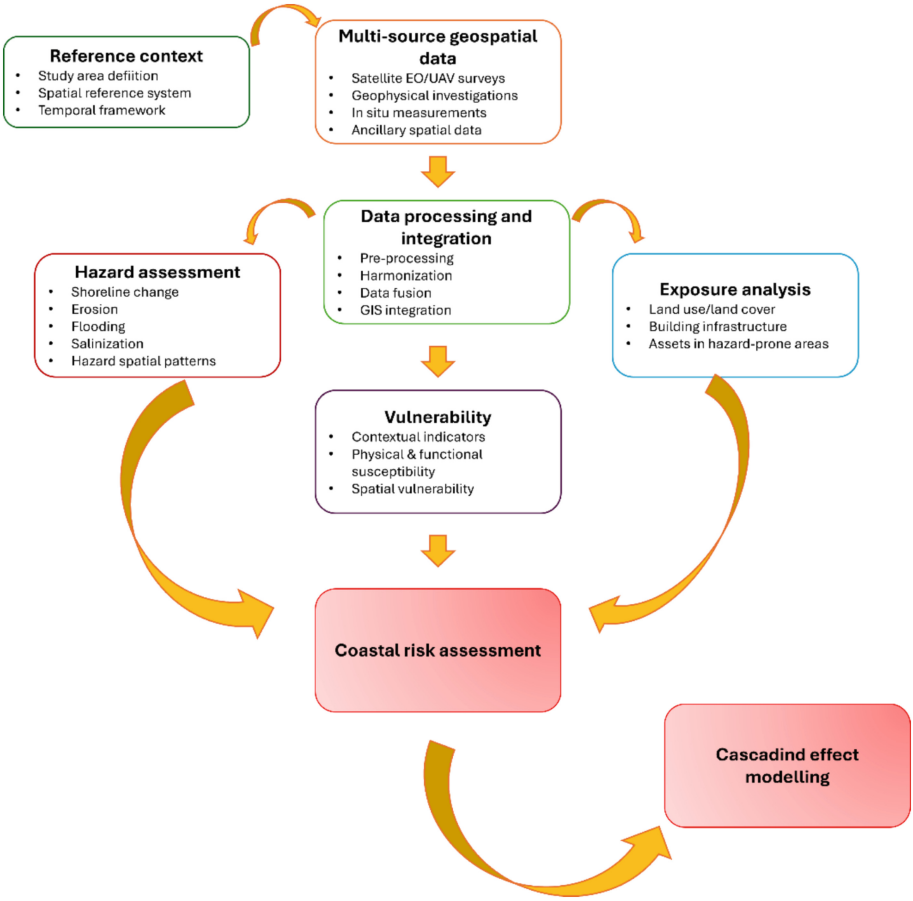

Fig. 1. Conceptual workflow of the methodology.

the spatial domain for each pilot site is defined on the basis of coastal boundaries, geomorphological units, and administrative limits. Lastly, to ensure time consistency, the temporal framework is defined to capture both long-term trends and short-term dynamics. Long-term processes are linked with phenomena evolving over extended periods and are described with multi-decadal datasets (e.g., shoreline evolution and relative sea-level changes); in contrast, short-term dynamics are associated with episodic events such as storms, extreme wave conditions, and coastal flooding. Thus, three pilot sites were selected to represent different Mediterranean coastal conditions: Elounda (Crete, Greece), the Paphos district (Cyprus), and Margherita di Savoia (Puglia Region, Southern Italy) (Fig. 2). This selection is aimed at capturing variability in geomorphological settings, environmental characteristics, and levels of anthropogenic pressure.

Elounda, located in northeastern Crete, is characterized by a complex tectonic setting associated with the subduction of the African plate beneath the Aegean microplate, with carbonate and karst formations and active fault systems influencing coastal dynamics.

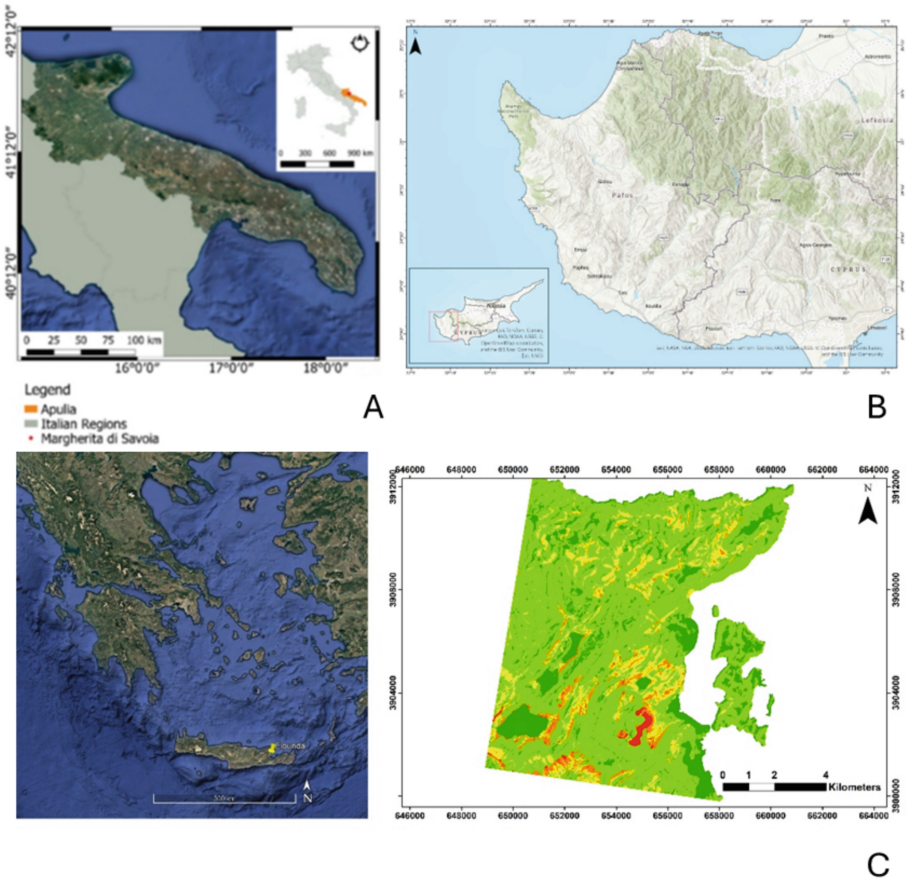

Fig. 2. COASTLINE pilot sites: (a) Margherita di Savoia (Italy); (b) Paphos (Cyprus); (c) Elounda (Crete, Greece).

The Paphos district, in western Cyprus, represents a coastal system of high ecological and cultural value, including protected ecosystems and archaeological heritage. Margherita di Savoia, along the Adriatic coast of southern Italy, is characterized by low-lying sandy shorelines, salt marshes, and pronounced morphological variability, with increasing exposure to coastal hazards.

2.2 Multi-source Geospatial Data

Following the definition of the reference context (Sect. 2.1), the methodology focuses on the acquisition, preprocessing, and integration of heterogeneous geospatial datasets describing both coastal dynamics and elements at risk. The objective is to combine data sources characterized by different spatial resolutions, temporal frequencies, and acquisition techniques in order to obtain a coherent and comprehensive representation

of coastal systems. The datasets considered include: (i) satellite imagery for exploring long-term processes; (ii) UAV-based surveys providing high-resolution topographic and geomorphological information; (iii) environmental and geophysical data, such as bathymetry, sediment characteristics, wave climate, and meteorological forcing; and (iv) socio-economic and infrastructural datasets describing exposed assets and human activities. Given their heterogeneity, these datasets require a harmonization process to ensure spatial and temporal consistency. This process includes georeferencing, spatial resampling, and normalization within a common coordinate reference system, as well as the alignment of datasets with different temporal resolutions. The integration of multi-temporal data allows for investigating coastal dynamics over time, supporting the identification of both long-term trends and short-term variability [20–22]. Hence, the combination of remote sensing and in situ observations improves the robustness and reliability of hazard assessment [23, 24]. This step provides the necessary substratum for all subsequent analyses.

2.3 Hazard Characterization in the Coastal System

Hazard characterization focuses on identifying, quantifying, and depicting coastal processes that pose risks. Contrary to classical methodology, which treats each hazard as an independent variable, coastal hazards are regarded as part of an interacting system in which more than one hazard may occur at the same place and time [25, 26]. This perspective reflects recent developments in multi-hazard and multi-risk assessment, which emphasize process interactions and systemic behavior in complex environments [10, 11]. This approach aligns with current multi-hazard and multi-risk assessment research, which focuses on interactions between processes and their systemic behavior in complex environments [24, 27].

Spatial indicators, which describe processes occurring in time and space, are used for hazard characterization, e.g., rates of shoreline changes, degree of inundation, frequency of extreme event exposure. Indicators of this type allow quantifying hazards in terms of their magnitude and spatial variability, thus providing the possibility to identify areas where risks may potentially be higher than elsewhere. A multi-temporal indicator-based approach has been widely applied in coastal risk analysis as it allows considering processes' evolution over time [21, 22]. The temporal element is essential for depicting the dynamic aspect of coastal risks, both long-term, like sea-level rise, and short-term processes linked to extreme events like storm surges. Both factors acquire significance in relation to coastal hazards, which are dependent on the interaction of gradual and episodic phenomena [3, 18]. In general, the study of hazards involves establishing the spatiotemporal characteristics of coastal phenomena, which serve as the foundation for their synthesis with exposure, vulnerability, and cascade effects.

2.4 Exposure and Vulnerability Assessment

In accordance with EU guidelines, exposure and vulnerability are considered as distinct components of coastal risk, although they are closely interconnected. Both concepts are based on the definition of elements at risk, understood as assets potentially affected

by coastal hazards (e.g., population, infrastructure, economic assets, and environmental resources). Hence, exposure refers to the spatial distribution of these elements at risk, typically categorized into homogeneous groups, including, for instance, built-up areas, critical infrastructure, land use classes, and environmental assets, using geospatial datasets [17, 27]. This classification enables the detection of concentrations of elements at risk in areas prone to hazards' impacts, providing a structured representation of the spatial dimension of risk.

In contrast, vulnerability describes the degree to which exposed elements are susceptible to damage under specific hazard conditions. It is determined by considering the physical characteristics of assets, the environmental sensitivity and adaptive capacity, as well as the socioeconomic factors. These indicators are combined to derive spatially distributed vulnerability levels, in accordance with established approaches to vulnerability analysis [29]. To ensure comparability across spatial units, indicators are normalized when necessary. In this context, vulnerability is recognized as a dynamic property that may evolve in response to repeated or interacting hazard events [28]. This dynamic perspective is particularly relevant in coastal environments, where sequential hazard impacts and process interactions can progressively increase system fragility. As a result, vulnerability is considered inherently linked to the temporal evolution of coastal processes and their cumulative effects.

The explicit distinction between exposure and vulnerability is essential to ensure conceptual clarity in risk assessment, as it separates the spatial distribution of assets from their susceptibility to damage. Their integration enables the identification of areas where high exposure coincides with high vulnerability, which are typically associated with elevated risk levels. Once exposure and vulnerability layers are calculated, they are integrated into hazard characterization and cascading process analysis in order to quantify the amplification of spatial risk patterns and supporting risk-informed decision-making.

2.5 Cascading Hazard Modelling

To explicitly represent cascading coastal hazards, hazard interactions are modeled as a directed weighted graph $G = (V,E)$, where nodes $H_i \in V$ correspond to hazard states derived from multi-source geospatial data, and edges $e_{ij} \in E$ encode dependency relationships between interacting processes. This formulation is in line with recent multi-hazard methodology based on modelling the interconnection among various hazards and the corresponding cascading effects, which are often neglected in conventional approaches. Each hazard is quantified through a data fusion process F based on the integration of multi-source heterogeneous datasets (satellite imagery, UAV surveys, and geophysical measurements):

$$H_i = F\left(D_i^{sat}, D_i^{UAV}, D_i^{geo}\right) \tag{1}$$

where D_i^{sat} represents satellite-derived indicators (i.e., shoreline change rates, spectral indices, and digital elevation models), D_i^{UAV} provides high-resolution topographic and morphological information (e.g., DSMs and orthophotos), and D_i^{geo} captures subsurface

characteristics relevant to sediment dynamics. To ensure cross-scale consistency, the data fusion process includes the co-registration, normalization, and spatial aggregation.

Instead, cascading dynamics are modeled by associating each edge e_{ij} with a weight $w_{ij} \in [0,1]$, representing the strength of interaction, and a conditional probability $P(H_j \mid H_i)$, expressing the likelihood of hazard propagation. This probabilistic interpretation is consistent with Bayesian and multi-risk approaches to compound hazards. The propagation of hazard intensity through the network is expressed as:

$$I(H_j) = \sum_{i \in N(j)} w_{ij} * P(H_j|H_i) * I(H_i) \tag{2}$$

where $I(H_i)$ denotes the normalized intensity of hazard H_i, and $\mathcal{N}(j)$ represents the set of hazards influencing H_j. Edge weights are estimated through spatial correlation between hazard layers:

$$w_{ij} = \frac{Cov(H_i, H_j)}{\sigma_{H_i}\sigma_{H_j}} \tag{3}$$

while conditional probabilities are computed from spatial co-occurrence patterns:

$$P(H_j|H_i) = \frac{N(H_i \cap H_j)}{N(H_i)} \tag{4}$$

where $N(\cdot)$ denotes the number of spatial units satisfying a given condition. This data-driven parameterization allows the framework to capture observed dependencies rather than relying on purely conceptual assumptions. Finally, cascading-aware risk is quantified by integrating the propagated hazard intensity with exposure and vulnerability components:

$$R = H * E * V \tag{5}$$

where H represents the aggregated hazard intensity resulting from graph propagation, E denotes exposure (e.g., infrastructure distribution), and V represents vulnerability factors. This formulation extends traditional risk models by explicitly incorporating hazard interdependencies, enabling a more realistic and dynamic representation of coastal risk processes.

3 Results

The introduced pipeline was applied to quantify the spatial distribution of hazards, as well as their associated vulnerability and exposure, cascading effects, and the resulting risks. Hazards layers are typically derived from satellite, UAV, and geophysical data. Following the data collection phase, these layers are processed and normalized to generate intensity maps $I(H_i)$, which are subsequently integrated into a graph-based model to simulate cascading effects. This approach allows the analysis of interdependencies among coastal processes and the propagation of consequences of hazard conditions in such environments. For instance, Fig. 3 illustrates the interconnection among coastal

erosion *(H_1)*, dune degradation *(H_2)*, flooding susceptibility *(H_3)*, and infrastructure damage *(H_4)*. Indeed, H_1 influences and increases the dune degradation, which, in return, enhances flooding susceptibility, specifically in low-elevation zones, characterized by weak natural protective barriers. The graph underlines both direct and indirect pathways by emphasizing the accumulation of hazard intensity along interconnected processes.

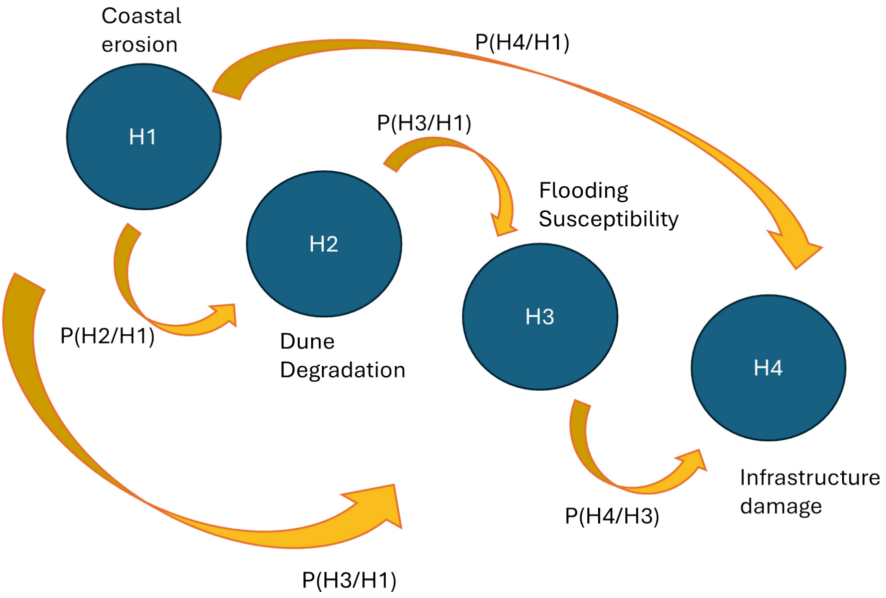

Fig. 3. Example of cascading processes in a coastal environment.

The resultant risk map R, computed by multiplying hazard, exposure, and vulnerability, identifies critical hotspots. Beyond the single-hazard assessment, the inclusion of cascading processes leads to an increased spatial extent and intensity of risk, providing a more comprehensive representation of its spatial distribution. This approach highlights areas that would not be detected when considering hazards independently, thereby enabling a more coherent understanding of complex coastal dynamics.

4 Discussion

The suggested framework provides evidence that the use of multi-source data analysis in the graph-based modeling of interrelated processes improves comprehension of coastal threats. In contrast to the conventional approach focusing on individual threats, the suggested method accounts for interrelationships among different types of coastal risk, allowing for obtaining an overall image of how geological and hydrological processes interact, thus increasing exposure to the hazard. This factor becomes crucial in the case of coastal territories, as any insignificant shift in the landscape, such as a shifting coastline,

leads to enhanced threats and consequences for coastal infrastructures. Nevertheless, there are also some drawbacks to the suggested framework, which should be considered. First, the relationships among different types of coastal risks are based on their concurrent manifestation, and, therefore, do not provide sufficient information regarding causal interactions or temporal dynamics. In addition, as coastal ecosystems possess inherent complexity, they include feedback loops that cannot be completely accounted for in the framework.

The quality of the information being used also proves essential in the analysis. The combination of various sources, including satellite imagery, UAV information, and geophysical measurements, leads to uncertainty caused by varying resolutions, accuracies, and acquisition methods. Even though much work was done towards aligning the datasets, some inconsistencies might still arise, affecting model predictions. Furthermore, the use of the simplified model that focuses only on several interactions between different parameters limits how realistic the analysis is. It is recommended that further improvements in the application include using more sophisticated models, such as dynamic and probabilistic ones, to improve the representation of nonlinear processes. Nevertheless, the framework gives substantial information when it comes to evaluating and mitigating risks. First of all, accounting for the cascading effects of various disasters provides a more comprehensive approach to risk assessment. For example, rising sea levels contribute to coastal erosion, which results in increased flood risks.

The methodology is also adaptable for application in various coastal settings, as long as the appropriate data can be obtained. In addition, it can help with spatial planning, infrastructure design, emergency planning, and the promotion of awareness about coastal hazards and preventive measures.

Future research needs to include temporal aspects in the model, refine the estimate of interaction coefficients using statistical and machine learning methods, and define uncertainty explicitly. Linking the model with scenarios will increase its capacity for decision support in coastal hazard management.

5 Conclusion

This study introduced the integrated geospatial pipeline developed within the COASTLINE project to assess the impact of multi-hazards on areas prone to coastal risk. Indeed, by integrating satellite, UAV, and geophysical data, this approach enables:

i) the identification of elements at risk and hazards occurred in specific coastal areas in Mediterranean regions;
ii) the delineation of coastal zones vulnerable to hazards defined in the previous step;
iii) the assessment of exposure, and, lastly
iv) the quantification of risk, including the combined risks raised from cascading processes.

The results demonstrate that the multi-risk approach facilitates the detection of hotspots caused by the amplification of the impacts of multi-hazards occurring in coastal vulnerable areas. In this way, this scalable and flexible approach provides an effective solution for capturing and describing complex hazard dynamics. Thus, in addition to its

methodological contribution, the developed framework supports coastal management and climate adaptation, fostering more informed and evidence-based decision-making.

Acknowledgments. This research has been supported by the European Union's Horizon Europe Framework Programme (COASTLINE Project - Grant Agreement N. 101130576 – CUP: D93C23000960006) under the grant agreement No 101130576. Views and opinions expressed are, however, those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

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Public Participation, Spatially-Informed Artificial Intelligence and Territorial Planning: Integrating GIS, Text Mining and Clustering for the Analysis of Stakeholder Preferences

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Abstract. The increasing complexity of territorial planning processes, particularly in the context of large-scale infrastructure projects, calls for the integration of participatory approaches, spatial analysis and advanced computational techniques. This paper proposes a comprehensive methodological framework that combines public participation, Geographic Information Systems (GIS), text mining, clustering algorithms, and AI-based analytical techniques within a structured and transparent workflow for the systematic analysis of stakeholder contributions. A central contribution of this work lies in the explicit incorporation of spatial variables into the analysis of stakeholder preferences, with particular attention to the relationship between geographical proximity and expressed sentiment. Based on developed theoretical paradigms such as spatial behavior theory, distance-decay models, and Not In My Back Yard (NIMBY) dynamics, the study explores how distance from an intervention impact on the strength and direction of stakeholder positions.

The proposed approach transforms unstructured textual data obtained by participatory processes into structured indicators of territorial consensus and dissent. These indicators provide a solid analytical foundation for understanding spatial patterns of conflict and support in complex planning environments. To achieve a thorough understanding of territorial transformation processes and their perception by stakeholders and locals, a case-study approach is adopted. The in-depth analysis implemented of the Paderno Bridge enables the implementation of a series of examinations aimed at investigating the relationships between public opinion, stakeholder positions, and decision-making processes.

Keywords: Public Participation · Clustering Analysis · Stakeholder Analysis · Geographic Information Systems (GIS) · Natural Language Processing (NLP) · Participatory Planning

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 60–76, 2026.
https://doi.org/10.1007/978-3-032-30524-4_5

1 Introduction

In the last decades, territorial planning has experienced a deep transformation, changing from a predominantly technocratic and expert-driven practice toward more inclusive and participatory models. This evolution has been particularly evident in the management of major infrastructure projects, where decision-making processes are characterized by a multiplicity of stakeholders, including public entities, local communities, economic operators, and civil society.

In such contexts, participatory mechanisms, such as public consultations, debates, and formal submissions, produce significant number of qualitative data. These contributions often reflect highly heterogeneous standpoints, ranging from technical observations to strongly articulated positions of support or opposition. While, on one hand these inputs are relevant for guaranteeing democratic legitimacy and for the enhancement of the quality of decisions, on the other hand they constitute significant analytical challenges due to their unstructured nature.

Simultaneously, decision-support frameworks, specifically those based on multi-criteria approaches, require structured and comparable information. Thus, a crucial methodological gap arises on how to systematically transform qualitative stakeholder contributions into quantitative or semi-quantitative indicators that can be integrated into decision-making processes.

Nevertheless, recent advances in Artificial Intelligence (AI), particularly in deep learning-based Natural Language Processing (NLP) and the emergence of Large Language Models (LLMs), offer encouraging solutions to this challenge. In particular, the extraction of significant patterns from large corpora of textual data is allowed by text mining and representation learning techniques, while clustering methods enables the identification of groups of stakeholders sharing similar positions. Still, the spatial embeddedness of stakeholder preferences represents a critical dimension often overlooked in such analyses. Indeed, it is necessary to consider that stakeholders are not abstract entities, since they are located in space and thus influenced by spatial factors and dynamics. Municipalities, associations, and committees operate within specific territorial contexts, and their perceptions are influenced by their geographical proximity to the intervention. This introduces a spatial dimension that is central to understanding the distribution of consensus and dissent.

This paper addresses this gap by proposing an integrated framework that combines participatory data analysis with spatial modeling, by investigating the hypothesis that distance from the intervention influences stakeholder sentiment, drawing on the well-established concept of the distance-decay effect.

2 Objectives

The necessity to involve stakeholders in decisional processes inherent territorial interventions, specifically those concerning infrastructures, has developed from a generic indication to a legal constraint. In this sense, the Economic Appraisal Vademecum highlights the relevance of considering the effects on those stakeholders that are indirectly affected by governance policies [1]. In particular, the Stakeholders Engagement (SE) is

prescribed as a fundamental step in the choices-making process to support the project decision aimed at determining part of the society's gains from the investment. In Italy, these indications are the basis of Public Debate, that is an obligatory procedure imposed by the Procurement Code with the objective of guaranteed transparency and stakeholders' participation, both private and public [2]. These impositions reinforce the fundamental principles of participatory planning: *i)* the population possesses a type of unstructured knowledge complementary to that of a technical-specialist type; *ii)* the success of a territorial transformation intervention requires the involvement of the population. The various challenges undoubtedly involve the participation of numerous actors, who are concerned in different ways by the social, economic, and environmental effects generated. Starting from this premise, the present work aims to provide a methodological approach that can support complex decision-making processes by enhancing the information derived from participatory procedures.

3 Theoretical Framework

The recorded difficulties in sustainable urban governance are mainly due to the heterogeneous nature of the societal domains and by the variety of the prospectives of the multiple actors involved concerned by the social, economic and environmental impacts [3]. In this sense, the integration of public opinion contributions represents, according to the recent academic literature [3–11], an effective tool to improve decision-making processes with respect to spatial planning. The theoretical foundation of participatory planning can be traced to two crucial works that conceptualize planning as a collaborative and communicative process [4, 5]. In this perspective, knowledge is co-produced through interaction among stakeholders, and planning outcomes emerge from negotiation rather than imposition. Moreover, involving multiple stakeholders in planning public land use has been considered promising in achieving better outcomes and increasing adaptability of social-ecological systems [6]. Additionally, the participation of citizens in the urban planification is recognized as key element in the requalification and revitalization projects [7]. The need to increase the population participation in the implementation of territorial transformation projects is also due by the imposition of legal requirements, community expectations and regulatory objectives. These requests, in fact, have led to the implementation of collaborative planning processes in solving urban problems [8]. It also possible to identify several benefits from public involvement in decision-making processes; it, in fact, allows to improve the effectiveness of projects; meet a growing demand for public participation, resolve conflicts, value knowledge, understanding and public awareness, manage resources more consciously, strengthen the local community, improve the decision-making process and better understand the needs of the real users of the project we intend to carry out [9]. In this sense, these approaches contribute to achieving the crucial objectives of inclusiveness, deliberation and consensus-building.

Although collaborative approaches are recognized as fundamental tools, their application is nevertheless characterized by some limits and issues [7, 9–11]. Specifically, the complexity of managing large-scale participatory processes increases when the number of actors and contributions rises significantly [4, 5]. In addition, contributions from the population are often restrained by lengthy and cumbersome bureaucratic procedures

for transmission to decision-making bodies. Also, requests for public opinion are often confined to a token procedure aimed at justifying decisions that have already been made [10]. Moreover, the limited awareness of social dynamics and structures by policymakers leads to a failure to recognize the heterogeneity of the population and to a flattening of the positions taken regarding the projects under consideration [11].

3.1 Spatial Behaviour and Distance-Decay

Some academic research highlights how the perspective of the population is closely linked to a range of factors, among which the perception of space emerges. The latter is a fundamental element as it shapes behaviors and affects how individuals relate and respond to spatial transformation interventions [12–14]. In line with these considerations, in the present study the spatial behaviour paradigm is considered as a key theoretical pillar. By examining how geographical factors influence human perceptions and decisions, it allows to deepen the comprehension of the public perspective. However, it is necessary to consider the distance-decay effect, which suggest that the intensity of interaction or perception decreases as distance increases. Specifically, in the context of urban governance, this principle has been widely observed in studies of environmental conflicts and infrastructure siting [15–19]. The distance-decay effect is indeed discussed as a fundamental feature of spatial economic processes, and therefore also of territorial planning, as spatial interactions decline with distance at different rates depending on the phenomenon considered [15]. Closely related is the concept of NIMBY (Not In My Backyard), which describes the tendency of local populations to oppose developments perceived as harmful when they are located nearby [20]. The NIMBY can also been considered as a political-economic conflict arising from the need to locate facilities that generate collective benefits but impose localized costs [21]. Such conflicts usually emerge when it comes to hazardous waste or nuclear facilities [22, 23] and wind energy technological innovation policies [24].

More recent research [25–27] extends these ideas through i) spatial econometrics, ii) geographically weighted models and iii) spatial decision support systems. For example, econometric methods have been used, specifically hedonic price model estimated with OLS and a Generalized Additive Model, to empirically analyze the NIMBY effect showing both distance-based and directional heterogeneity [25]. Accordingly, it has been shown that geographically weighted regression (GWR) is essential to capture spatial heterogeneity in the valuation of environmental amenities, revealing that their impact on housing prices varies significantly across space [26]. Moreover, a prototype Spatial Decision Support System (SUDSS) has been presented that integrates GIS and collaborative decision-making tools to support public participation in spatial planning problems, including conflicts such as NIMBY [27]. These approaches demonstrate that preferences are not spatially uniform but vary across space in systematic ways.

3.2 Toward Spatially-Informed Preference Analysis

The analysis and investigation models, discussed in the previous section, focused on the population spatial perception and on its effects on its perspective on the territorial transformations is a key starting point. In particular, the integration of spatial analysis with

textual data analysis represents an emerging research frontier [28]. While sentiment analysis has been widely applied in various domains, its integration with spatial variables has given rise to approaches that can be broadly defined as spatially-informed sentiment and preference analysis [29, 30]. This paradigm, by contextualizing the emerged opinions within a geographical framework, allows the identification of spatial patterns in attitudes and perceptions, thus going beyond the sole classification of the examined standpoints [31, 32]. For example, an approach that integrates spatial data with human emotional data with the objective to analyse how urban environments influence people sentiment has been proposed. Specifically, through the use of geolocated social media content and artificial intelligence techniques, physical characteristics of urban space have been associated to people's emotional responses, displaying that sentiment varies considerably according to the geographical context. In this sense, the study proves how the integration of spatial variables with collective perception data contributes to the development of a "spatially-informed" sentiment analysis [31]. Likewise, sentiment expressed on Twitter have been examined using geolocated data, combining sentiment analysis techniques with spatial and temporal methods to study how emotions are distributed across different locations. By using spatial indicators and mapping, it demonstrates that users' opinions and perceptions are not uniformly distributed; in fact, they vary forming distinct geographical patterns and local clusters related to place characteristics and social activities. In this sense, the study extends beyond simple sentiment classification, demonstrating how opinions can be interpreted within a geographical framework, in accordance with the idea of a spatially-informed sentiment analysis [32].

4 Methodological Approach

The analytical procedure followed a sequential and structured approach to text analysis, making use of NLP techniques supported by LLMs. Rather than relying on a fully automated or opaque process, each stage of the analysis was carried out in a controlled and explicit manner. The workflow included the extraction of key themes from the textual corpus, their subsequent organization through hierarchical clustering (represented by dendrograms), and finally a structured sentiment evaluation. Each step was subject to iterative checks and refinements to ensure consistency and methodological robustness. This approach allows the analytical process to remain transparent and interpretable, while still benefiting from the capabilities offered by advanced AI-based tools.

4.1 Text Processing and Representation

The analysis is based on textual documents derived from participatory processes (e.g., PDF submissions). These documents are first pre-processed through standard NLP procedures, including tokenization, stopword removal, and lemmatization. Following preprocessing, the textual corpus is transformed into numerical representations. In this study, both term-frequency-based approaches (e.g., TF-IDF) and embedding-based representations are considered, allowing documents to be mapped into a high-dimensional vector space suitable for further analysis.

The TF-IDF weighting scheme is defined as:

$$TF - IDF(t, d) = TF(t, d) \bullet \log\left(\frac{N}{DF(t)}\right)$$

This representation enables the identification of relevant terms within documents while reducing the impact of commonly occurring words.

4.2 Clustering Techniques

To identify groups of stakeholders with similar positions, clustering algorithms are applied. The K-means algorithm minimizes the within-cluster variance:

$$J = \sum_{i=1}^{k} \sum_{x \in C_i} \|x - \mu_i\|^2$$

4.3 Guided AI-Based Analysis

A key methodological aspect of the proposed approach lies in the guided use of AI-based techniques. Rather than relying on fully automated procedures, the analytical workflow is structured in a sequential and transparent manner, where each phase is explicitly defined and contributes to the overall interpretability of the results. The process include:

- the selection of appropriate text representation models (e.g., TF-IDF or embedding-based approaches),
- the application and comparison of clustering techniques,
- the interpretation of thematic and sentiment-related outputs in relation to planning issues.

This structured approach ensures that the analytical process remains transparent and interpretable, which is particularly relevant in planning contexts where the legitimacy of results depends on their clarity and traceability.

4.4 GIS Integration

Stakeholders were geolocated within a GIS environment by associating each actor—municipalities, committees, and associations—to their corresponding spatial reference (centroid or representative location). This process enabled the construction of a spatially explicit dataset linking stakeholder attributes to their geographical position. Subsequently, the distance between each stakeholder and the intervention site was calculated using proximity analysis tools, generating a continuous variable expressed in meters. This variable represents a key spatial metric used to investigate the relationship between territorial proximity and stakeholder positioning. The integration of GIS within the analytical framework allows for a multi-level spatial interpretation of participatory data. Specifically, it enables:

- the mapping of stakeholder distribution, highlighting the spatial configuration and density of actors involved in the participatory process;
- the identification of spatial clustering patterns, distinguishing between a core area of high stakeholder concentration and more peripheral zones;
- the interpretation of spatial gradients in stakeholder behavior, by linking geographical distance to qualitative evaluations expressed in the documents.

Rather than relying solely on descriptive mapping, the GIS component supports a structured spatial reading of the data, allowing the identification of territorial patterns in stakeholder engagement. This integration represents a crucial step in bridging qualitative participatory inputs with spatially grounded analytical perspectives, providing a more comprehensive understanding of how geographical context shapes stakeholder responses.

5 The Case Study

5.1 Description of the Intervention Area

The Paderno Bridge, also known as the San Michele Bridge or Röthlisberger Bridge, represents a major relevance infrastructure, particularly in light of the latest regional and European planning frameworks aimed at promoting transport networks and connectivity systems. The bridge is a relevant crossing over the Adda River, it is indeed characterized by a motor vehicle traffic (single lane with alternating flow), a regional railway line (single track), and cycling and pedestrian routes (including the Alpine foothills cycle path and the Adda cycle path). The bridge was constructed between 1887 and 1889 to connect the municipalities of Paderno d'Adda and Calusco d'Adda, it spans a segment of the Adda River characterized by significant elevation differences. From the historical point of view, the infrastructure falls into the broader and fundamental process of expansion and rationalization of the Lombard railway network in the second half of the nineteenth century. The expansion and enhancement of territorials' infrastructures was crucial to support the industrial development of the region. In the aftermath of the unification of Italy, the need to reorganize railway lines, earlier managed by different companies, became increasingly evident with the objective to improve connectivity between economically strategic areas and to promote the production and export of different goods. Within this context, the bridge shows the fundamental role of transport infrastructure in fostering economic integration between the two main productive areas of Milanese and Bergamo, while also representing a significant example of nineteenth-century technological progress in metal building engineering.

The construction of the bridge implicated the resolution of different complex technical challenges. The adopted design was indeed based on an innovative structural approach, aligning the project with contemporary European achievements in large-scale metal bridge construction. From a technical point of view, the bridge in made by an iron arch structure with riveted beams, extending over a total length of 266 m, with a central span of 150 m. The deck is divided in two functional levels: the upper one is dedicated to road traffic while the lower one to railway traffic. The structure rises approximately 85 m above the river level.

At present, the discrepancy between the bridge's structural capacity and the demands of modern traffic has necessitated the introduction of stringent traffic regulations, including speed limitations. However, such measures constitute only a partial response to emerging territorial needs. In particular, the inadequacy of the bridge in accommodating inter-municipal and regional traffic flows, as well as broader connectivity requirements, has prompted public authorities to explore alternative and more efficient strategies. These strategies aim not only to address infrastructural demands but also to preserve the historical and cultural value of the bridge, which is protected under Legislative Decree No. 42/2004. In response to the increasing pressure exerted on transport networks serving major urban hubs in the region (such as Milan, Monza, and Bergamo), the Ferrovie dello Stato Italiane Group has proposed a project to upgrade the Carnate–Ponte San Pietro railway line. Presented by Rete Ferroviaria Italiana (RFI) in July 2023, the project outlines three alternative design scenarios aimed at enhancing the crossing capacity of the railway system, currently recognized as a critical connection between the Brivio–Trezzo and Cisano Bergamasco–Capriate San Gervasio corridors.

The proposed intervention includes the enhancement of the Seregno/Monza–Bergamo transport corridor, a significant connection segment due to the high volume of commuter traffic, above all in the city of Seregno, which represent as a crucial interchange node with both the Milan–Chiasso line and the Ferrovie Nord network.

In particular, the project aims to achieve two purposes: on the one hand, it wants to guarantee the structural safety and the conservation of the existing bridge, preserving its historical, cultural, and landscape value. On the other hand, it aims to reduce traffic pressure through the enhancement of complementary infrastructure addressed at overcoming recent limitations. The overarching objective is to improve service performance along the Carnate–Ponte San Pietro line, thereby increasing new patterns of territorial use both within the directly affected area and across the broader connected regions.

The three proposed alternatives are defined as follows: Alternative 1 includes the construction of a single structure adjacent to the existing bridge, replicating its functional configuration, with road traffic on the upper level and railway traffic on the lower level (Fig. 1); Alternative 2 involves the development of a new railway alignment to the south of the existing route, combined with a road connection located to the north at a distance of approximately 3.5 km from the current crossing (Fig. 2); Alternative 3 represents a hybrid solution, combining elements of the previous scenarios, including a railway bridge closely aligned with the existing structure and a separate road bridge located approximately 3.5 km to the north, consistent with the spatial configuration defined in Alternative 2 (Fig. 3). Unlike Alternative 1, this scenario does not integrate road infrastructure within the railway bridge structure.

The comparative analysis of the three alternatives is aimed at identifying the most suitable option based on a set of explicitly defined criteria. In this sense, RFI's options analysis is a systematic and multidisciplinary evaluation process aimed at supporting the following implementation phases. In particular, the applied approach, instead of adopting unstructured techniques in the selection process, implements a more structured decision-making framework basing on predefined evaluation criteria, including environmental impact, economic sustainability, accessibility, and alignment with strategic international objectives. Within complex infrastructure projects, such as the case study,

this method enables the clear identification of trade-offs among the examined alternatives, contributing both to minimize the risk of ineffective decisions and to ensure that the final choice is drawn on a transparent and structured evaluation process. Consecutively, this approach influences the maximization of stakeholder value and develops long-term operational effectiveness.

Within this framework, the options analysis can be considered as a practical application of multi-criteria decision analysis methodologies applied in a complex decision-making context.



Fig. 1. Proposed intervention, alternative 1.

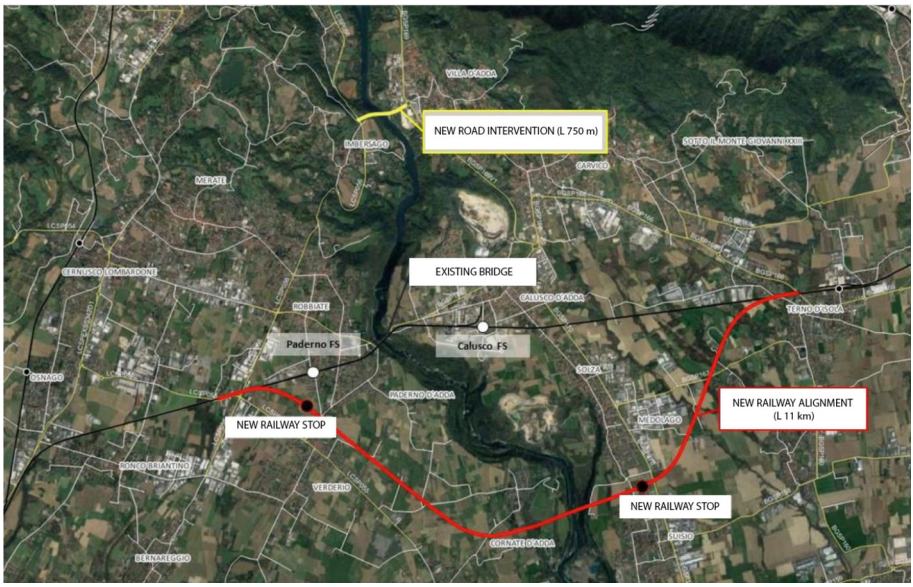

Fig. 2. Proposed intervention, alternative 2.

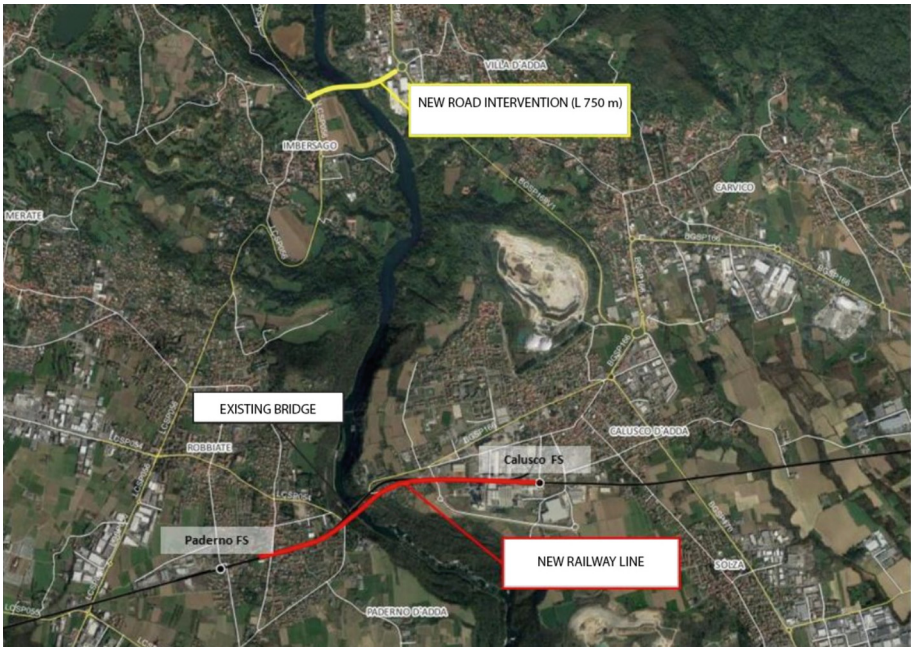

Fig. 3. Proposed intervention, alternative 3.

5.2 Application of the Methodological Approach

Spatial Distribution of Stakeholders

The spatial distribution of stakeholders (Fig. 4), derived from the calculated distances and administrative localization, reveals a clearly structured and multi-scalar configuration centered around the intervention area.

At the core, a highly concentrated local cluster emerges within a radius of approximately 0.8 km to 3 km, including municipalities such as Paderno d'Adda (≈0.8 km), Robbiate (≈1.3 km), Calusco d'Adda (≈2.1 km), Imbersago and Solza (≈2.8 km). This inner nucleus is further reinforced by the presence of local committees located at very short distances, indicating a strong territorial proximity to the project site.

A second spatial layer can be identified between approximately 3 km and 7 km, comprising municipalities such as Merate, Cernusco Lombardone, Osnago, Ronco Briantino, Aicurzio, Bernareggio, and Carnate. This intermediate ring reflects a broader area of territorial involvement, still closely connected to the intervention corridor but with a slightly reduced spatial centrality.

Beyond this, a peripheral and regional scale becomes evident, with stakeholders located at distances exceeding 10 km, including Trezzo sull'Adda (~9 km) and various associations and institutional actors extending up to 40 km (e.g., Lodi, Milano, Como). These actors define a more dispersed spatial pattern, extending the participatory process to a wider territorial context.

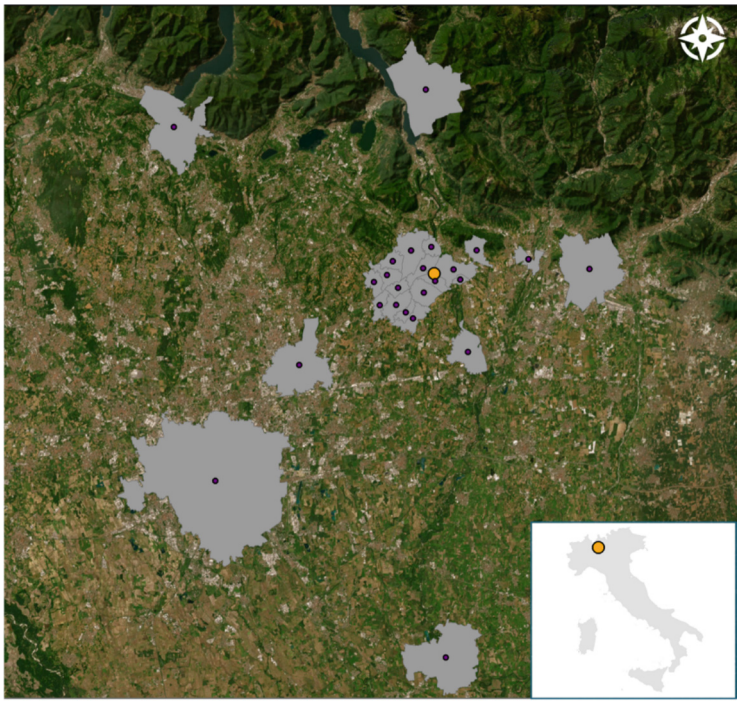

Fig. 4. Territorial distribution of municipalities contributing to the public debate.

Overall, the distribution delineates a concentric spatial structure, characterized by:

- a dense local core of municipalities and committees,
- an intermediate municipal belt,
- and a diffuse outer layer of regional stakeholders.

This configuration reflects a clear spatial gradient of stakeholder presence, transitioning from strong local concentration to broader regional dispersion.

AI-Assisted Structuring of Stakeholder Evaluations

In order to transform the unstructured textual contributions collected during the participatory process into a structured and comparable dataset, a Large Language Model (LLM) was employed as a support tool for qualitative synthesis and categorization. The LLM was used to systematically extract, organize, and standardize key information from each document, including stakeholder identity, institutional type, municipality, and evaluation of the three project scenarios.

Specifically, the model supported the construction of a synthetic table in which each contribution was codified according to: (i) the qualitative assessment of each scenario, (ii) an overall classification of the stakeholder's position, (iii) a set of representative keywords summarizing the main arguments, and (iv) a methodological note explaining the rationale behind the assigned judgment.

Importantly, the use of the LLM did not replace the interpretative role of the researcher. Instead, it operated within a guided and supervised framework, where outputs were iteratively reviewed, validated, and refined to ensure consistency, coherence, and adherence to the original content of the documents. This approach allowed for the efficient processing of a large textual corpus while maintaining transparency and interpretability in the analytical process.

The resulting table represents a structured synthesis of stakeholder position (Table 1).

Table 1. Synthesis of the stakeholder position obtained using the LLM approach (M = Municipality, BA = Business association, C = Committee, CA = Category association).

Stakeholder	Type	Scen.1	Scen.2	Scen.3	Overall Classification	Keywords
Aicurzio	M	Predom negative	Neutral	Neutral	Territorial critique	project disruption; territorial impact; line doubling
AIB Isola Bergamasca Association	BA	Neutral	Neutral	Neutral	Economic position	logistics mobility; enterprises
Bernareggio	M	Negative	Negative	Negative	Territorial opposition	traffic issues; severe impacts; road congestion

(*continued*)

Table 1. (*continued*)

Stakeholder	Type	Scen.1	Scen.2	Scen.3	Overall Classification	Keywords
Calusco d'Adda	M	Moderately Positive	Neutral	Neutral	Conditional support	single bridge; direct connection; reduced impact; mobility continuity
Carnate	M	Negative	Negative	Negative	Territorial opposition	traffic issues; severe impacts; road congestion
Cernusco Lombardone	M	Negative	Negative	Negative	Territorial opposition	traffic issues; severe impacts; road congestion
Citizens Committee Ponti	C	Negative	Negative	Negative	Civic opposition	environmental damage; landscape degradation
New Mobility Isola Bergamasca Committee	C	Negative	Negative	Negative	Strategic opposition	ecological damage; lack of systemic vision; traffic dominance
Ponte e Monastero dei Verghi Committee	C	Negative	Negative	Negative	Environmental opposition	health impact; expropriation; hydrogeological risk; vibrations
Confagricoltura Como	CA	Neutral	Neutral	Neutral	Agricultural position	agricultural land impact
Confagricoltura Lecco	CA	Neutral	Neutral	Neutral	Agricultural position	agricultural land impact
Confagricoltura Lodi	CA	Neutral	Neutral	Neutral	Agricultural position	rural land protection
Confagricoltura Milano	CA	Neutral	Neutral	Neutral	Agricultural position	rural land protection
Confagricoltura Monza	CA	Neutral	Neutral	Neutral	Agricultural position	rural land protection
CONFAPI Lecco	CA	Neutral	Neutral	Neutral	Economic-technical position	productive activities; business mobility
Imbersago	M	Negative	Negative	Negative	Territorial opposition	traffic issues; severe impacts
Lomagna	M	Negative	Negative	Negative	Territorial opposition	traffic issues; severe impacts

(*continued*)

Table 1. (*continued*)

Stakeholder	Type	Scen.1	Scen.2	Scen.3	Overall Classification	Keywords
Merate	M	Negative	Negative	Negative	Territorial opposition	traffic issues; severe impacts
Osnago	M	Negative	Negative	Negative	Territorial opposition	traffic issues; severe impacts
Paderno d'Adda	M	Negative	Negative	Negative	Territorial opposition	traffic issues; severe impacts
Robbiate	M	Negative	Negative	Negative	Territorial opposition	traffic issues; severe impacts
Ronco Briantino	M	Negative	Negative	Negative	Territorial opposition	traffic issues; severe impacts
Solza	M	Neutral	Neutral	Neutral	Technical observations	impact evaluation; sustainable mobility
Sotto il Monte Giovanni XXIII	M	Negative	Negative	Negative	Project opposition	multiple critical issues; no evident benefits
Sulbiate	M	Negative	Negative	Negative	Territorial opposition	traffic issues; severe impacts
Trezzo sull'Adda	M	Predom negative	Neutral	Neutral	Institutional critique	road network issues; uncertainty in mobility
Verderio	M	Negative	Negative	Negative	Territorial opposition	traffic issues; severe impacts

6 Analysis of the Results

The integration between spatial data (distance from the intervention) and stakeholder evaluations reveals a clear and interpretable territorial pattern in the distribution of judgments. At the local scale, stakeholders located near the intervention—generally within a few kilometers—tend to express uniformly negative evaluations across all scenarios. Municipalities such as Paderno d'Adda, Robbiate, Imbersago, Merate, and the surrounding cluster show a strong alignment in their positions, consistently highlighting critical issues. This spatial concentration of negative judgments suggests that actors directly embedded in the area of impact perceive the project primarily through its immediate territorial consequences.

Moving to an intermediate spatial range, roughly between 5 and 10 km, the pattern becomes slightly more differentiated. While negative judgments still prevail, some stakeholders express less polarized or scenario-specific evaluations, as in the case of Aicurzio and Trezzo sull'Adda. This indicates a partial attenuation of opposition, where

the perceived impacts remain relevant but are less uniformly interpreted across all project alternatives.

At the regional scale, corresponding to distances exceedingly approximately 10–15 km, a clear shift in stakeholder positioning emerges. Actors located farther from the intervention—particularly sectoral and economic associations such as Confagricoltura and AIB—tend to adopt neutral or non-committal evaluations across all scenarios. Their contributions focus more on general or sector-specific considerations rather than direct territorial impacts.

Overall, the observed distribution highlights a spatial gradient in stakeholder judgments, characterized by:

- strong and homogeneous opposition in close proximity;
- moderate variability at intermediate distances;
- and increasing neutrality at greater distances.

This pattern suggests that the intensity and orientation of stakeholder evaluations are closely associated with their geographical position relative to the intervention, reflecting a structured spatial differentiation in the participatory process.

7 Conclusions and Future Insights

The high complexity of the decision processes at the base of the implementation of major territorial transformation has revealed the growing importance of integrated participatory approaches. The positive effects conferred by the stakeholders' approval have made it necessary to take their standpoint into greater consideration in order to contribute to a more sustainable and resilient projects. In particular, the development of infrastructure projects often generates opposition from local communities, which tend to perceive such interventions as top-down impositions that provide limited or no tangible benefits to the territories in which they are implemented.

In order to mitigate this phenomenon and to leverage stakeholders' knowledge, both national and international regulatory frameworks participatory processes aimed at involving the population and fostering the identification of broadly shared solutions.

Despite these provisions, decision-makers frequently approach such processes as a formal requirement rather than as a genuine opportunity to incorporate unstructured knowledge. At the same time, representatives of local communities often adopt predefined and rigid positions, which can hinder constructive dialogue.

Starting from these premises, this study proposes an approach that integrates NLP and GIS techniques to systematize and enhance the contributions emerging from public participation. By the TF-IDF and of clustering techniques, the described framework allows transforming non-structural textual data into quantitative indicators. In addition, the use of GIS-based tools and the georeferencing of data enables the visualization of such information into specific maps that permit to link sentiments and opinions to the place they are made. At the same time, it also makes this information accessible to non-expert users. This reduces the risk of the public debate being perceived as a mere bureaucratic procedure, while enhancing the actors' opinions as a key resource.

The proposed case study provides a relevant testing ground for assessing both the limitations and the potential of the approach. Specifically, the obtained results from

the Paderno bridge analysis are coherent with the hypothesized spatial-dependence of preferences varying the distance-decay paradigm. It is indeed possible to observe a negative polarization in the areas nearest to the intervention typical of NIMBY dynamics. The results through the application to the case study thus confirm the validity of the proposed approach.

Finally, the spatial-informed framework offers a sound operative medium for more inclusive and democratic planning strategies by recognizing the diversity of the population involved preventing the flattening of positions. Through the overcoming the traditional procedures, the proposed model thus allows to integrate stakeholders varied positions in a decision support tool while also granting trackability of the mad choices.

Acknowledgments. The research has been carried put within the PRIN research project entitled "Digitalized life-cycle management of historic bridges by an integrated monitoring and modelling CDE platform – HBridgeIM (Historic Bridge Information Modelling)" (Grant number 2022744YM9).

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A Geostatistical Approach for the Geomatics Characterization of a Landslide Phenomenon

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Abstract. Monitoring ground deformation in urbanized areas is a significant challenge for hydrogeological risk management and land-use planning. Starting from the combination and integration of remote sensing techniques with geostatistical modelling, this study focuses on characterizing, from a geomatic side, an ongoing landslide phenomenon in the municipality of Chieuti (FG), in southern Italy.

The analysis is based on the use of the MT-InSAR (Multi-Temporal Interferometric Synthetic Aperture Radar) technique, applied to data acquired from the Sentinel-1 (S1) constellation. Considering the discrete nature of these measurements, limited to Persistent Scatterers (PS), a geostatistical approach is proposed for the continuous reconstruction of the deformation field.

In particular, the spatial correlation structure was analyzed using an empirical variogram and theoretical modelling. Subsequently, ordinary kriging interpolation was applied to obtain velocity estimates even in areas lacking direct observations, enabling the generation of continuous deformation maps within a GIS environment. The kinematic analysis allowed the identification and delineation of an area of active instability characterized by predominantly vertical deformations. The results showed a high level of consistency, confirming the reliability of the proposed methodology. The integrated approach developed is a useful tool for supporting decision-making in geomorphological risk management, particularly in urban contexts characterized by soil instability phenomena.

Keywords: Geostatistical analysis · SAR · geomatics monitoring · landslides · Kriging

1 Introduction

The interaction between natural evolutionary dynamics of natural phenomena and human pressure—which increasingly gives rise to catastrophic and devastating scenarios—is today one of the most complex challenges facing society and the scientific community. Hydrogeological instability represents one of the most critical and immediate manifestations of this, where the geomorphological fragility inherent to the Earth's surface intersects with the transformative impact of human activity. Given the Italian territory's structural vulnerability and natural predisposition to phenomena such as landslides and

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2026
O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 77–92, 2026.
https://doi.org/10.1007/978-3-032-30524-4_6

subsidence, the impact of the climate crisis and the partially unsustainable management of the territory have exacerbated their magnitude and frequency, expanding their scale. The country's history confirms the urgency of a decisive shift in approach: emergency management of events can no longer substitute for, nor take the place of, a phase of failed or insufficient prevention [1]. The scale of the phenomenon is reflected in the Inventory of Landslide Phenomena in Italy (IFFI Project), compiled by ISPRA, which records over 636000 landslides, covering approximately 8.3% of the national territory. This is a consistent body of data that highlights the intrinsic danger of the peninsula, where approximately 28% of the phenomena are rapid-moving (collapses, mudflows, and debris flows) and highly destructive [2].

The history of this territory has been deeply shaped by its susceptibility to natural disasters, as evidenced by the enduring scars of the Sarno and Quindici disaster (May 1998), the tragic occurrences on the Island of Ischia (November 2022), and the recent landslides that affected the municipality of Niscemi (January 2026) and the Petacciato area in the Molise region (April 2026). These critical occurrences confirm that uncontrolled urbanization and inadequate maintenance act as risk multipliers, with devastating social and economic consequences [3].

A further warning comes from the data in the 2024 ISPRA Report, which estimates that 94.5% of Italian municipalities are currently exposed to risks arising from landslides, floods, or coastal erosion. In this scenario, the resilience of territories becomes directly dependent on the monitoring plans put in place. Tools such as the national IdroGEO platform have now become invaluable instruments for prediction, management, and proper communication of hydrogeological risk [4]. This vulnerability is particularly evident in the Apulian territory, where the necessity of enhancing the resilience of both urban fabric and cultural heritage against extreme weather events has been extensively documented [5–8].

Effective measures to counter deformation phenomena must be based on their proper characterization; one of the tools capable of supporting these objectives is the geomatics-based monitoring. In this case, the development of the European Copernicus program, specifically through S1, has made extensive radar data archives with high spatial and temporal resolution available [9, 10].

The MT-InSAR technique now allows for the detection of millimeter-scale displacements over large areas, providing a fundamental database for both real-time monitoring and retrospective analyses (back-analyses)[11–13].

The temporal and spatial advantages are offset by the inherent disadvantage of the data, namely that it is point-based and discrete.

Displacement information is, in fact, dependent on the presence of stable reflectors (PS), leaving large portions of the territory without direct measurements. This results in a purely deterministic approach that may sometimes be insufficient to describe the complexity of the case, given the uncertainty factors governing it and the fragmented nature of the information.

The transition from a discrete to a continuous nature can be achieved through a probabilistic approach, and geostatistics steps in to bridge this gap [14–17], allowing for the analysis of the spatial correlation structure of the data to transform point-based information into continuous surfaces through estimation techniques such as kriging. It

is thus possible to spatialize the deformation field, quantifying the associated uncertainty and providing a coherent overview even where satellite sensors do not return a signal [18]. The study proposes the application of this methodology to a municipality of Chieuti, located in the Dauno Sub-Apennines area, suffering from an active landslide phenomenon that is still ongoing (Fig. 1). The integration of MT-InSAR data and geostatistical tools aims to reconstruct the spatiotemporal evolution of the landslide accurately, providing decision-making support crucial for the protection of public safety.



Fig. 1. Geographical localization of the study area: the satellite image shows the town center of Chieuti (Apulia Region, southern Italy) and its rural surrounding area (source: Google Maps). The inset map in the upper right corner illustrates the precise geographical location of the study area within the Italian peninsula.

2 The Study Area

The municipality of Chieuti is located in the northern sector of the Apulian territory, on the border between the Apulia and Molise regions. The site is affected by an extensive landslide phenomenon that has historically required continuous interventions by competent authorities to plan appropriate consolidation works. The instability of the slope has been documented since the late 19th century. To mitigate the effects of the movement, various structures have been built since 1950, with the most recent being a retaining wall constructed in 2006 along the critical sector of the slope. Despite these interventions, the continuing subsidence has compromised the structural integrity of several buildings,

making it necessary to declare them uninhabitable. The landslide phenomenon affects both the residential area and the Crojo spring area, which is characterized by complex hydrogeological dynamics and is located northwest of the historic center. The severity of the situation in the area is amply confirmed by official data from the national IdroGEO platform (ISPRA), based on the mosaic of basin-level hydrogeological plans (PAI) (Fig. 2). The risk of landslides affects a significant portion of the local socio-economic fabric: 1.213 km^2 of the territory are classified as High (P3) and Very High (P4) risk, directly affecting 17 buildings and approximately 5.4% of the resident population.

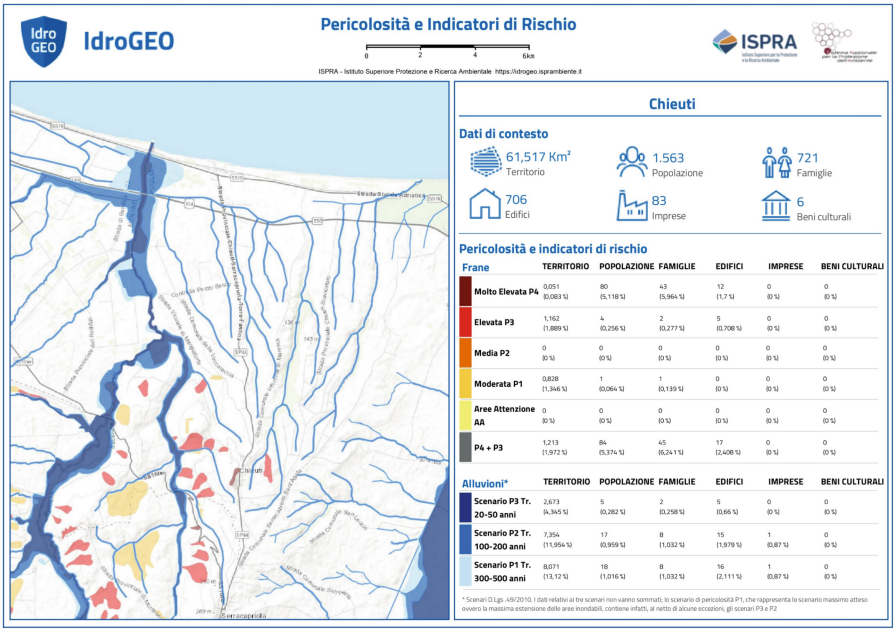

Fig. 2. Landslide and hydraulic hazard indicators for the municipality of Chieuti, according to the national IdroGEO platform (ISPRA).

3 Methodologies Employed

Integrating a geostatistical approach into the analysis workflow was necessary to overcome the intrinsic limitation of the point-based and discrete nature of InSAR data, enabling the transition from a set of scattered measurements to a continuous reconstruction of the deformation field [15]. Assuming the displacement velocity V_LOS as a regionalized variable, the analysis was divided into an exploratory data analysis phase and a subsequent stochastic modeling of spatial dependence.

3.1 The MT-InSAR Technique

The MT-InSAR technique, with its millimeter-level precision in monitoring slow ground displacement velocities over years, is considered a trusted and consistent choice for analyzing ground subsidence in urban contexts.

This methodology takes advantage of the phase difference between radar signals acquired by the SAR sensor at successive times, allowing for the quantification of displacement along the satellite line of sight (LoS). The historical and temporal reconstruction relied on the systematic use of the S1 constellation dataset. By leveraging the high temporal resolution and consistent revisit time of this mission, it was possible to delineate a continuous and coherent deformation history. The S1 Mission of the Copernicus program provided a high degree of temporal continuity thanks to a data archive available since 2015. Despite the moderate spatial resolution (20x5m), the revisit frequency—initially 6 days and 12 days for a limited time interval—ensures the statistical robustness necessary for estimating long-term deformation trends. The technical specifications are further detailed in the table below (Table 1) [8].

Table 1. S1 Mission specifications

Satellite	Acquisition mode	Spatial resolution (Azimuth × Range)	Wavelength (λ)	Orbit	Temporal resolution	Monitoring period	N. of images	Angle of incidence
S1	Interferometric wide-swath	20 m ×5 m	5.6 cm	Ascending	6 days (12 days after Dec. 2021)	Apr 2015-May 2022	367	42.1°
				Descending		Apr 2015-May 2022	361	41.2°

3.2 Geostatistical Analysis

The study of spatial correlation is typically performed through variogram analysis, as it serves as a spatial dependence model that describes data variance between two locations as a function of their distance. The variogram estimates the average degree of variance between values based on their separation in geographic space, defined as

$$\gamma(h)=\frac{1}{2N(h)}\Sigma_{i=1}^{N}\,[Z(u+h)-Z(u)]^2$$

- Z(u) represents the value measured at point (u);
- h is the distance between two points;
- N(h) indicates the number of pairs of points separated by distance (h).

The variogram is, by definition, zero at the origin ($\gamma(0) = 0$), however, as $h \to 0$, it often does not tend to zero, instead tending to a positive definite value. Although the variogram appears to have a non-zero value at the origin, it increases sharply as soon as it moves away from it. This discontinuity can be due to either a sampling grid that is too sparse to capture the microvariability of the natural phenomenon or to measurement errors and is defined as the nugget effect. If the semivariogram reaches a limit value, allowing the identification of a threshold, there exists a distance known as the range, beyond which the random variables Z(u) and Z(u + h) are no longer correlated. From this

perspective, the range provides a precise definition of the traditional concept of a zone of influence: a variable Z(u) will be correlated with any other variable whose position falls within a neighbourhood centred at (u) with a radius equal to the range. Both the range and the threshold typically depend on the direction along which the semivariogram is defined.

3.2.1 Ordinary Kriging

To switch from a point-based representation to a continuous, deformable surface, the Ordinary Kriging (OK) technique was applied. This stochastic interpolation method allows for the estimation of the displacement velocity at unsampled points in the domain, minimizing the variance of the error.

The estimation of kinematic variables at unsampled points is central to determining the displacement field, allowing the transition from a point-based representation to a continuous surface. To obtain an estimate of the variables under investigation at unsampled points, a stochastic interpolation technique called Kriging is used. The technique employs information derived from observed values at certain points in the domain and allows for the evaluation of the dynamics of the characteristic of interest at points within the same domain with no available data. Accuracy depends on several factors, such as the number of observations and data quality, the geometry of the sampled points, the distance between points, and the uniformity of the spatial variable under examination. Kriging is an estimation method that allows for the appropriate consideration of all the factors listed above. In particular, the term "kriging" is used in spatial statistics as a synonym for "optimal estimation method," as it is capable of making the best use of observations from points near the point of interest.

In general, for each unsampled point u_o where the value of the variable $Z(u_o)$ is unknown, the estimate $Z^*(u_o)$ is determined using a weighted linear combination of a set of sampled values $Z(u_i)$ within the same domain of interest:

$$Z^*(u_o) = \Sigma_{i=1}^{N} \lambda_i Z_{(u_i)}$$

where λ_i represents the Kriging weights assigned to each observed point $Z(u_i)$.

Prediction maps are subsequently generated by calculating the estimated value $Z^*(u_o)$ for each cell of a regular grid covering the study area.

3.3 Cross-Validation

A cross-validation technique has been applied to compare the expected values with the observed values using only sample data. This procedure enables the comparison of different models and the selection of the one that best fits the kinematics of the object of study.

Operationally, the cross-validation method encompasses dividing the PS database into multiple subsets; in turn, the values at specific points are temporarily removed from the set of available observations to be subsequently estimated using the remaining data and the variogram model under test. It is essential to note that the points subject to validation are not used in any way in the geometry used to estimate them, thus ensuring the impartiality of the statistical test.

Once the procedure is completed for all sub-databases, the observed values are compared with the predicted values by calculating the multiple coefficients of determination R^2 and analysing the slope of the regression line.

4 Results and Discussion

4.1 Dataset Selection and Domain Definition

The geostatistical analysis phase was preceded by a rigorous process of selecting and preprocessing the SAR data. The estimated variables are the average annual displacement velocity (mm/year) and the overall displacement (mm), both measured along the LoS. Negative values indicate that the distance between the satellite sensor and the PS is increasing, meaning the sensor is moving away from the PS, which is consistent with the slope kinematics. For the Chieuti case study, a S1 dataset collected in the descending orbit was used. The S1 MT-InSAR dataset employed in this study was not processed ex novo for the current research. Rather, this work builds upon a previously validated product. The entire interferometric processing chain, including the data extraction stages and validation procedures, has been extensively documented in previous studies [12, 20].

Figure 3 shows the spatial distribution of average velocities in the historic center: the color scale highlights the most critical sectors in red (velocities between -12 and -10 mm/year) and stable areas in blue (0 to + 2 mm/year).

To ensure the robustness of the deformation field, the quality of the PSs was assessed using the coherence parameter (COH), which ranges from 0 to 1. Specifically, within the study area, the S1 dataset consists of 1,713 sampled points, of which approximately 80% (1,394 PS) have a COH value greater than 0.5, while 30% of the dataset (544 points) maintain a COH greater than 0.8. By using the high-coherence PS, considered trustworthy for describing the landslide's temporal evolution, there is an attempt to minimize uncertainty during the subsequent geostatistical interpolation phase.

The application of ordinary kriging could only be continued once the trend had been analysed and the variogram had been examined. The variogram has reached a plateau (Sill), which means that the mean is locally stationary. This confirms that Kriging is the appropriate method and that there is no need to complicate the model with deterministic polynomials.

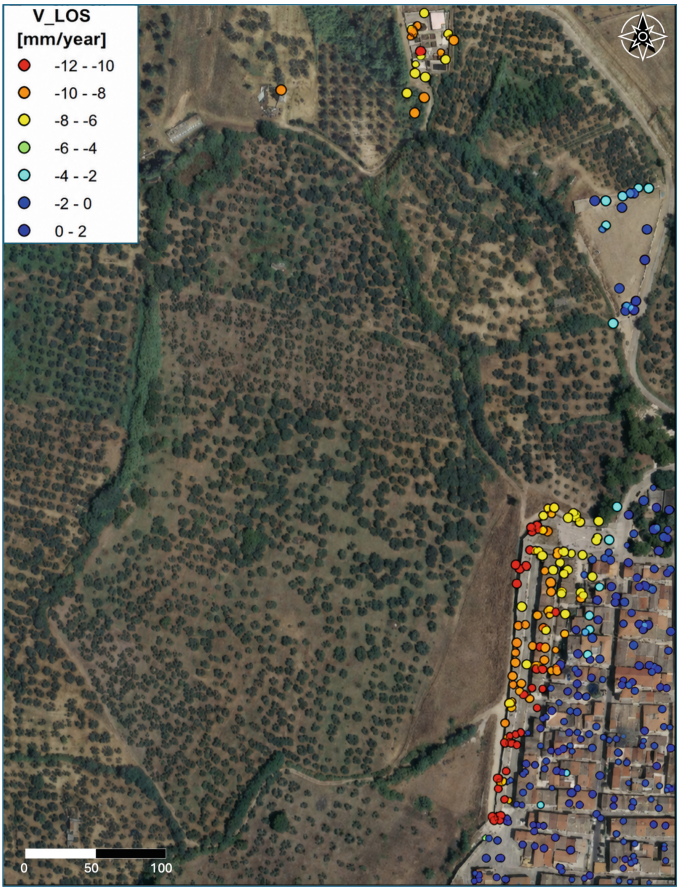

Fig. 3. Spatial distribution of average annual displacement velocities (V_LOS) in the historic center of Chieuti

4.2 Analysis of Entropy and Anisotropy

However, to better characterize the system's stability and study local variations, Voronoi entropy analysis was incorporated into the study. The method is based on dividing the study area into polygons, where each cell is defined such that any point within it is geometrically closer to its own "generating point" than to any other PP present in the dataset [21].

Through this spatial subdivision, it was possible to calculate the local entropy, a parameter that measures the degree of disorder or distortion in the velocity field. An entropy close to zero indicates homogeneous kinematic behaviour (stability or block motion), while high values signal strong heterogeneity among the displacement vectors of adjacent PSs (Fig. 4). This analysis allows to link the the magnitude of the displacement with the presence of differential settlements. Likewise, variability—particularly in terms of spatial and directional velocity—was identified through semivariogram analysis, which revealed marked anisotropy in the system. These statistics have a direct

interpretation in the territory and an objective correlation in the area under study, as the spatial distribution of pairs of points with maximum variance at short distances accurately reflects the geometry of the cracks and structural settlements detected in the buildings on the western slope.

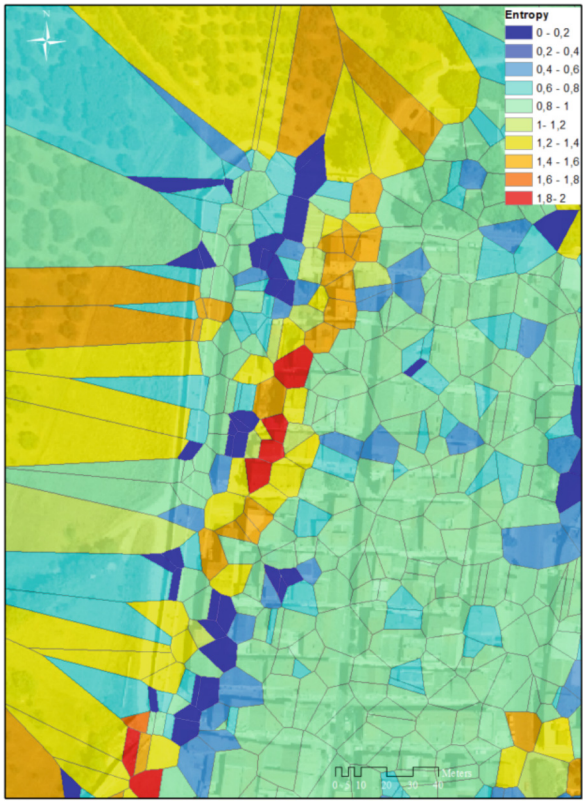

Fig. 4. Local entropy map derived from Voronoi tessellation of the PS dataset.

The presence of pairs of PSs with significantly contrasting velocity values just a few meters from each other—located along the western slope, where the maximum velocity gradients are recorded—cannot be interpreted as a simple measurement error, nor can it be mistaken for an isolated data anomaly. Instead, it constitutes the kinematic manifestation of a discontinuity in the ground; where the diagram shows a marked jump in variance, the physical reality reveals a fracture line that causes damage and differential settlements in the structures.

4.3 Modelling and Validation of the Semivariogram

After the exploratory analysis, it was decided that the theoretical model that best matches the spatial correlation structure of V_LOS is the spherical model. This is described by

a threshold (sill) of 6.2 $(mm/year)^2$, a value that indicates the reach of local stationarity of the variance. The key to the modelling is the integration of geometric anisotropy. As previously discussed, statistical weights do not get assigned in an isotropic method (equal in all directions) in Ordinary Kriging, but rather follow the kinematic morphology of the slope, which is characterised by two directions: that of maximum continuity and that of maximum variance. The direction of maximum continuity—the orientation along which the ground exhibits the most homogeneous behaviour, enabling the model to 'trust' nearby points more for estimation and assigning the highest weights—is equal to 20°.

The anisotropy of the model is defined by the polar angle α of the orientation of the search ellipse and its major and minor semi-axes. Setting a maximum search radius of 90 m enables micro-variations in the annual average velocity to be accurately mapped, ensuring the local kinematic trend is preserved.

Model validation is based on the procedure described above; therefore, the dataset consisting of S1 pixels segregated by coherence (greater than 0.5) and identified within the study area (Fig. 5) has been divided into two equal parts identified by the codes S1_COH05_01 and S1_COH05_02, whose characteristics are shown in the following table (Table 2).

Table 2. Characteristics of the validation and training subsets (S1_COH05_01 and S1_COH05_02) split for cross-validation

Dataset	Satellite	Acquisition Mode	Spatial resolution	Revisit time	Orbit	N. of Images	Number of PS
S1_COH05_01	Sentinel-1	IW-Swath	20x5m	16 days	Descending	361	**719**
S1_COH05_02	Sentinel-1	IW-Swath	20x5m	16 days	Descending	361	**719**

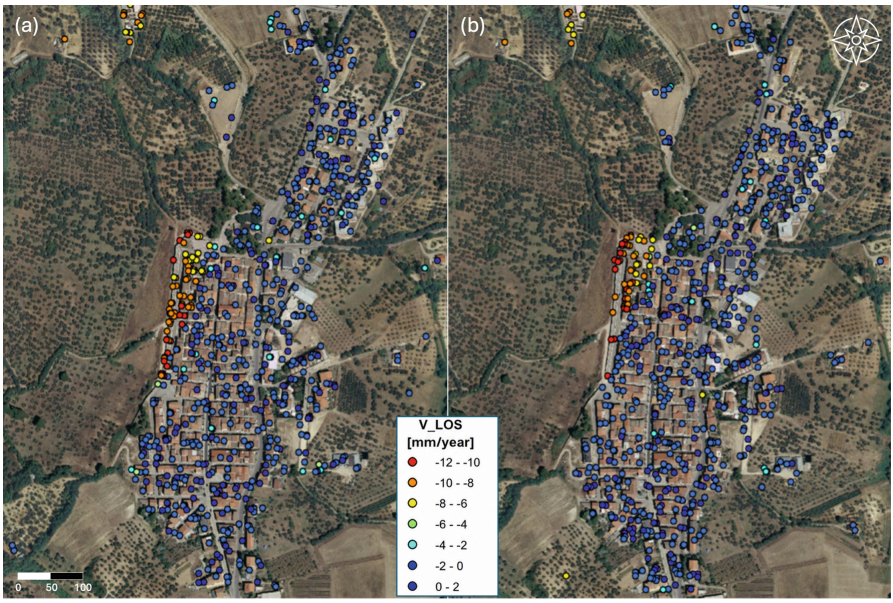

Fig. 5. Validation (a) and training subset (b) (S1_COH05_01 and S1_COH05_02) spatially displayed within the study area for cross-validation purposes

Following the validation phase, the optimized geostatistical parameters (spherical model, 20°/110° anisotropy, and 90-m search radius) were applied to generate the continuous surface of the deformation velocity V_LOS across the entire investigation area. The subsequent stage entailed the creation of a prediction map employing ordinary kriging with one of the two datasets, utilising the second dataset as the validator and advancing to the cross-validation phase.

This process was then repeated with the two datasets swapped.

The multiple R^2 coefficient obtained was 0.85 and the slope of the regression line was 0.97. The variogram model was chosen as it showed the highest multiple R^2 coefficient value compared to the various repeated models, thus representing the spatial correlation model of V_LOS for the analysed system best. The table below (Table 3) provides a comprehensive overview of the various attempts made.

Table 3. Geostatistical parameters and cross-validation results for the different semivariogram models tested

Input Dataset	Validation Dataset	Angle α [°]	a max [m]	a min [m]	Model	R^2	Slope
S1_COH05_01	S1_COH05_02	20	90	40	Stable	0,77	0,97
S1_COH05_01	S1_COH05_02	20	90	40	Spherical	0,85	0,97
S1_COH05_01	S1_COH05_02	20	90	40	Exponential	0,8	0,97
S1_COH05_02	S1_COH05_01	20	90	40	Stable	0,77	0,95

(*continued*)

Table 3. (*continued*)

Input Dataset	Validation Dataset	Angle α [°]	a max [m]	a min [m]	Model	R^2	Slope
S1_COH05_02	S1_COH05_01	20	90	40	Spherical	0,85	0,97
S1_COH05_02	S1_COH05_01	20	90	40	Exponential	0,8	0,97

Although the S1 dataset is characterized by moderate spatial resolution (20 × 5m) and intrinsic signal noise, the ordinary kriging technique allowed for the effective estimation of kinematic trends. To demonstrate the filtering capability of the optimized spatial model, prediction maps were generated under two different conditions. The final prediction maps are presented below: the first obtained using the complete S1 dataset without consistency-based segregation (Fig. 6) and the second by applying the consistency filter > 0.5 (Fig. 7).

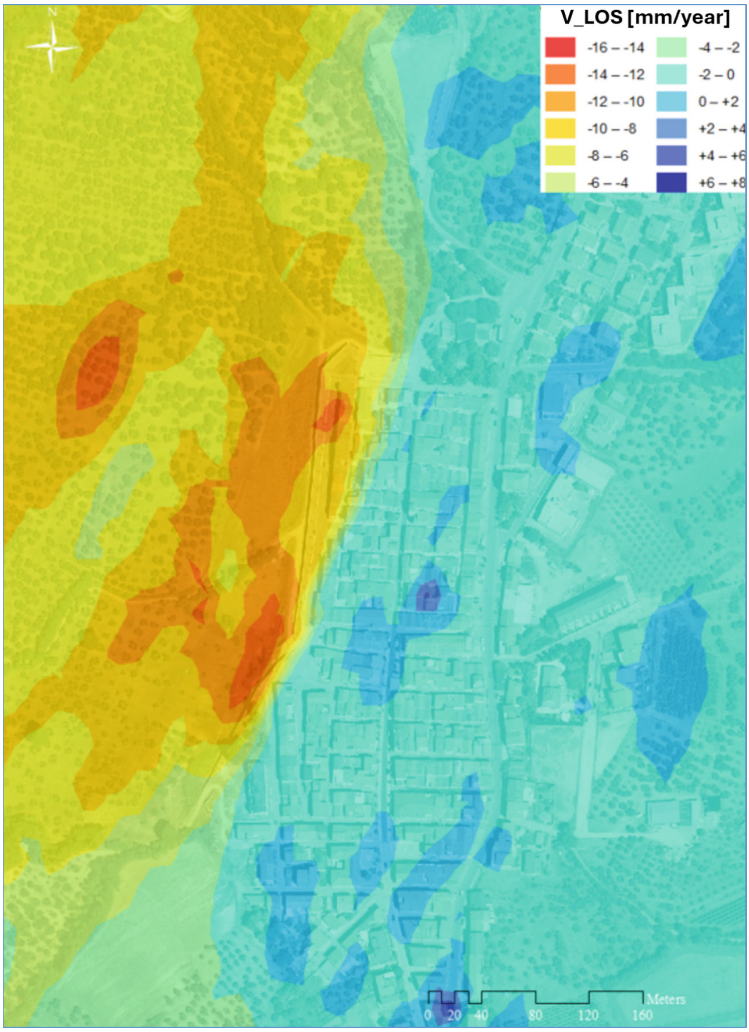

Fig. 6. Continuous V_LOS prediction maps generated via Ordinary Kriging, obtained from the complete S1 dataset without consistency-based segregation

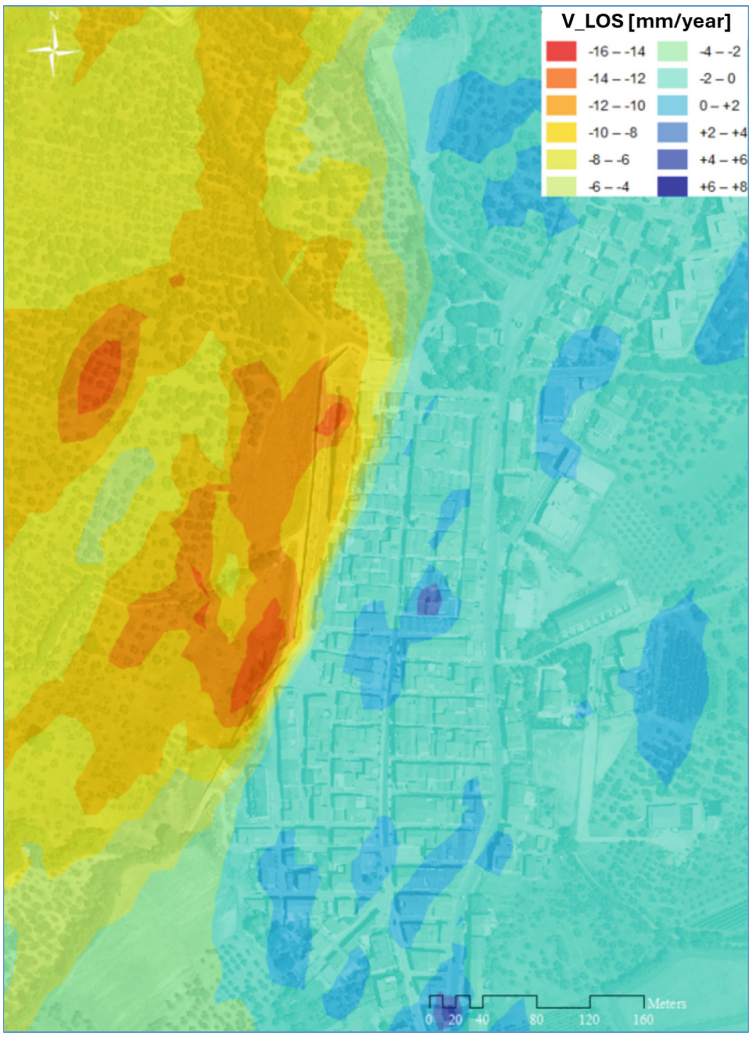

Fig. 7. Continuous V_LOS prediction maps generated via Ordinary Kriging. Obtained from the S1 dataset by applying a coherence filter (COH > 0.5)

5 Conclusions

The present study was developed to delineate a kinematic and spatiotemporal framework of the landslide phenomenon affecting the municipality of Chieuti, by applying a geostatistical approach to geomatic datasets. Although the area has been extensively monitored, retrieving the extent of the unstable urban area and the velocity gradients toward the retaining structure, the discrete nature of MT-InSAR data and the medium resolution of S1 sensors presented a significant methodological challenge: the need to transition from a point-based characterization to a continuous representation of the deformation field.

While the use of geomatic data, particularly satellite data, remains indispensable due to its extensive coverage and historical depth, the true added value of this research lies in having critically addressed the intrinsic nature of the data. The study fully exploited the informational potential of the signal through advanced spatial analysis. The validation process followed a rigorous protocol: starting from data exploration and the definition of parameters for the application of the most appropriate Kriging method, the model developed on S1 data was initially subjected to internal validation, testing its consistency on portions of the original dataset. To strengthen the significance of the analysis and lay the groundwork for future developments, these results could be compared with data from the COSMO-SkyMed constellation; such external validation would further evaluate the solidity of the identified trends.

The originality of this work lies in the transformation of purely numerical and fragmented measurements into descriptive indicators of slope dynamics and, consequently, into predictive capabilities. The map produced is not a static snapshot, but an interpretive synthesis that allows for the hypothesis of future evolutionary trends of the phenomenon. The transition from the measured point to the continuous field enables the identification of acceleration trends and areas of potential instability propagation, providing a solid scientific basis for early warning models and the planning of targeted structural interventions.

Ultimately, this study demonstrates how the integration of geostatistical techniques can overcome the technological constraints of current sensors, serving as an effective decision-support tool.

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Integrating Multi-source Geospatial Datasets in Distributed Hydrological Modelling: A Case Study of the Podoniftis Basin (Athens)

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Abstract. Recent advances in geospatial data availability enable the integration of high-resolution terrain, land use, and soil information within distributed hydrological models. However, many flood assessment workflows still rely on lumped rainfall–runoff approaches, which do not fully exploit the information provided by modern geospatial datasets.

This study presents a distributed hydrological modelling framework applied to the Podoniftis basin (~80 km^2), a highly urbanized catchment in the metropolitan region of Athens, Greece. The modelling approach is based on an adaptation of the grid-based hydrological model DREAM, implemented at a spatial resolution of 10 × 10 m and a time step of 10 min. Multi-source geospatial datasets were processed within a unified GIS workflow to derive terrain parameters, soil hydraulic properties, and distributed model inputs. Design rainfall corresponding to a 100-year return period was generated and transformed into a basin-average hyetograph using an areal reduction factor.

Simulation results show a rapid increase in discharge, with a peak of approximately 658 m^3/s. Time-varying runoff maps are produced throughout the simulation; the map at peak conditions highlights higher runoff in urbanized areas and lower values in semi-natural zones, reflecting the combined influence of topography, land use, and imperviousness.

The study demonstrates how the integration of multi-source geospatial data and distributed modelling can support more reliable flood hazard assessment, providing gridded runoff outputs suitable for coupling with two-dimensional hydrodynamic simulations.

Keywords: Urban flood hazard · Distributed hydrological model · Geospatial data integration

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 93–105, 2026.
https://doi.org/10.1007/978-3-032-30524-4_7

1 Introduction

In a changing environment, the non-stationarity of hydrological series demands robust distributed approaches to assess flood risk [1]. Building on decades of GIS-hydrology integration [2], high-resolution datasets such as DEMs, land cover, and soil data now enable physically consistent and spatially explicit representations of urban catchments.

With the increasing availability of digital terrain data and geospatial processing tools, high-resolution DEMs and geomorphic descriptors are now widely adopted in flood risk studies, showing high effectiveness in detecting flood-prone areas within ephemeral Mediterranean basins [3, 4].

In urban environments, hydrological response is driven by fine-scale heterogeneity [5]. High imperviousness and engineered drainage generate complex runoff patterns that aggregated approaches fail to represent. Here, processes operate at short time scales, making detailed distributed analysis of local terrain and surface properties essential [6].

However, many flood assessment workflows still rely on lumped or semi-empirical methods, such as the Curve Number [7] or unit hydrographs [8]. While computationally efficient, these approaches cannot fully exploit high-resolution geospatial datasets due to their reliance on basin-averaged parameters.

In contrast, distributed grid-based models overcome these limitations by discretizing the basin into fine-resolution cells. This allows for an explicit representation of the spatial variability of hydrological processes, allowing a more realistic description of runoff generation and flow concentration processes at the basin scale [9].

Within this framework, geomatics plays a central role in bridging data acquisition and environmental modelling. The integration of multi-source datasets, such as high-resolution DEMs, land cover, and soil databases, requires robust GIS workflows for harmonization, georeferencing, and parameter derivation. Far from being mere preparatory steps, these operations constitute the structural foundation of distributed hydrological modelling.

This study applies a distributed hydrological framework to the Podoniftis basin, Athens (Greece), using an adapted version of the DREAM model [10]. The model is implemented on a 10 m resolution grid for event-based simulations, driven by a 100-year design storm in accordance with the EU Floods Directive (2007/60/EC) and the Greek Flood Risk Management Plans (FRMP).

Applying distributed models in urban environments calls for careful consideration of the methodological choices involved. The selection of spatial resolution, for instance, reflects a balance between the model's ability to capture terrain variability and the inherent uncertainty of the available datasets. In this context, the distributed hydrological model is intended to provide gridded runoff inputs, while finer-scale urban flow processes can be addressed in subsequent hydrodynamic simulations (e.g., Runoff-On-Grid approaches, [11]). Likewise, the 10-min time step was chosen as a practical compromise: refined enough to represent the fast dynamics of intense events typical of Mediterranean basins, while still ensuring manageable computational effort.

The objective of the present study is to evaluate how a multi-source geomatics workflow can enhance the representation of distributed runoff through a consistent integration of terrain, land use, and soil information within a distributed hydrological model. Particular emphasis is placed on the role of GIS-based preprocessing in ensuring coherent

parameterization and on the ability of the model to generate physically consistent runoff fields. These outputs are intended to support urban flood hazard assessment and to provide suitable inputs for subsequent hydrodynamic modelling.

2 Study Area

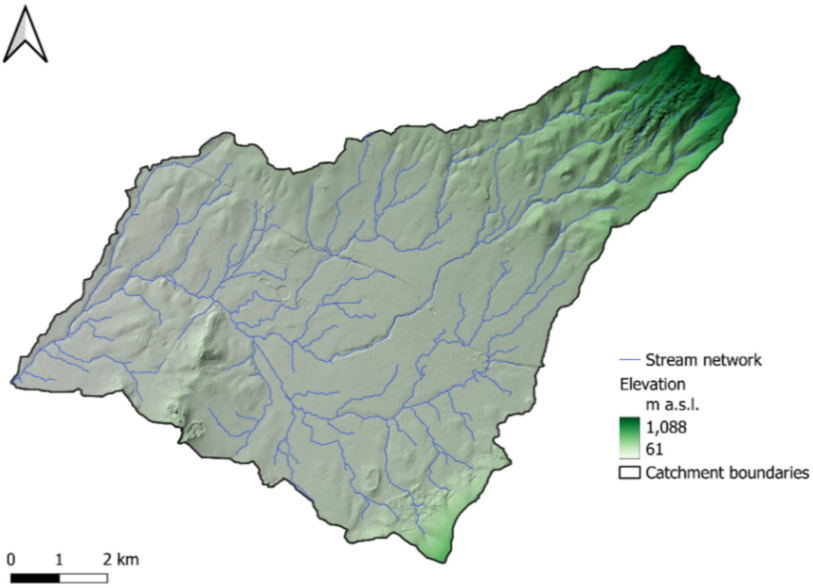

Fig. 1. Digital elevation model of the Podoniftis catchment and its stream network.

The Podoniftis basin is located in the metropolitan region of Athens, Attica, Greece. The total contributing area considered in this study is 77.59 km^2, with the outlet section defined upstream of the confluence with the Kifissos River (Fig. 1).

The basin originates from the Penteli massif and drains southwestward through a densely urbanized environment before joining the Kifissos system. The mean basin slope is approximately 14%, with steep upper slopes that transition to gentler gradients downstream.

A large portion of the catchment is highly urbanized, with impervious surfaces covering more than half of the total area, particularly in the central and downstream sectors. In several reaches, the stream channel is confined within engineered structures, reflecting the strong anthropogenic modification of the drainage network [12]. The basin is therefore characterized by a rapid hydrological response, with a time of concentration of approximately 2.7 h.

3 Geospatial Data and Processing Framework

All geospatial inputs used in this study were processed within a unified GIS-based preprocessing framework. A distinction is made between (i) model parameterization variables, including the Intensity–Duration–Frequency (IDF) curves [13], land cover classes, and soil-related parameters (e.g., root depth, Manning's n) [14, 15], and (ii) spatial input datasets, such as topography (DEM) and soil properties, summarized in Table 1.

Table 1. Spatial input datasets used for the model implementation.

Variable/Grid	Data set	Native resolution	Reference
Land use	CORINE Land Cover 2018	100 m	[16]
Soil type, Percentage of sand, Percentage of clay	LUCAS database	500 m	[17]
Organic matter	LUCAS database	500 m	[18]
Topography	DEM-LSO25	2 m	[19]

A common preprocessing workflow was applied. First, all geospatial inputs were reprojected into a common coordinate reference system (EPSG:2100 - Hellenic Geodetic Reference System 1987). The datasets were then clipped to the predefined domain covering the Podoniftis basin. Subsequently, all layers were resampled and aligned to a common computational grid with a spatial resolution of 10 m. The resampling procedure varied depending on the nature of the dataset (e.g., categorical versus continuous variables) and is described in detail in the following sections.

Vector datasets (e.g., land use) were rasterized, while continuous variables, such as soil properties, were interpolated or aggregated to the model grid. Finally, the processed layers were exported in ASCII raster format (.asc), which constitutes the input format required by the hydrological model.

3.1 Topographic Data and Terrain Processing

Basin delineation and topographic analysis relied on the high-resolution DEM-LSO25, a dataset provided by the National Observatory of Athens and based on the Large Scale Orthophotos (LSO25) project.

The original dataset has a resolution of 2 m, allowing a detailed representation of the terrain morphology of the Podoniftis basin. The DEM was resampled to the model's 10 m computational grid using bilinear interpolation, a method that preserves the continuity of the elevation surface. The 10 m resolution represents a compromise between morphological detail, data uncertainty, and computational efficiency. While finer DEMs capture urban features more accurately, they may introduce artefacts that affect flow representation. A coarser grid reduces these effects and ensures a more robust and physically plausible hydrological response, while remaining suitable for distributed runoff modelling and subsequent hydrodynamic applications.

Prior to hydrological analysis, the DEM was hydrologically conditioned using depression filling to remove spurious pits and ensure the continuity of flow paths. Several terrain derivatives required for the hydrological model were calculated from the DEM, including local slope, flow direction, flow accumulation, and contributing drainage area.

3.2 Land Use Parametrization

Land use information was derived from the CORINE Land Cover 2018 dataset (Level IV). To adapt CORINE classes to the hydrological model structure, the following reclassification was implemented:

1. CORINE classes were first mapped into 17 intermediate categories following the WetSpa extension manual [14] and Hlavčová et al. [15];
2. Each intermediate class was assigned a Manning's roughness coefficient (n) and a root depth (D), according to literature sources;
3. The 17 categories were subsequently aggregated into the five macro-classes of DREAM model (Forest, Grass, Cropland, Bare soil, Impervious areas).

The procedure consisted of associating the CORINE land-cover classes and the root depth and Manning's roughness values in the shapefile. The resulting parameter layers were then rasterized and resampled to the 10 m computational grid using a nearest-neighbor approach to preserve categorical integrity; then, they were exported as ASCII grid files (.asc) for use in the hydrological model.

The Manning coefficient controls overland flow velocity within the kinematic routing component, whereas root depth regulates soil water storage capacity and runoff generation thresholds.

Although CORINE provides consistent land use information at the European scale, its 100 m resolution does not resolve the fine-scale structure of urban environments, including street canyons, small parks, narrow impervious corridors, and roof patterns. For distributed hydrological modelling, this implies that imperviousness is represented at a generalized level, potentially smoothing local contrasts that influence flow connectivity during intense rainfall. Nonetheless, at the catchment scale considered here, CORINE has been successfully used in previous urban hydrology studies and remains adequate for parameterizing roughness and vegetation-related processes [11].

3.3 Soil Data

Soil properties were derived from the LUCAS topsoil database, which provides point measurements of sand and clay fractions as well as organic matter content. In addition, a soil classification layer was used to define the dominant soil types across the basin.

The soil class map was resampled to the model grid using nearest-neighbour interpolation in order to preserve the categorical nature of the data. Continuous soil variables, including sand and clay percentages and organic matter content, were instead interpolated using bilinear interpolation and subsequently resampled to match the 10 m computational grid of the hydrological model. These inputs were then processed through pedotransfer functions [20] to define the soil hydraulic parameters governing infiltration and water storage.

It is important to note that the original resolution of the LUCAS dataset (500 m) is significantly coarser than the 10 m computational grid. As a result, the representation of soil parameters should be interpreted as indicative rather than locally accurate. Urban basins frequently exhibit highly heterogeneous soil conditions, including fill materials, compacted layers, and anthropogenic sealing, which are not captured in continental-scale soil databases. This limitation must be considered when interpreting infiltration dynamics.

3.4 Design Rainfall Modelling

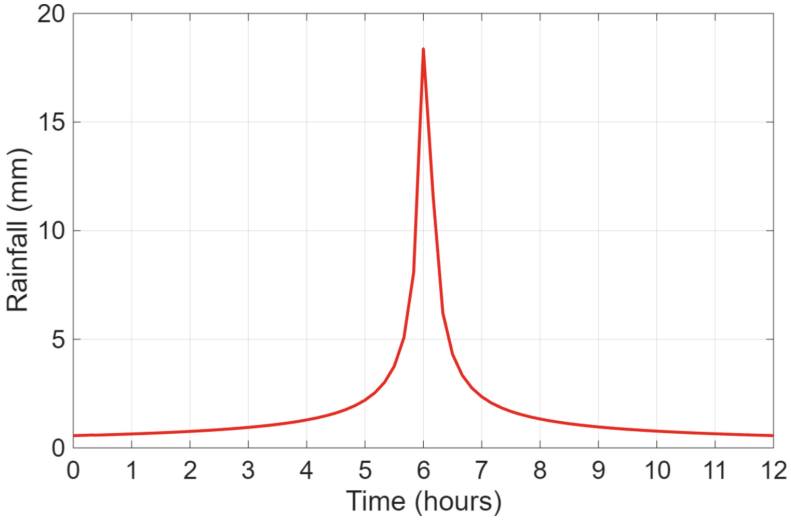

Fig. 2. Design rainfall hyetograph for a 100-year return period.

The selection of rainfall Depth-Duration-Frequency (DDF) formulations is a critical step, as it significantly affects the estimation of peak discharges in distributed modelling [21]. Design rainfall was derived following the procedure adopted in the national flood-risk assessment framework for Greece. The methodology is based on the probabilistic rainfall model proposed by Koutsoyiannis et al. [13], which describes the relationship between rainfall intensity, event duration, and return period.

In this study, the same formulation and parameterization used by Alexopoulos et al. [22] were adopted, where a design storm corresponding to a return period of 100 years was constructed using the Alternating Block Method [23].

Consistently with the reference study, the total storm duration was set to 12 h. However, the catchment considered in the present work differs slightly from that analysed in Alexopoulos et al. [22], as the diversion of the Penteli branch to Rafina was included in the delineation of the drainage area. As a result, the contributing basin area is larger than that adopted in the original study.

The design rainfall was then converted to spatially averaged rainfall over the basin using an areal reduction factor (ARF), computed according to the analytical formulation proposed by Koutsoyiannis and Xanthopoulos [24]. The ARF was calculated using the whole area of 77.59 km2 and applied to the point rainfall intensities to obtain the design hyetograph used in the hydrological simulations (Fig. 2).

4 Methodology

4.1 Model Structure

In this study, a grid-based hydrological model derived from the DREAM framework was used. While the original model operates at daily (D-DREAM) or hourly (H-REAM) scales, the latter was here adapted by discretizing the basin into a 10 × 10 m grid and a 10-min time step. This spatiotemporal resolution captures the high variability and rapid discharge fluctuations of the urbanized Podoniftis catchment while maintaining computational efficiency.

Each grid cell is conceptualized as a storage bucket whose capacity depends on soil type and root depth, and is governed by incoming and outgoing fluxes such as precipitation, evapotranspiration, surface runoff, subsurface flow, and groundwater recharge.

Soil moisture dynamics are described through a water balance equation accounting for precipitation inputs and losses. Vegetation intercepts part of the rainfall before it reaches the soil surface, while the remaining water may be temporarily stored in surface depressions. Effective precipitation is then partitioned into surface runoff and infiltration.

4.2 Initial Soil Moisture Condition

In the absence of discharge records for calibration, initial soil moisture represents the main state variable influencing runoff response under event-based simulation. Observations from streams in the Athens basin indicate that hydrological responses are strongly influenced by episodic high-intensity rainfall events and seasonal variability, with limited influence of persistent wet conditions [25].

In the model, soil water storage at time t is expressed as:

$$S_t = \theta_t * D \tag{1}$$

where D (m) is soil depth and θ_t (mm/m) is the volumetric water content. Rather than being calibrated against observed hydrographs, its initial value was treated as a physically admissible scenario parameter within the range bounded by wilting point (S_{wp}) and the maximum soil water storage capacity (S_{max}).

Considering the typically dry antecedent conditions of Mediterranean environments and the prevalence of event-driven responses, often associated with ephemeral flow regimes, a moderately dry initial state was assumed. Residual soil moisture from previous events and urban contributions was also considered. Specifically, an initial soil moisture equal to 20% of the storage interval between wilting point and field capacity (S_c) was

selected as a representative compromise between dry and partially replenished conditions (Eq. 2):

$$S_t = S_{wp} + \left(S_c - S_{wp}\right) * 0.2 \tag{2}$$

Antecedent soil moisture is known to be a dominant source of uncertainty in Mediterranean basins characterized by short-lived, high-intensity storm events. By assuming low initial soil moisture to avoid artificial pre-saturation, this configuration realistically captures rapid, saturation-driven runoff during intense storms within a basin characterized by shallow soils and limited storage capacity.

In the absence of streamflow observations, adopting a mid-to-low initial water content is physically reasonable, but alternative scenarios (e.g., wetter conditions following prior frontal systems) could substantially alter infiltration dynamics. A future sensitivity analysis could quantify the impact of these assumptions on simulated peak discharge.

4.3 Runoff Generation and Propagation

The model adopts a Dunnian runoff generation scheme based on saturation excess, following Manfreda et al. [10]. Under these conditions, rainfall exceeding the local storage capacity is converted into surface runoff. Subsurface runoff is generated when soil moisture exceeds the maximum storage capacity, and is computed as the corresponding excess. The total runoff is therefore obtained as the sum of surface and subsurface contributions.

Flow travel time is computed in a distributed manner based on local slopes and the drainage network structure, with flow velocities estimated using Manning's equation. Roughness and hydraulic radius are treated as static terrain properties. Following Manfreda et al. [10], a simplified routing scheme based on pure translation of runoff is adopted. While this assumption neglects attenuation and diffusion processes, as well as additional hydraulic complexities related to urban drainage infrastructure, it provides a parsimonious representation of flow routing and is considered appropriate for the present application, which focuses on capturing rapid runoff dynamics in a highly urbanized basin.

Total discharge at the basin outlet is obtained by summing the contributions from all grid cells, each delayed according to its travel time. The resulting hydrograph includes surface runoff, subsurface flow, and baseflow components.

5 Results

The simulated 100-year rainfall event produces a rapid hydrological response, with discharge rising sharply and peaking at 658.32 m^3/s, approximately one hour after the rainfall maximum (Fig. 3). This brief lag time, combined with a quick recession, is closely aligned with the estimated basin time of concentration ($t_c = 2.7$ h). Such timing reflects the fast hydrological response typical of urbanized catchments with limited buffering capacity. The dominance of rapid surface runoff processes is driven by the combined effect of steep upstream slopes and extensive impervious surfaces, which minimize soil storage and lead to a rapid synchronization of runoff contributions at the outlet.

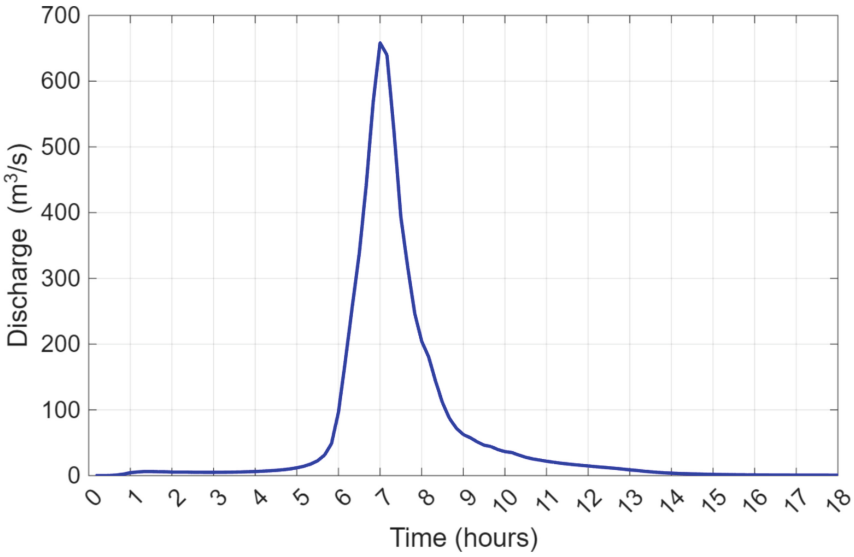

Fig. 3. Simulated hydrograph for a 100-year return period event.

The runoff map at the seventh hour (Fig. 4), corresponding to peak flow conditions, highlights a heterogeneous response across the basin, effectively capturing the transition from upstream areas to the urbanized outlet. Higher runoff depths (up to 8.6 mm) are clearly delineated along the drainage network, where flow accumulation is most prominent. In the downstream sectors, the high runoff values also reflect the impact of extensive impervious surfaces, which inhibit infiltration. Conversely, the fragmented pattern in the semi-natural areas exhibits significantly lower runoff, illustrating the variability in infiltration capacity and topographic control across the domain.

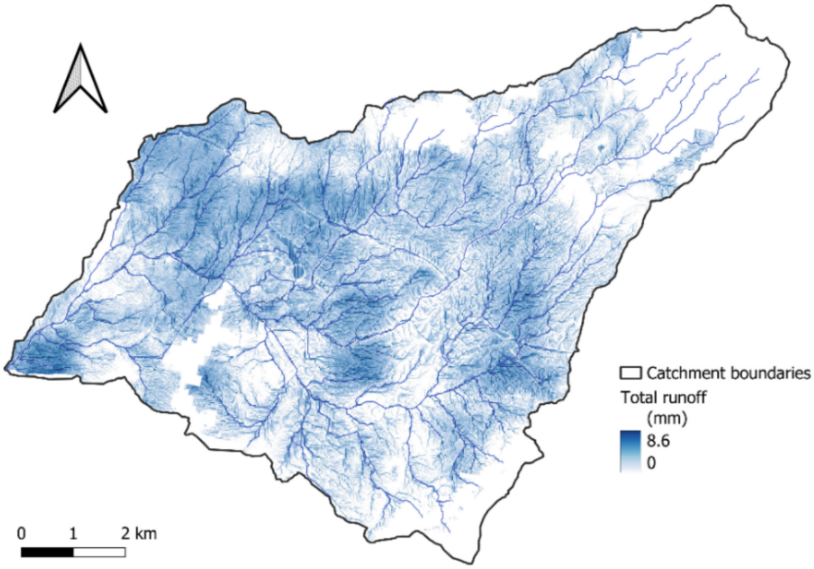

Fig. 4. Total runoff map for the seventh hour of the simulation.

6 Discussion

The grid-based implementation proves suitable for complex peri-urban systems where land use, soil, and topography vary significantly over short distances.

The results highlight three main aspects.

First, integrating multi-source geospatial datasets ensures a process-consistent parameterization, confirming the importance of geomatics-based workflows for urban modelling.

Second, the distributed modelling framework captures localized dynamics often undetected in traditional lumped schemes. The 10-m resolution provides time-varying runoff maps (Fig. 4) essential for street-scale hydraulic coupling and accurate urban flood reconstruction [26].

Third, urban imperviousness strongly accelerates runoff, producing steep rising limbs. While buildings are not explicitly treated as hydraulic obstacles in this study, this simplification can be addressed in subsequent 2D hydraulic simulations [27, 28].

Comparable discharge magnitudes were reported by Alexopoulos et al. [22], who used a 10-m hydraulic model on part of the Podoniftis basin. Their study evaluated several modelling configurations, including simulations with and without buildings represented as flow obstacles, the latter providing a more conservative scenario. Despite differences in modelling frameworks, such as the use of Curve Number approach, the resulting discharge estimates remain consistent with the peak flows obtained in the present study.

Despite the advantages of the distributed framework, several limitations should be acknowledged, mainly related to the level of process representation adopted. The model does not explicitly represent urban drainage infrastructure (e.g., pipes, inlets, culverts), which can significantly influence flow routing in densely built environments. In addition,

surface properties are parameterized in a simplified manner, and the resampling of the 2 m DEM to a 10 m grid smooths micro-topographic features that may affect local flow paths. Soil properties derived from coarse-resolution datasets provide only a generalized representation and do not fully capture the heterogeneity typical of urban environments. Furthermore, the absence of discharge observations prevents model calibration, and the use of a uniform design storm across the domain neglects rainfall variability.

These limitations are consistent with the scope of the present study, which focuses on the integration of multi-source geospatial data and on the generation of distributed runoff fields within a grid-based hydrological framework. In this context, the model is conceived as an intermediate layer, while finer-scale hydraulic processes can be addressed in subsequent hydrodynamic simulations. These aspects should be considered when interpreting the results and represent directions for future refinement and model coupling.

7 Conclusions

This study demonstrated the applicability of a fully distributed hydrological model to a highly urbanized Mediterranean basin in Athens. The grid-based implementation (10 × 10 m) enabled explicit representation of topographic controls and land-use heterogeneity, which govern runoff generation under extreme design rainfall.

Unlike traditional lumped approaches, this distributed framework identifies specific sub-catchment source areas and localized runoff concentrations that would be smoothed out by basin-wide averaging. Furthermore, it allows for a physically realistic parameterization of surface–subsurface interactions and antecedent soil moisture, which are known to significantly influence hydrograph shape and peak timing [11]. By accounting for soil water redistribution, this formulation accurately simulates saturation-driven processes and delayed subsurface contributions, which can generate runoff even after the rainfall event ends.

The resulting gridded, time-varying runoff fields are particularly suitable for coupling with 2D hydrodynamic models, supporting improved assessment of pluvial flood hazards in complex urban environments. Overall, the approach represents a robust and physically consistent tool for urban flood hazard assessment in Mediterranean catchments.

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Integrating Computer Vision Models into SfM Photogrammetry: An Automated Pipeline for Occlusion Mask Generation

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Abstract. This paper presents an automated and scalable pipeline for occlusion mask generation in Structure-from-Motion (SfM) photogrammetric workflows, addressing a well-known limitation related to dynamic elements, such as pedestrians, vehicles, and other transient objects, that introduce geometric artifacts and reduce the metric reliability of 3D reconstructions. To overcome the inefficiencies and subjectivity of manual masking, the proposed approach integrates pre-trained computer vision models into the preprocessing stage, enabling a reproducible solution that does not require domain-specific training data. The pipeline is structured into three modular components. The first module performs automated image quality assessment based on sharpness, exposure, and resolution, ensuring dataset consistency and reducing error propagation during feature extraction. The second module implements a detect-then-segment strategy, combining instance-level detection via YOLOv8-seg with optional pixel-wise refinement using the Segment Anything Model (SAM2), improving segmentation accuracy in high-resolution and close-range scenarios. The third module handles automatic mask generation and formatting for compatibility with major SfM platforms, including morphology-based post-processing to enhance robustness. A proof-of-concept implementation was developed in Python using exclusively pre-trained models, allowing immediate applicability while minimizing computational and operational overhead. Experimental results highlight the efficiency of the automated masking process, while maintaining improved or comparable reconstruction quality. The approach proves particularly effective in architectural and cultural heritage surveys conducted in complex and uncontrolled environments.

Keywords: Structure-from-Motion · Photogrammetric Masking · Computer Vision

1 Introduction

Short-range photogrammetry and the Structure-from-Motion (SfM) technique have established themselves as standard practices in architectural surveying, cultural heritage documentation, urban mapping and the inspection of civil infrastructure. Continuous improvements in photogrammetric software, combined with the growing availability of

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2026
O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 106–122, 2026.
https://doi.org/10.1007/978-3-032-30524-4_8

high-resolution consumer cameras and Unmanned Aerial Vehicles (UAVs), have drastically reduced the technical barriers to producing georeferenced point clouds and accurate textured mesh models [1].

Despite these advances, the quality of SfM-based reconstructions depends critically on the composition and consistency of the photographic dataset. One of the most persistent sources of error in photogrammetric pipelines is the presence of non-stationary objects (such as pedestrians, cyclists, parked or moving vehicles, and other transient elements) within the scene at the time of acquisition. Such elements introduce inconsistencies during the feature matching phase, as the same physical point is projected onto different positions in the overlapping images, violating the fundamental assumption of scene rigidity upon which block-based adjustment relies [2, 7].

The conventional solution to this problem involves manually drawing occlusion masks for each image, designating the pixels occupied by unwanted elements so that they are excluded from feature extraction and matching. Although effective, manual masking is time-consuming, operator-dependent and inherently non-scalable.

In recent years, several studies have highlighted how these limitations can be overcome by integrating automatic segmentation techniques into photogrammetric pipelines. In particular, approaches based on semantic segmentation allow unwanted elements in images to be automatically isolated, significantly reducing the need for human intervention [3]. Recent advances in deep learning, particularly in the fields of computer vision and object detection, offer a concrete opportunity to automate this pre-processing stage. Models such as YOLO (You Only Look Once)[4], Mask R-CNN [5] and the Segment Anything Model (SAM) [6] have demonstrated remarkable performance across a wide range of scene categories without the need for domain-specific retraining, making them immediately applicable in photogrammetric workflows.

This article proposes an automated and modular pipeline for the pre-processing of photogrammetric data in Structure from Motion (SfM) contexts, based on the integration of state-of-the-art pre-trained computer vision models. The aim is to reduce reliance on manual intervention during dataset preparation, whilst improving the scalability, reproducibility and robustness of the process. In this context, the work introduces a domain-independent pipeline for the automatic generation of occlusion masks, designed to be applicable to heterogeneous photogrammetric datasets. Upstream of this process, an automatic image quality assessment module is integrated, aimed at ensuring the consistency of the dataset and reducing the propagation of errors in subsequent stages. The pipeline also adopts a hierarchical ‘detect-then-segment’ strategy, which allows for a balance between computational efficiency and accuracy in defining the contours of segmented objects. Finally, a mask export module compatible with the main SfM software packages is implemented, facilitating the integration of the methodology into established operational workflows. Experimental validation is conducted across diverse scenarios to assess the method’s performance under significantly different operational conditions.

2 State of the Art

The impact of non-stationary elements on the quality of SfM reconstruction is widely recognised in the literature on computer vision and photogrammetry, which typically assumes static scenarios and highlights the sensitivity of SfM pipelines to inconsistent matches. Hartley and Zisserman [7] provide a fundamental analysis of the assumption of rigidity in multi-view geometry. Lowe [8], in his in-depth work on SIFT, recognised the vulnerability of feature matching to scene dynamics. More recent contributions have quantified the degradation in point cloud density and accuracy caused by pedestrian occlusions in urban scenarios [9], confirming that exclusion strategies based on masks remain the most effective countermeasure.

In the field of cultural heritage documentation, this issue is particularly evident: many monuments, urban contexts and archaeological sites must necessarily be surveyed during public opening hours, making it almost impossible to obtain occlusion-free acquisitions [10, 11]. Several authors have proposed dedicated acquisition protocols, such as multi-time-lapse surveys or controlled partial closures, but these approaches impose logistical constraints that are often impractical in real-world applications [12–14].

The application of convolutional neural networks (CNNs) to photogrammetric pre-processing has gained momentum following the success of deep learning in image recognition tasks. The U-Net architecture, introduced by Olaf Ronneberger et al. [15], represents one of the benchmark models for semantic segmentation thanks to its encoder–decoder structure, which allows for the combination of contextual information and high-resolution spatial details. Although originally developed for biomedical applications, this architecture has subsequently been successfully adapted to various contexts of urban and architectural analysis. In particular, variants and implementations derived from U-Net have been used for the semantic parsing of building façades, the extraction of road networks and the mapping of vegetation from aerial images and remote sensing data [16], demonstrating high effectiveness in scenarios characterised by high geometric complexity and radiometric variability.

These developments form part of a broader evolutionary trajectory of semantic segmentation methods, the conceptual foundations of which were laid by the Fully Convolutional Networks (FCN) introduced by Long, Shelhamer and Darrell [17]. FCNs defined, for the first time, an end-to-end paradigm for dense prediction, replacing traditional patch-based approaches with fully convolutional models capable of operating directly on the entire image. This shift has enabled not only a significant improvement in computational efficiency but also greater spatial consistency in predictions, laying the foundations for the development of subsequent architectures, including U-Net itself, which extends these principles by introducing more effective mechanisms for spatial information retrieval and fine-grained localisation.

Within this methodological framework, alongside dense prediction-based semantic segmentation models, instance segmentation methods are employed, which produce distinct masks for each object rather than assigning class labels at the pixel level. This formulation is particularly well-suited to scenarios characterised by the presence of non-stationary elements, as it allows for the identification and isolation of individual dynamic objects to be excluded in subsequent processing stages. In this vein, Kaiming He et al. [5] introduced Mask R-CNN, extending the previous architecture by adding a parallel

branch dedicated to mask prediction, thereby enabling simultaneous instance-level object localisation and segmentation.

Subsequently, the evolution of one-stage detectors led to a significant reduction in computational cost, making such approaches easier to integrate into operational pipelines. In particular, the YOLO family [4] has progressively improved the trade-off between accuracy and efficiency, culminating in recent models such as YOLOv8 [18], capable of achieving state-of-the-art performance on standard benchmarks such as MS COCO [19], whilst maintaining compatibility with mid-range hardware. The YOLOv8-seg variant further extends these capabilities by natively introducing instance segmentation, thus offering an effective and scalable tool for the automatic identification of unwanted objects within complex photogrammetric datasets.

3 Methodology

The proposed methodology addresses the presence of dynamic elements in photogrammetric datasets through an automated preprocessing pipeline, designed to be modular, reproducible, and independent of the application domain. The approach is based on the principle that the quality of three-dimensional reconstruction critically depends on the consistency of the input dataset: systematically intervening in the preprocessing stage, prior to feature extraction and image alignment, allows the root causes of degradation to be eliminated without modifying the internal parameters of SfM software.

The proposed pipeline is structured into three logically independent modules, connected sequentially as illustrated in Fig. 1. The modular architecture facilitates component replacement and independent validation, allowing users to activate only the stages relevant to the specific characteristics of their dataset.

3.1 Module 1: Automatic Image Quality Assessment

Before the masking process begins, the integrity of the dataset is verified using an automated Image Quality Assessment (IQA) module. This preliminary stage serves a dual purpose: it filters out images that are unlikely to contribute useful information to the reconstruction, and flags potential issues that could compromise the reliability of feature extraction in subsequent stages.

Three complementary metrics are calculated for each image. The sharpness score is estimated using the variance of the Laplacian operator applied to the luminance channel, effectively removing blurred or out-of-focus images. The exposure metric is derived from the normalised histogram of the luminance channel, assessing the proportion of pixels in shadow areas (< 30) and highlight areas (> 225). Finally, adequate resolution is verified by comparing the image dimensions with a configurable minimum threshold. The three scores are aggregated into a composite quality index via weighted linear combination, and the module produces a report in JSON format.

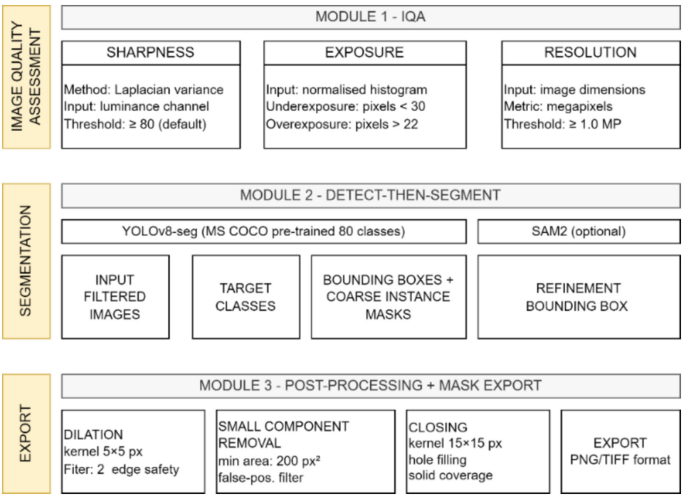

Fig. 1. Proposed pipeline architecture

3.2 Module 2: Detect-Then-Segment

The central masking module implements a two-stage strategy designed to balance inference speed, segmentation accuracy and generalisability across different acquisition scenarios.

In the first stage, each image is processed by a YOLOv8-seg model pre-trained on the MS COCO dataset, which comprises 80 object categories including the most common classes of dynamic elements: person, bicycle, car, motorcycle, bus, truck and road infrastructure. The model simultaneously produces bounding boxes, classification scores and coarse instance masks. Only objects belonging to a configurable set of categories are retained; a confidence threshold (default: 0.45) suppresses low-confidence detections.

In the second stage, refinement is implemented using SAM2. This implementation is justified by the fact that in short-range architectural surveys or high-resolution acquisitions, where precise edge delineation is critical, the coarse masks produced by Stage A may not be sufficiently accurate. The bounding boxes produced by YOLOv8-seg are used as geometric prompts to guide the SAM2 mask decoder, which utilises a hierarchical encoder based on the Hiera architecture [20] to generate high-fidelity edges. Refinement is recommended for datasets with resolutions exceeding 20 megapixels or when the survey object features fine structural elements in the vicinity of dynamic occluders.

3.3 Module 3: Mask Generation and Export

Binary instance masks are aggregated into occlusion masks for each image and post-processed prior to export. Three morphological operations are applied in sequence: a dilation with a configurable kernel (default: 5×5 pixels) expands the edges to account for segmentation uncertainties; disconnected components below an area threshold (default: 200 pixels) are removed as probable false positives; internal gaps are filled to ensure solid coverage of the occluded area.

The resulting masks are exported in the formats required by the three target SfM platforms. For Agisoft Metashape: 8-bit PNG with the occluded region in white, accompanied by a Python script for batch import via API. For OpenDroneMap: co-located format with an underscore suffix naming convention. For RealityCapture: TIFF images following the platform's mask channel convention.

4 Experimental Setup

The pipeline is developed in Python[1] (version 3.10) and is structured as a command-line application, allowing the entire pipeline to be configured via YAML files without the need to modify the source code, thereby facilitating the reproducibility of experiments. The computer vision operations rely exclusively on pre-trained models, whose weights are automatically retrieved from official repositories, eliminating the need for application-domain-specific training phases. In particular, the system utilises established open-source libraries: Ultralytics for inference with YOLOv8-seg [18], the official Segment Anything Model 2 (SAM2) repository [21], OpenCV for image processing and morphological transformations, and NumPy for the efficient manipulation of numerical data structures. Image inference is performed using the YOLOv8x-seg variant to maximise recall on small or partially occluded objects.

5 Results

The evaluation of the proposed pipeline focuses on its effectiveness within the photogrammetric workflow, where the primary objective is to ensure the functional suitability of the generated masks for downstream 3D reconstruction. Within this context, mask quality was assessed through a composite internal metric that integrates image sharpness response and spatial mask consistency, providing a reproducible and operator-independent measure of reliability across the dataset.

The results highlight the robustness of the approach in handling heterogeneous acquisition conditions, demonstrating consistent mask generation and stable performance across different scenarios. This evaluation framework allows for a comprehensive assessment of the pipeline's effectiveness, directly aligned with its intended application in photogrammetric preprocessing.

5.1 Dataset a - Survey in an Urbanised Area.

Dataset A consists of 91 images captured using a CANON 1100D DSLR camera and a DJI MINI 3 drone. The images were captured in conditions of diffused natural light and a predominantly cloudy sky, during daylight hours with varying numbers of pedestrians and vehicles present. The Image Quality Assessment (IQA) report, Fig. 2, shows a distribution of scores with a strong concentration towards high values, with an average of 0.93 and all samples above the acceptable quality threshold (0.5). In total, 91 images were

[1] The developed application is available online: https://github.com/3DMAULabITA/CV_SfM_Mask.

deemed suitable, with no exclusions, indicating generally favourable acquisition conditions and good qualitative consistency across the dataset. Analysis of the correlation matrix highlights the predominant role of exposure conditions in determining overall quality. In particular, the composite score shows a strong negative correlation with overexposure (−0.85) and a significant negative correlation with underexposure (−0.69), confirming that deviations from optimal exposure represent the main factor contributing to image degradation. Conversely, sharpness contributes positively, albeit to a lesser extent (0.16). One interesting finding is the negative correlation between sharpness and the number of megapixels (−0.68), which suggests that higher-resolution images do not automatically translate into higher perceived quality, likely due to effects related to noise, compression or depth of field. The other correlations are generally moderate or weak, indicating that the metrics used complement one another well.

Overall, the results confirm a high-quality dataset, in which the main critical factors are attributable to exposure conditions. This level of quality provides a solid foundation for the subsequent stages of the pipeline, helping to improve the reliability of the detection and segmentation processes.

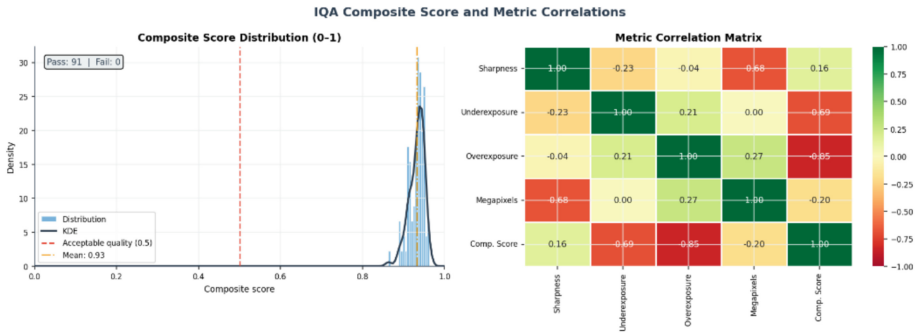

Fig. 2. IQA report on dataset A

Completion of the pipelines results in a summary report consolidating the results of the identification and segmentation phase. As shown in Fig. 3, the number of objects detected per image exhibits a heterogeneous distribution, averaging 9, reflecting the variability of the acquisition contexts. The class distribution is dominated by ‘car’, followed by ‘people’ and ‘truck’, in line with typical urban scenarios. Processing times exhibit an asymmetric distribution, with a median of approximately 514 ms, with higher values associated with aerial images, which feature more complex scenarios. Finally, the average confidence per class, ranging from 0.5 to 0.7, indicates robust overall performance, with greater stability for the more frequent classes.

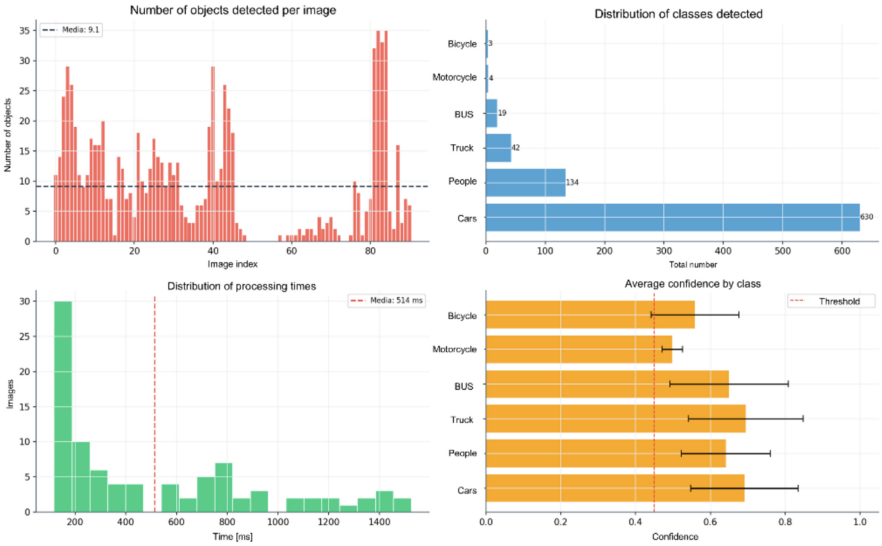

Fig. 3. Results of the classification process on dataset A

5.2 Dataset B - Survey in Rural Area.

Dataset B includes 67 images captured using a DJI MINI 3 drone during an aerial photogrammetric survey carried out during daylight hours. The area surveyed is characterised by the predominant presence of vegetation and, in some photographs, of vehicles and people. The IQA analysis reveals a distribution of values with a marked concentration towards the upper end of the range, with a mean of 0.97 and all samples above the acceptable quality threshold (0.5). In particular, the analysed dataset is fully compliant with the defined quality criteria, indicating generally favourable acquisition conditions.

Analysis of the correlation matrix between the quality metrics provides further insights. The composite score shows a significant negative correlation with the underexposure (-0.82) and overexposure (-0.73) metrics, highlighting that lighting conditions are the main limiting factor for overall quality. Conversely, sharpness shows a positive, albeit moderate, correlation (0.17), suggesting a less decisive but still significant contribution to the final assessment. The correlations between the basic metrics are generally modest, indicating good complementarity between the indicators used and limited informational redundancy. In particular, the weak correlation between sharpness and exposure confirms that these aspects capture different properties of the image (Fig. 4).

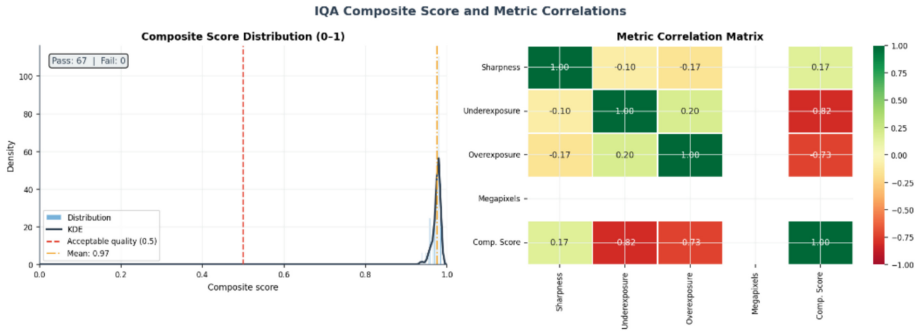

Fig. 4. IQA report on dataset B

Overall, the results indicate a high-quality dataset, with limited exposure-related issues and good general homogeneity. This ensures favourable conditions for the subsequent stages of the pipeline, reducing the risk of errors in detection and segmentation and contributing to the overall stability of the process. The number of objects detected per image shows a relatively narrow distribution (mean ≈ 2.8), indicating a lower average complexity of the scenes compared to other analysed scenarios, whilst maintaining a certain degree of variability between images (Fig. 5).

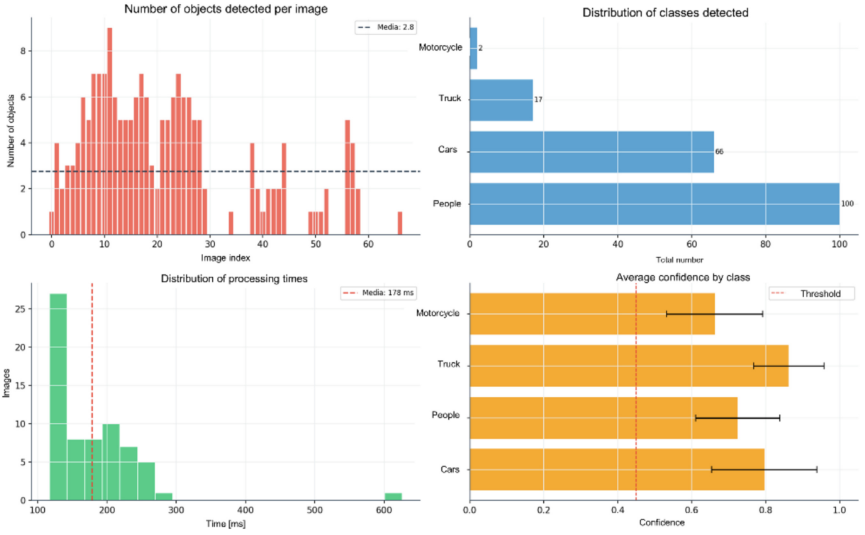

Fig. 5. Results of the classification process of dataset B

The class distribution shows a predominance of the ‘people’ class, followed by ‘car’ and ‘truck’, whilst the less frequent categories are marginal. From a computational perspective, processing times show a concentrated distribution, with a median of approximately 178 ms per image, suggesting a lower computational load and greater consistency in performance compared to more complex scenarios. Any higher values are associated

with images containing a greater number of objects or greater visual variability. Analysis of the average class confidence reveals robust overall performance, with values generally ranging between approximately 0.6 and 0.8. The most frequently occurring classes, such as 'people' and 'car', show good stability in predictions, whilst the less frequent classes exhibit greater dispersion. Overall, the results confirm the pipeline's effectiveness even in scenarios with low object density, with reduced processing times and good levels of accuracy.

5.3 Dataset C - Indoor Survey

Dataset C comprises 124 images captured inside the Piccinni Theatre in Bari, under conditions of both spot and diffused artificial lighting, with the occasional presence of people moving about.

The IQA phase reveals a significant variation in quality scores, with an average of 0.58 and a substantial proportion of images falling below the acceptable quality threshold (0.5). In particular, only 30 images are deemed suitable, whilst 94 are excluded, indicating marked variability in acquisition conditions and an overall lower quality compared to the previously analysed scenarios. This phenomenon is attributable to the more unfavourable lighting conditions caused by the presence of point light sources, which necessitates longer exposure times, affecting image stability.

Analysis of the correlation matrix highlights the dominant role of sharpness in determining the composite score, with a strongly positive correlation (0.86). This suggests that the perceived quality of the dataset is strongly influenced by the presence of sharp images, whilst degradation due to blur or loss of detail represents the main limiting factor. In contrast, the under-exposure and over-exposure metrics show weaker negative correlations (-0.46 and -0.20 respectively), indicating a secondary impact compared to sharpness.

The correlations between the basic metrics are generally weak, confirming their complementary nature. In particular, the weak correlation between sharpness and exposure suggests that quality issues stem from distinct factors that are not necessarily concurrent. Overall, the dataset presents significant issues, mainly related to image quality in terms of definition and detail. This highlights the need for a more selective filtering or pre-processing stage, in order to ensure suitable conditions for the subsequent stages of the pipeline and improve the reliability of detection and segmentation results.

In subsequent processing stages, the experiment resulted in a very low number of detected objects per image (average ≈ 0.3), highlighting scenarios with extremely low object density and a prevalence of images with few or no detectable elements. The class distribution indeed shows the exclusive presence of the 'people' class, confirming the highly selective nature of the analysed dataset. From a computational perspective, processing times are heavily concentrated at low values, with a median of approximately 132 ms per image, indicating high efficiency of the pipeline under low-complexity conditions (Figs. 6 and 7).

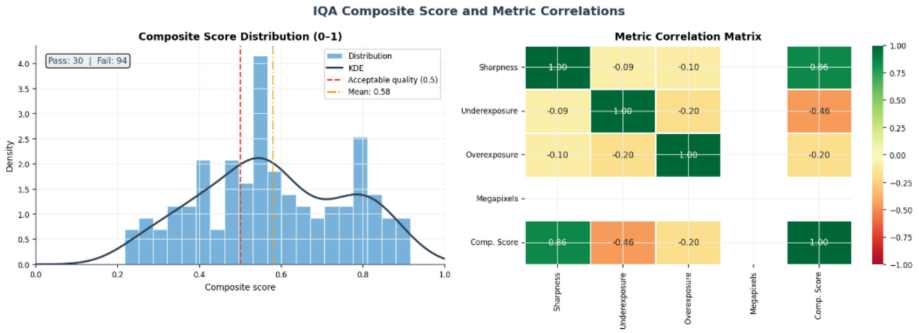

Fig. 6. IQA report on dataset C

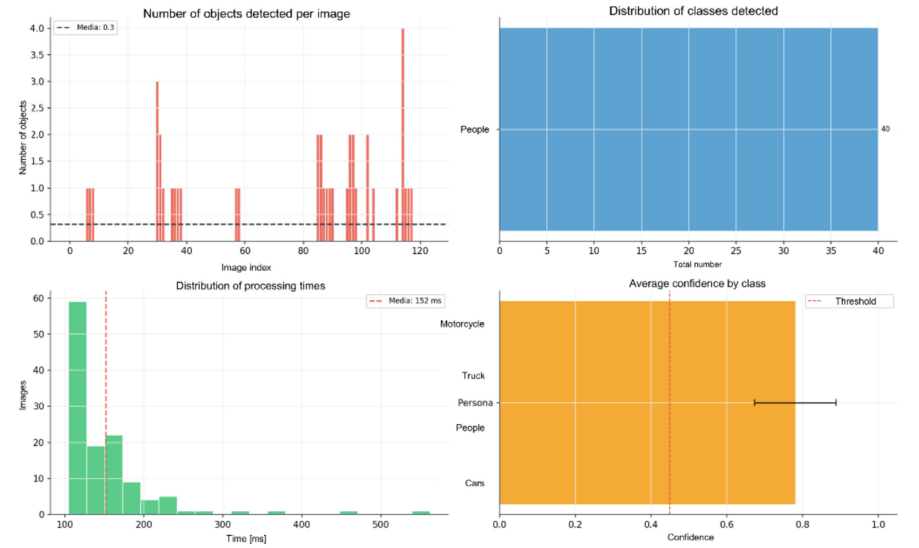

Fig. 7. Results of the classification process of dataset C

The few instances of longer processing times are attributable to isolated cases with a higher computational load. Analysis of the average confidence score reveals high values (≈ 0.8), suggesting good reliability of predictions even in the presence of a limited number of objects. Overall, the results confirm that the pipeline maintains efficient and stable performance even in extremely simple and sparsely populated scenarios.

6 Discussion

The results confirm that pre-trained deep learning models can be effectively reused for photogrammetric pre-processing without domain-specific retraining, in line with the growing body of literature on the transferability of models trained on COCO to architectural and urban scenes [18]. The two-stage 'detect-then-segment' strategy proves robust under different acquisition conditions. A comparison of the different experimental contexts highlights how the pipeline exhibits complementary performance characteristics, effectively adapting to the specificities of the analysed scenarios (Fig. 8).

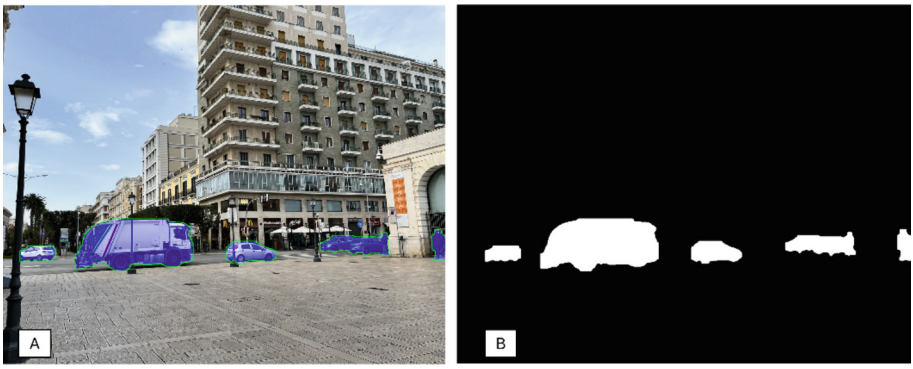

Fig. 8. Results of masking process in terrestrial surveying in an urban context. A: classification and segmentation; B: masking results

In an urban environment, the main benefit lies in the greater cleanliness of the SfM and the reduction of outliers generated by the presence of pedestrian and vehicular traffic, which represent one of the main sources of inconsistency in SfM pipelines. In rural settings, the most significant contribution lies in the automatic exclusion of temporary man-made elements, such as operators or equipment present during acquisition, thereby improving the geometric consistency of the reconstructed model.

In indoor settings, however, the contribution of the Image Quality Assessment (IQA) phase is predominant, enabling preliminary image filtering that ensures optimal conditions for subsequent processing stages. In particular, the selection of images characterised by adequate sharpness and correct exposure conditions helps to reduce the propagation of errors during the matching and reconstruction phases, increasing the overall stability of the pipeline.

Overall, these results confirm the versatility of the proposed approach, which allows for addressing different challenges, related both to the presence of dynamic objects and to the intrinsic quality of the images, while maintaining an effective balance between robustness, accuracy and operational scalability.

This differentiation suggests that the optimal configuration of parameters, and in particular the selection of COCO categories to be masked and the confidence threshold, should always be adapted to the specific acquisition context, so as to serve the purposes of the processing. This scalability highlights the experimental potential of this

configuration: operators can adjust confidence thresholds, category filters and morphological parameters to adapt to the characteristics of their specific survey context. The platform-independent export module reduces the integration burden, making the pipeline immediately usable within established photogrammetric workflows (Figs. 9 and 10).

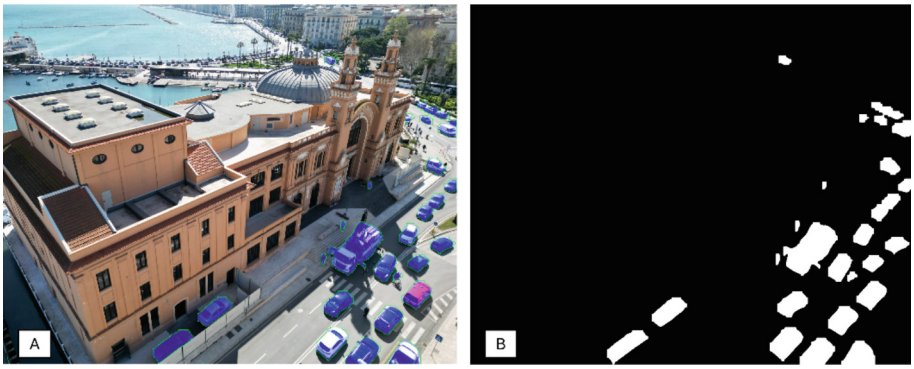

Fig. 9. Results of masking process in urban aerial surveying. A: classification and segmentation; B: masking results



Fig. 10. Example of masking process in rural aerial surveying. A: classification and segmentation; B: masking results

Some limitations warrant consideration. Firstly, performance degrades in the presence of dynamic objects with severe overlaps, such as dense crowds where individual silhouettes are indistinguishable to the detector. Secondly, the integration of SAM2 for mask refinement introduces a significant computational overhead, increasing processing time by approximately four times compared to the use of YOLOv8 alone. Furthermore,

the current approach does not explicitly distinguish between static and dynamic vegetation, as COCO-trained models lack this semantic differentiation. As a result, additional filtering strategies, such as optical flow analysis, are required in rural contexts to effectively identify and exclude only truly dynamic elements (Figs. 11 and 12).

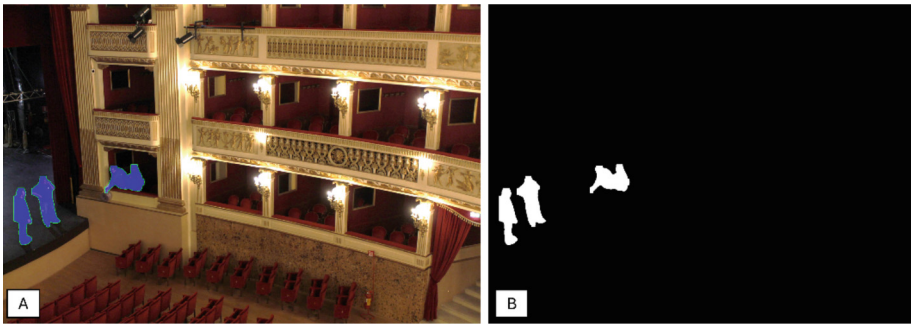

Fig. 11. Result of the masking process in indoor survey. Ref. A: classification and segmentation; Ref. B: masking results



Fig. 12. Result of the masking process in indoor survey. Ref. A: classification and segmentation; Ref. B: masking results

7 Conclusion

This research presents a modular and scalable pipeline for the automated generation of occlusion masks in SfM photogrammetric workflows. By integrating YOLOv8-seg for instance detection and SAM2 for edge refinement into a unified pre-processing framework, the proposed approach demonstrates consistent and reproducible mask generation across heterogeneous acquisition conditions.

Experimental validation on three distinct datasets demonstrates reliable and sufficient metric accuracy, which is scalable and configurable according to the survey's objectives and operational context. These results establish automated mask generation as a mature and practically adoptable component in modern photogrammetric practice. Future prospects for this work lie in the increasingly close integration of digital surveying techniques and advanced computer vision models, with the aim of making

photogrammetric pipelines more autonomous, robust and adaptable to complex operational contexts. In this direction, an initial development concerns the extension of the approach to sequential datasets, exploiting the temporal consistency between images to improve the stability of the masks and the geometric consistency of the reconstructions, particularly in the presence of occlusions and dynamic elements.

A comparative experiment was conducted to assess the effect of the automatically generated masks on the SfM reconstruction process. Each of the three datasets was processed twice under identical parameter configurations: once without masks (baseline) and once with the occlusion masks generated by the proposed pipeline (masked). Seven indicators were extracted from the processing reports to characterise the reconstruction quality. Relative variations are computed as $\Delta\ (\%) = (\text{Masked} - \text{Baseline})/\text{Baseline} \times 100$; the sign does not imply a directional judgment, which depends on the nature of the specific metric (Fig. 13).

	DATASET A			DATASET B			DATASET C		
	baseline	masked	Δ	baseline	masked	Δ	baseline	masked	Δ
Tie Points	162.977	163264	0,18	131093	132983	1,44	175013	176030	0,58
Projections	496235	499142	0,59	400391	401021	0,16	501009	501934	0,18
RMS reprojection error (pix)	0,876	0,794	-9,36	0,93	0,891	-4,19	0,894	0,801	-10,40
Mean key point size (pix)	4115	4101	-0,34	4012	4002	-0,25	4093	4090	-0,07
Avg. tie point multiplicity	2977	2998	0,71	2830	2895	2,30	3014	3028	0,46
Dense cloud points	39.435.132	38.770.471	-1,69	27.401.954	26.901.921	-1,82	40.585.444	39.985.019	-1,48
Total processing time (min)	38	29	-23,68	23	19	-17,39	46	41	-10,87

Fig. 13. Comparison of SfM reconstruction metrics across the three datasets, with and without occlusion masks generated by the proposed pipeline.

The results indicate a measurable, though numerically modest, improvement in the geometric quality of the SfM reconstruction across all three datasets. The RMS reprojection error decreases consistently in the masked configuration (Dataset A: $-$ 0.57%; Dataset B: $-$ 0.75%; Dataset C: $-$ 0.92%), confirming that the exclusion of dynamic elements prior to feature matching reduces the number of inconsistent correspondences propagated into the bundle adjustment stage. The simultaneous increase in tie point multiplicity (most evident for Dataset B, + 2.30%) indicates that the surviving correspondences are observed by a larger number of cameras, and therefore correspond to more stable scene features. The reduction in dense cloud points (between $-$ 1.48% and $-$ 1.82%) reflects the targeted exclusion of points associated with transient elements that would otherwise have been reconstructed as geometric noise within the static scene. The consistency of these effects across three heterogeneous acquisition contexts supports the interpretation that the pipeline acts predictably and proportionally to the actual presence of dynamic content. Total processing time remains substantially unchanged across configurations, confirming that the geometric benefits of masking are obtained without significant computational overhead.

A further area of research concerns the integration of spatio-temporal and semantic information for more effective discrimination between permanent and transient components of the scene, with particular attention to natural and rural contexts, where the distinction between static and dynamic vegetation remains an unresolved challenge. In parallel, optimising the pipeline in terms of portability and scalability will enable the

application of the proposed techniques to be extended to the acquisition phase as well, fostering a more interactive and adaptive approach to surveying.

Finally, extending the validation protocol to broader architectural and geographical contexts will allow us to assess the generalisability of the method and its impact on the quality of digital representation, in terms of geometric accuracy, completeness and the cleanliness of 3D models. In this scenario, the integration of automatic segmentation and photogrammetric surveying represents a key step towards increasingly intelligent acquisition and modelling systems, capable of effectively supporting the documentation, analysis and management of built heritage and the landscape.

8 Disclosure of Interests.

The author has no competing interests to declare that are relevant to the content of this article.

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Desertification in Italy: Legal Responses Among EU Influence, National Regulation and Differentiated Regionalism

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Abstract. The article examines the desertification within the Italian legal order on the background of international law, European Union law and domestic implementation, with a specific focus on the southern regions of Apulia and Sicily. The phenomenon is not governed by a single coherent body of rules, but through a fragmented set of legal instruments crossing soil protection, water governance, spatial planning, agricultural policies and climate adaptation. The analysis combines a multi-level legal-institutional approach with the examination of planning tools, programming documents and financial instruments, in order to assess how far international and EU guidance has been translated into effective measures at national and regional levels. Particular attention is devoted to territorial asymmetries between North and South Italy where formal unity of the legal framework coexists with differentiated implementation capacities and uneven use of available resources. The case studies of Apulia and Sicily show two distinct regional patterns: integration of desertification into broader environmental southern regions and landscape planning, on the one hand, and the adoption of an explicit regional strategy backed by dedicated cartography and projects, on the other. The article further considers the growing relevance of recent EU developments, especially Directive (EU) 2025/2360 on soil monitoring and resilience and Regulation (EU) 2024/1991 on nature restoration, which may strengthen the binding dimension of desertification-related obligations. In this perspective, desertification emerges as a advantageous point of view to understand the relationship among EU influence, national regulation and differentiated regionalism in contemporary environmental law.

Keywords: Desertification · Italy · Italian Region · European Union Law Environment

1 Introduction

The phenomenon of desertification represents a growing environmental threat for Italy, most severe in southern regions, where soil degradation processes affect a significant share of the national territory, as shown by the most recent ISPRA data and by UNCCD and European assessments of soil-related risks [1–3]. In a context of accelerated climate

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 123–138, 2026.
https://doi.org/10.1007/978-3-032-30524-4_9

change, it produces significant impacts on biodiversity, agricultural productivity and sustainable development, with structural repercussions on local economies and natural systems.

This contribution builds on the analysis carried out in relation to European legislation on desertification [4], highlighting the absence of a specific EU regulatory framework and, conversely, the existence of a complex set of sectoral regulatory and financial instruments, whose implementation so far produced uneven results.

On this basis, the article focuses on the national and regional levels in Italy, with the aim of assessing the extent to which international and European guidelines have been effectively translated into domestic law and, above all, into its territorial articulations. The underlying assumption is that, in the Italian experience, the desertification process is not yet governed by a single self-standing body of rules, but rather emerges as a point of convergence among soil policies, water governance, climate adaptation, river basin planning, rural development and financial programming instruments. As a consequence, the influence of the "European matrix" does not emerge through a concentrated reception in a single legislative act, but through a diffuse and sectoral transposition, entrusted to heterogeneous sources, planning methods and coordination mechanisms between the State and the Region.

The analysis adopts a multi-level legal-institutional approach, focusing on international, European and national sources and on their repercussions in regional law. It combines the examination of legal norms with the analysis of planning acts, programming documents and key financial instruments, in order to verify whether, and to what extent, the objectives of preventing soil degradation are translated into coherent and territorially differentiated measures.

From this perspective, the article pursues two main aims: first, to reconstruct critically the evolution of Italian legislation in this field; second, to assess whether regionalism has enabled closer adaptation to diverse territorial vulnerabilities or, on the contrary, has exacerbated fragmentation, uneven implementation and dependence on programs and financial instruments, with particularly evident effects in the divide between North and South. The focus on the *Mezzogiorno* is grounded not only in empirical evidence, reflecting the greater exposure of these territories to the phenomena of aridity, erosion, salinization and water stress, but also fulfils a systemic function: in this light, the case studies on Apulia and Sicily southern regions serve to test the robustness of the national model in two highly vulnerable contexts, which differ in their administrative structures, regional instruments and capacity to mobilise programming and financial leverage.

The paper seeks to show that in the current evolutionary phase of environmental law, the desertification provides a particularly significant test case for assessing the relationship among the European integration, the complexity of domestic competences and the adequacy of administrative responses. In the absence of a structured national legislative framework devoted to the desertification phenomenon, the problem concerns not only the quantity of measures adopted, but also their systemic coherence, their standard-setting capacity and the possibility to unify interventions currently dispersed across multiple regulatory sectors and various levels of government.

2 International and European Framework: An Overview

The measures adopted by Italy to combat soil desertification lie within the framework of international obligations arising from the 1994 United Nations Convention to Combat Desertification (UNCCD) and a European context which, although for a long time lacking a unified set of rules expressly devoted to the phenomenon, has undergone a progressive normative densification, further strengthened by the regulatory agenda of the European Green Deal [5–9].

In EU law, desertification continues to emerge primarily through sectoral instruments that contribute to soil protection, ecosystem resilience and climate adaptation. From this perspective, particular importance attaches, to the recent Directive (EU) 2025/2360 on soil monitoring and resilience, which introduced a harmonised framework for monitoring and assessing soil health, soil resilience and the management of contaminated sites, which requires Member States to transpose it by 17 December 2028 [10–13]. On the other hand, Regulation (EU) 2024/1991 on nature restoration lays down binding targets to restore nature on at least 20% of the Union's land and sea areas by 2030 [14].

In addition, Regulation (EU) 2023/839 amends Regulation (EU) 2018/841 on land use, land-use change and forestry (LULUCF) as part of the *Fit for 55* package, thereby strengthening the contribution to the Union's climate objectives [15, 16].

More generally, Regulation (EU) 2021/1119 (the European Climate Law) consolidates the centrality of clime adaptation in EU law, within a framework where soil degradation and desertification increasingly manifest the territorial vulnerability [17].

Also relevant, as indirect instruments for implementing soil protection, are the 2023–2027 European Agricultural Policy and Regulation (EU) 2021/2115 on CAP Strategic Plans [18] financed by the European Agricultural Guarantee Fund (EAGF) and by the European Agricultural Fund for Rural Development (EAFRD) measures, under which eco-schemes, agri-environment-climate measures and rural development tools may all contribute to prevent land degradation [19].

Closely connected with soil protection and the fight against desertification are also the rules on air quality, the management and protection of water resources, the Floods Directive and the rules on deforestation. All these measures are sustained and supported by a complex set of financial instruments contributing to soil prevention and protection, as already analysed.

It follows that the European framework can no longer be regarded as a mere collection of sectoral interventions, but rather as an increasingly integrated body of rules in which the prevention of land degradation, the restoration of ecosystems and soil monitoring jointly steer national legal orders to a greater extent.

On this background, the Italian legal framework on soil desertification must be examined in order to assess how far these European and international impulses have been translated into a coherent domestic regime, notwithstanding a context marked by strong sectoral fragmentation and differentiated regional implementation.

3 Italian Law on Desertification Among the NAP, the NRRP and Sectoral Legislation

The Italian regulatory framework on soil desertification yelds a multi-level legal and administrative system where the implementation of obligations arising from the UNCCD and from the reception of EU guidance do occur through a plurality of sectoral sources, programming acts and financial instruments.

The first cornerstone of this architecture is the National Action Programme to Combat Drought and Desertification (NAP), adopted by the Resolution of the Interministerial Committee for Economic Planning (CIPE) of 21 December 1999, no. 299. It provided domestic implementation of Italy's commitments under the UNCCD through a strategy centred on preventing soil degradation, managing water resources, reducing productive pressures and identifying the most vulnerable territorial areas.

However, NAP's legal nature is essentially a programming instrument. While constituting the national strategic reference document, it not established a self-standing legislative regime nor introduced uniform standards, specific obligations or enforcement mechanisms directly targeting the desertification problem [20].

As a result, the Italian system continues to rely on a technique of indirect integration, whereby desertification is addressed as the outcome of a plurality of legal regimes concerning soil, water, climate adaptation and spatial planning.

The normative core of this construction remains the Legislative Decree 3 April 2006, no. 152 (Environmental Code). Its Part III - devoted to soil protection, desertification fight, water pollution prevention and water resources management – approaches the phenomenon of the desertification within an integrated logic of territorial governance. In particular, Article 53 expressly includes the fight against desertification among the objectives of the legislation, while the transposition of Directive 2000/60/EC on water management is implemented, inter alia, through the river basin district planning and the institutional framework for River Basin District Authorities.

This systematic choice represents, at the same time, the strength and the limitation of the Italian model: it allows reliance on already consolidated planning and management tools, but, it deprives also desertification of an autonomous legislative definition.

Additional sectoral sources affecting indirectly the drivers of Italy's desertification include Legislative Decree 18 May 2001 no.227 on forestry matters, Legislative Decree 22 January 2004 no.42 on landscape protection and Law 28 December 2015 no.221 that strengthened the integration of environmental and sustainability criteria into public policies. Altogether, these instruments form a fragmented set of rules where soil protection and the prevention of territorial degradation emerge primarily through functional connections rather than through a unified legislative regime.

A major responsibility for State-level coordination lies with the Ministry of the Environment and Energy Security (MASE), which leads national climate adaptation policies and translates European and international guidance into domestic planning instruments. In parallel, ISPRA performs a central technical-scientific function by providing support for monitoring soil degradation, assessing territorial vulnerability and building the knowledge base required for administrative action. According to ISPRA, almost 30% of the Italian territory shows clear signs of soil degradation and desertification, with a higher concentration in southern regions.

Many sectoral initiatives now converge in the National Climate Change Adaptation Plan (PNACC), approved by Ministerial Decree 21 December 2023 no.434, which strengthens the integration of adaptation measures into national, regional and local policies. Although missing legislative status, the PNACC carries on an important coordinating function, linking EU climate law, national planning and the management of territorial risks, including water resources, agriculture and hydrogeological instability among the sectors considered.

Along legal sources and planning desertification's fight, the financial dimension is also crucial. In particular, the National Recovery and Resilience Plan (NRRP) – although not containing a component exclusively devoted to desertification – finances measures that directly affect its structural drivers, especially under Mission 2, Component 4, concerning the protection of land and water resources [21].

For the investment line coordinated by the Civil Protection Department, the overall allocation amounts to 1.2 billion €, of which 800 M€ are earmarked for new projects, with a minimum share of 40% reserved to the *Mezzogiorno*. Among the official allocations, 63.7 M€ are assigned to Sicily and 50.6 M€ to Apulia regions [22].

In addition, Investment 4.3 of the NRRP, entrusted to the Ministry of Agriculture, Food Sovereignty and Forestry (MASAF), concerns the resilience of irrigated agro-eco-systems, with a budget of 880 M€ aimed at improving the efficiency of irrigation networks and the management of water resources in agriculture [23].

A similar supporting role is played by the 2023–2027 Common Agricultural Policy, implemented through Regulation (EU) 2021/2115 on national Strategic Plans and interventions financed by the European Agricultural Guarantee Fund (EAGF) and the European Agricultural Fund for Rural Development (EAFRD) measures. In this framework, eco-schemes fall under Article 31, while, pursuant to Article 93, at least 35% of EAFRD resources must be devoted to interventions with environmental, climate and animal-welfare objectives, with significant implications for soil protection, sustainable water management and conservation-oriented agricultural practices.

However, the national system effectiveness depends crucially on Italian regionalism. The interplay between the State's exclusive competence for environmental protection under Article 117 of the Constitution and the relevant regional competences in agriculture, spatial planning and landscape planning requires a model of cooperative regionalism based on political-institutional coordination. As stated authoritatively: "Environmental protection operates less as a narrow legislative field and more as a transversal value, allowing the State to set uniform minimum standards, without excluding regional competence to pursue functionally related interests" (Constitutional Court judgment no. 407/2002) [24].

From this perspective, the State-Regions Conference plays a central coordinating role, while, at procedural level, the Conference of Services (governed by Articles 14 et seq. of Law 7 August 1990 no.241) constitutes one of the main instruments for reconciling the public interests involved in complex environmental planning and projects.

Constitutional case-law has also recognised that, in special-statute regions like Sicily, the power over spatial planning, public waters and landscape protection acquires particular relevance in shaping the regional scope for environmental action, still complying with State-level standards (Constitutional Court judgment no.380/2007) [25].

The result is a form of cooperative regionalism weakly oriented towards common and measurable objectives in the field of soil degradation, explaining the pronounced territorial disparities in the implementation of policies against desertification.

From a broader perspective, the Italian system is characterised by its ability to integrate legal sources, planning instruments and funding mechanisms, while its weakness remains the absence of an organic statute capable of turning these plural tools into a uniform framework of definitions, standards and responsibilities. Such tension between integration and functional normative fragmentation underpins Italy's territorial asymmetries between North and South, where the differing regional implementation capacities weakens the environmental law effectiveness.

4 Territorial Asymmetry and Different Implementation: The North–South Divide in Efforts to Combat Desertification

The divide between North and South Italy in the fight against desertification is legally and administratively significant. It highlights the different capacities of territories to implement - within a formally unified regulatory framework - the instruments for soil protection, water resource management and climate adaptation. Territorial differences are not limited to greater or lesser environmental exposure, reducing the efficacy of planning operations, the effectiveness of inter-institutional coordination and the allocation of public financial resources.

Official data from Italy's National System for Environmental Protection show that the *Mezzogiorno* concentrates the most vulnerable areas. According to SNPA/ISPRA, 10% of Italian territory is classified "highly vulnerable", with Sicily the most critical case with 42.9% of its overall surface vulnerable, followed by Apulia (28%), Molise (24.4%), Basilicata (24.4%) and Sardinia (19.1%) regions [26].

The relevance of this asymmetry emerges from the national rules on soil and water. When regulating soil protection, fight against desertification, protection of waters and management of water resources, Part III of the Environmental Code establishes a unified environmental protection framework applicable to the whole national territory. However, its real operativity depends on river basin district planning and on the action of territorial administrations, pursuant in particular to Articles 63 and 64 of the Code. It follows that, although the uniform regulatory basis, the effectiveness of the measures is conditioned by regional capacity for programming, coordination and implementation.

Another significant indicator of territorial differentiation is offered by the governance of the National Recovery and Resilience Plan. The article 2(6-bis) of Law 29 July 2021 no.108 states that at least 40% of the available financial resources must be allocated to the *Mezzogiorno*, expliciting the normative prominence to territorial rebalancing.

Such provision is consistent with Regulation (EU) 2021/241, which establishes the Recovery and Resilience Facility also with a view to strengthen economic, social and territorial cohesion [27]. Italy's North *vs.* South dualism, therefore, provides a criterion for guiding the administrative action and financial programming. This approach is implemented in Mission 2, Component 4 of the NRRP, which also concerns the restoration of (infra)structures damaged by natural disasters and the reduction of hydrogeological risk. Institutional documents of the Civil Protection Department indicate a total investment

of 1.2 billion €, with 800 million € allocated to new projects, with a minimum share of 40% still reserved to the *Mezzogiorno*. From a legal perspective, this is relevant not only for the amount of resources involved, but also for their implementation, governed by formal allocation criteria and by agreements with the Regions and Autonomous Provinces, according to Article 15 of Law 7 August 1990, no.241, that regulates responsibilities, monitoring and reporting.

It follows that, in the more exposed Italian southern regions, the fight against soil degradation is largely carried out through forms of cooperative administration and integrated financial instruments rather than through special legislation expressly devoted to desertification. Case-law likewise confirms, albeit indirectly, this approach. The most significant references do not stem from litigation explicitly centred on desertification, but from constitutional and administrative case-law on water protection and soil conservation. In particular, the judgment no.254/2009 of Constitutional Court stated that the provisions of Part III of the Environmental Code fall within the field of environmental protection, which is reserved to State competence [28], while in a 2022 judgment the Regional Administrative Court for Liguria assessed the jurisdiction of the Higher Water Tribunal over planning acts that affect significantly the public waters regime [29]. This approach makes it possible to construe the territorial divide not in terms of full-blown normative pluralism, but as an issue of differentiated implementation of a unitary environmental protection framework, wherein cooperation between the State and the Region plays a central role.

Taken as a whole, the *Mezzogiorno* is the area where both the territorial vulnerability and the intensity of planning and financing intervention are most clearly concentrated. It follows that the North–South divide, in the field under consideration, does not concern only the geographical distribution of risk, but also the degree of effectiveness of environmental law, the administrative capacity of territorial levels of government and the functionality of multi-level coordination mechanisms (Tables 1 and 2).

Table 1. Land degradation in Southern Italy

Region	Vulnerable area and main issues	Institutional response capacity/framework	Source
Sicily	42.9% – Erosion, salinization, drought	Regional desertification strategy; strong dependence on PNRR "Water package"	ISPRA-SNPA, *Focus Sicily* 2020–2024
Basilicata	24.4% – Arid/semi-arid degradation, erosion	Measures within rural development and soil protection plans; limited administrative capacity	ISPRA Reports 2020–2024
Sardinia	19.1% – Habitat loss, soil sealing	Integration within landscape and forestry planning	SNPA Webinar 2022; 2024 analysis

(*continued*)

Table 1. (*continued*)

Region	Vulnerable area and main issues	Institutional response capacity/framework	Source
Apulia (Puglia)	28% – Salinization of agricultural soils	Territorial and agricultural planning tools; targeted use of CAP/RDP funds	ISPRA 2022–2024, regional fact sheets
Calabria	Significant (Southern focus) – Coastal erosion, rural degradation	Fragmented interventions between coastal defense and rural development	ISPRA-SNPA, *Southern Reports* 2024–2025
Campania	Vulnerable area included within the 18% of national degraded land – Soil compaction, contamination	Actions within land reclamation and urban plans; attention to soil consumption	ISPRA 2024; *Desertification in Italy* analysis
Molise	High – Widespread agricultural degradation	Measures included in agricultural/RDP instruments; limited regional structure	SNPA/ISPRA, *Focus Molise* 2020–2024

Table 2. Main initiatives against soil desertification in Southern Italy

Measure/Initiative	Regions involved	Main objectives (ISPRA data)	Funding and legal framework	Status (2026)
PAN 2021–2030	Apulia, Sicily, Sardinia, Calabria, Campania	Monitoring land degradation (17.4% of national soil)	Ministerial Decree 21/12/2000; UNCCD; Legislative Decree 152/2006	Under implementation; ISPRA Report 2025
PNRR – Mission 2	Entire Southern Italy	Hydrogeological resilience against erosion/salinization	PNRR (Ministerial Decree 31/12/2021); €15.5 billion	60% completed
RDP (EAFRD) – CAP 2023–2027	Apulia, Sicily, Sardinia	Anti-degradation eco-schemes (28% of southern territory at risk)	Regulation (EU) 2021/2115; Regional RDPs	Payments ongoing (2024–2025)
PNACC (updated 2023)	Sicily, Sardinia	Adaptation; dams for drought control (Sicily 42.9% vulnerable)	Prime Minister's Decree 12/03/2015; Legislative Decree 36/2023	Dams: 2/3 operational

(*continued*)

Table 2. (*continued*)

Measure/Initiative	Regions involved	Main objectives (ISPRA data)	Funding and legal framework	Status (2026)
LIFE Desert-Adapt	Apulia, Sicily	Restoration of arid habitats	LIFE20 CCM/IT/001665	In progress (until 2026)
FSC 2021–2027	Calabria, Campania, Basilicata	Soil recovery (Basilicata 24.4% at risk)	FSC Ministerial Decree 20/02/2022; €40 billion	30% spent
LULUCF Italy	National (Southern focus)	Carbon sink vs. degradation	Regulation (EU) 2023/839	2030 target: + 10 Mt CO_2eq/year

5 The Apulia Region Between Soil Protection and Regulatory Instruments

Within southern Italian regions (*Mezzogiorno*) exposed to soil degradation, Apulia is particularly interesting because the desertification issue enters the regional legal order not through a dedicated statute, but through a range of acts on soil, landscape and vulnerable areas. Accordingly, the Region has gradually brought the problem within environmental programming and spatial planning at local level rather than by an autonomous set of rules dedicated to the desertification.

A first Apulian reference is the Regional Government Resolution of 18 September 2007, no.1464, that approved the programme agreement with the Ministry of the Environment and the National Committee to Combat Drought and/or Desertification [30]. The agreement implemented the National Action Programme at regional level through a pilot project for the mapping and delimitation of areas at risk, the definition of interventions and an experimental action of prevention and mitigation accompanied by information activities. In this context falls the Action Programme to Combat Drought and Desertification in Apulia, based on the MEDALUS methodology for assessing sensitivity to desertification and classifying Apulian territorial units [31]. These instruments have produced an advanced knowledge base, but miss the adoption of a regional framework law on soil degradation as well as the systematic integration of the mapping results into the main sectoral regimes.

A second line of intervention is planning the landscape. The Apulian Regional Law 7 October 2009, no.20 (Landscape planning) assigns to Regional Territorial Landscape Plan (PPTR) the function of protecting environmental values and sustainable development. Although not expressly regulating the desertification, this line places the protection of territorial balances within a unified regulatory framework, with the result that soil degradation is legally approached through the PPTR rather than by one autonomous category.

The centrality accorded to the PPTR in governing the land use also emerges from administrative case-law, which subjects to close scrutiny the delineation of landscape

restrictions and the classification of land, in the light of historical changes in land conditions, (TAR Puglia, Bari, 25 February 2025, no.272). In a complementary way, case-law used the PPTR as a benchmark for assessing the effects of irreversible transformations of agricultural land – in particular for ground-installed photovoltaic plants – in terms of land coverage, rural landscape alteration and impairment of ecological functionality (TAR Puglia, Lecce, 10 February 2022, no.248).

To account for more recent evolution of the Apulian framework, it is also appropriate to recall the 2025 initiatives on the renaturalization of degraded and yet degrading soils. Apulia Region recently launched a call for proposals addressed to local authorities for projects to restore degraded land to be used as public green areas, under the National Fund for Combating Land Take [32]. Although not specifically aimed to desertification, also this measure reinforces soil protection and restoration policies.

In Apulia these dynamics are also intertwined with the devastating effects of the unbeatable spread of the *Xylella fastidiosa* bacterium (classified in the EPPO Alert List A2 of UE Reg. 2019/1702), causing one of the most severe agricolture disasters in Europe, with essiccation yet of over 21M olive grove trees in Apulia in the last 10 years. Started in Salento province, this ongoing tragedy has contributed to the depreciation of 40% of overall agricultural areas and still increases the risks of land abandonment, landscape alteration and soil vulnerability [33, 34].

Alongside this framework, rural development policy plays an important role. Under the 2023–2027 CAP Strategic Plan, the Rural Development Complement (CSR) of the Apulia Region has a total budget over 1.18 billion €, with agri-climate-environmental calls which, in the 2024, for 11 area-based interventions, attracted around 18,430 applications for 131 M€ in requested aid *vs.* a total annual allocation of 96 M€. A significant share of interventions addressed sustainable soil and water management (conservation practices, organic farming, more efficient irrigation etc.), contributing, at least potentially, to mitigate degradation and salinization processes that make Apulia one of the most exposed Italian regions to soil desertification.

As a whole, the Apulian experience presents a fragmented, but broadly coherent, picture: there is no specific statute and no unified legal category devoted to soil desertification, but there is a set of instruments that permits to bring soil degradation within regional law on land use, landscape and soil protection, although with a limited capacity to create specific obligations, monitoring and accountability mechanisms specifically calibrated to desertification.

6 The Sicily Region Between Special Autonomy and Territorial Governance

Within the Italian context, Sicily has a distinctive profile because soil desertification falls within a regional legal order with a special Statute, endowed with exclusive or shared legislative powers in fields such as agriculture, forestry, land reclamation, urban planning, public works and public waters, closely linked to soil degradation and management of territorial resources [35]. Although not amounting to full environmental competence yet, such Statute makes Sicily a particularly suitable context for observing how special autonomy can be utilised in building its own instruments to combat soil desertification.

The central pillar is the Regional Action Strategy to Combat Desertification, drawn up by the River Basin Authority of the Hydrographic District of Sicily in June 2019 as a strategic programmation act [36]. The strategy refers to the UNCCD, to CIPE Resolution of 21 December 1999, no. 299 and to Legislative Decree no. 152/2006, underlining the need for unified governance of sectoral measures and placing soil desertification at the centre of a framework that links programs, plans and intervention priorities. Implementing CIPE Resolution, the strategy transfers at regional level the task of identifying vulnerable areas associable with programmes of measures, without taking the form of a real statute, but organising administrative action within the national and river-basin frameworks [37].

The knowledge basis of this Strategy includes the Map of Sensitivity to Desertification and the Desertification Sensitivity Index in Sicily (both available by the regional geo-portal and linked to the Urban Planning Department and to the Department for Territory and Environment) as well as the MEDALUS model and the Sensitive Areas to Desertification Index [38, 39]. Although lacking regulatory force, these instruments provide a legally-relevant function that make it possible to locate the most exposed areas, to set priorities and to guide measures.

Alongside the Strategy, there are various projects and technical-scientific initiatives: Sicily's ARPA promoted pilot projects to monitor soil desertification phenomena at basin and at farm scale and in 2024 launched jointly with the Region, SNPA and ISPRA a study on desertification and coastal erosion, indicating an integrated reading of territorial risks [40, 41].

Another reference is the LIFE DESERT-ADAPT project (LIFE16 CCA/IT/000011), funded under the LIFE Program, aimed at preparing areas at risk of desertification for increasing climate impacts through an integrated territorial adaptive management model (Desert Adaptation Model, DAM). Tested in particular in Sicily – among other places, in agricultural areas of Caltanissetta and Catania provinces and in the small islands of Lampedusa and Linosa – the project involved farms and local authorities in testing agroforestry practices, regenerative agriculture and soil and water management systems capable of increasing the resilience of Mediterranean soils [42].

From a financial perspective, Sicily also benefits of substantial NRRP resources for the protection of land and water infrastructures. The 2023–2027 Rural Development Complement (CSR) for Sicily, under the CAP Strategic Plan, finances interventions aimed at sustainable soil management to prevent soil erosion and to efficient water use, with conservation practices, agroforestry and the upgrading of irrigation systems that contribute to contrast desertification processes [43, 44].

Although not expressly focused on desertification, Sicily's Regional Law 13 August no.19/2020 on territorial governance updates the framework of spatial planning, where soil protection and degradation prevention policies are also situated, offering a potential point of regulatory linkage for implementing the Strategy [45].

Taken as a whole, the Sicilian case shows a more explicit legal emergence of the problem than in other regional contexts: the Region uses its autonomy by developping a dedicated Strategy whit official cartography and monitoring and funding instruments. Nevertheless, the response concerns primarily the strategic-programmatic as well as the

cartographic and financial planes, while an organic regional statute specifically devoted to soil desertification as an autonomous field is still lacking.

The comparison between Apulia and Sicily shows two partially different regional modalities of legal emergence of the problem of soil desertification. In Apulia, the phenomenon is contrasted mainly through acts implementing the National Action Programme, landscape-planning instruments and, more recently, with special measures to restore degraded soils; in Sicily, by contrast, desertification is the object of an explicit regional strategy developed within the framework of the River Basin Authority and backed by an official knowledge-base more explicitly devoted to the phenomenon.

The difference is due not only to the varying intensity of territorial risk, but also to the different institutional configuration of the two regional legal orders. Indeed, while Apulia operates within the ordinary model of cooperative regionalism, Sicily can anchor its action to a special statute that grants exclusive powers in areas such as agriculture and forestry, land reclamation, urban planning, public works and public waters, i.e., in fields closely connected with the prevention of soil degradation.

The Apulian case is particularly significant as an example of integration between environmental programming and spatial planning, whereas the Sicilian case is closer to the regional recognition of soil desertification as an issue to be addressed through a dedicated strategy. In both cases, however, a common limit persists: the regional response remains predominantly entrusted to programming, planning, monitoring and sectoral intervention instruments, rather than to an organic and autonomous legislative framework on soil desertification.

7 Conclusions: Legal Challenges and Future Prospects

The analysis conducted shows that soil desertification occupies a legally significant, yet still unfinished, position in the Italian legal order. The phenomenon is expressly referred in the Environmental Code, appearing in national and regional programs and addressing a variety of financial and planning instruments. Nevertheless, it continues to be regulated in a fragmented manner, without an organic framework capable to unify its concept, preconditions, intervention standards and criteria of public responsibility.

A first issue hence concerns the regulation. In the Italian experience, soil desertification is not treated as an autonomous field, but as a point of intersection among soil and water protection, spatial planning, agricultural policies, climate adaptation and environmental restoration. This approach has the advantage of fostering integration, but it also produces normative dispersion, since the phenomenon is constantly absorbed into broader regulatory regimes and ultimately lacks its own legal parameters, specific obligations and clear instruments for monitoring its prevention and reduction.

A further aspect deserving attention addresses the relationship between the unity of environmental protection and the territorial differentiation of implementation. Constitutional case-law clarified that the provisions contained in Part III of Italy's Environmental Code fall within the field of environmental protection, reserved to the exclusive competence of the State, although intersecting areas wherein the Regions retain significant administrative and programming functions. However, in the fight against desertification the gap between a unitary regulatory framework and territorial effectiveness proves particularly pronounced: State intervention defines the general perimeter, but the real impact

of measures depends on regional capacity to produce risk maps and programme interventions, to use the available funds and to coordinate the different administrative levels. It follows that the problem is not only the allocation of competences and resources, but the more substantive issue of equal implementation of environmental law across the national territory.

A third dimension concerns the legal value of programming instruments. Both the NAP and many of the regional initiatives examined – from the 2019 Sicilian Strategy to the Apulian pilot projects and the more recent measures for the renaturalisation of degraded soils – show that the Italian system rather relies predominantly on strategic documents, agreements, plans and calls for proposals.

In this perspective, initiatives such as the Life Desert Adapt project - that tested an integrated adaptive land-management model in Sicily and other Mediterranean areas, involving farms, local authorities and networks of actors in southern Italy - also offer important operational indications for translating European and national objectives to figth soil desertification into more effective practices. These instruments are undoubtedly important to lead administrative action. However, they often lack a sufficiently determinate framework of obligations, controls and consequences in cases of inertia or non-compliance, thereby raising the issue of the gap between planning capacity and binding force.

It is precisely on this ground, however, that the gap between planning capacity and binding force becomes apparent: the multiplication of strategies, plans and projects tends to lie on the borderline between "soft" and "weak" law, producing a surplus of programmatic statements and a deficit of legally enforceable responsibility, particularly in the most fragile territorial contexts. This gives rise to a structural tension between the role of planning as a technique for integrating sectoral policies and the difficulty of translating such instruments into verifiable operational obligations, supported by effective monitoring mechanisms, forms of conditionality in the use of financial resources and legal consequences in cases of inertia or non-compliance.

It is in this context that European Union law seems destined to play an increasingly decisive role. Whereas in the past the impact of the EU on this issue occurred itself mainly indirectly, through rules on climate, water, agriculture and biodiversity, the most recent developments in EU soil law and ecological restoration appear to steer the system towards a more intense legalisation of the field. Directive (EU) 2025/2360 on soil monitoring and resilience and Regulation (EU) 2024/1991 on nature restoration can, in this respect, be seen as potential factors in strengthening the binding dimension of the subject, insofar as they require more structured monitoring, more clearly defined targets and tighter linkages among scientific knowledge, planned and expected results.

Yet the question remains: whether are these developments actually capable to reduce reliance on predominantly non-binding planning or whether, on the contrary, they risk to fuel additional layers of planning deprived of adequate enforcement tools?

The challenge does not seem to lie so much in drafting new strategic documents rather than linking existing and future ones to common minimum standards for soil protection. Monitoring obligations, comparable reporting among the Regions and stricter access to financial resources may prevent territorial differentiation from turning into structural inequalities in the actual levels of soil protection.

In the light of these developments, it seems possible to argue that the main issue is not the absence of a legal references to soil desertification rather than the still dispersed and uneven character of its regulation. In other words, the problem does not seem to lie in a lack of instruments, but in the difficulty to bring them within a framework sufficiently coherent, measurable and coordinated, capable to ensure a minimum degree of uniformity in the soil protection standards while at the same time adequately taking account of territorial specificities.

From this perspective, soil desertification is also of interest for a broader consideration on national and European environmental law. The issue shows, first, how difficult is to keep the traditional fields of soil, water, landscape, agriculture and climate separately. It further highlights the growing centrality of knowledge-building and mapping as the prerequisites for public action. Finally, it suggests that environmental protection has to contend increasingly not only with the definition of competences, but also with the quality of the coordination tools, the monitoring systems and the criteria for assessing the effectiveness of the measures adopted.

It may hence be concluded that soil desertification represents a particularly significant vantage point from which to grasp current tensions among the unity of environmental protection, the plurality of levels of government and the growing influence of EU law. For this reason, that phenomenon seems destined to acquire increasing importance not only for public action, but also for the legal system's capacity to build more mature forms of integration among Science, Administration and Regulation.

Acknowledgments. This study was carried out within the PRIN 2022 RESEARCH PROJECTS OF RELEVANT NATIONAL INTEREST funded by the Ministry of University and Research (MUR) (Grant Assignment Decree n. 20437 adopted on 06.11.2024 - CUP n. D53C24004290006).

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An Integration Framework of InfraHBIM-HGIS for Reconstructing Infrastructure Heritage Evolution: The Taipingling Corridor Along the Chinese Eastern Railway

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Abstract. Infrastructure heritage corridors are characterized by large spatial extents, dispersed asset distribution, complex historical transformations, and heterogeneous data sources, which make their documentation and reconstruction particularly challenged. To address these barriers, this study proposes a corridor-oriented InfraHBIM–HGIS framework for the reconstruction and documentation of infrastructure heritage, using the Taipingling Corridor of the Chinese Eastern Railway (CER) as a case study. The framework integrates an archival database, a geospatial database, InfraHBIM-based modelling, and HGIS within a unified workflow. Multi-source datasets, including georeferenced historical maps, raster and vector geospatial data, and point clouds generated through drone-based photogrammetry, are systematically organized and linked through a previously developed 12-digit identification system. A condition-based modelling strategy is adopted to combine forward modelling from archival records with reverse modelling from point-cloud data, enabling the reconstruction of extant, vanished, and transformed heritage assets across multiple historical stages. The integrated results are consolidated in a GIS-centered environment to support cross-scale visualization, semantic linkage, and spatial analysis, and are further disseminated through a WebGIS platform for remote access and interactive exploration. The study demonstrates that the proposed framework provides an operational approach for the multi-scale and multi-temporal integration of documentary, spatial, and model-based information in corridor-scale infrastructure heritage.

Keywords: Infrastructure Heritage Building Information Modelling (InfraHBIM) · Historical Geographic Information System (HGIS) · InfraHBIM-HGIS integration · Corridor heritage · Chinese Eastern Railway (CER)

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 139–156, 2026.
https://doi.org/10.1007/978-3-032-30524-4_10

1 Introduction

Building Information Modeling (BIM) was originally developed for newly constructed buildings to manage digital assets throughout their lifecycle [27, 47]. With its rapid advancement in the Architecture, Engineering, Construction, and Operations (AECO) sector, BIM has expanded beyond design and construction into broader domains [24]. Its extension to cultural heritage led to the development of Heritage BIM (HBIM), introduced from the concept of Historic BIM [38], as a methodology for documenting, analyzing, preserving, and managing historical assets through semantically enriched 3D models [4, 34]. In parallel, BIM has also been applied to infrastructure domains, giving rise to Infrastructure BIM (InfraBIM), while Infrastructure HBIM (InfraHBIM) has emerged as a promising methodology for large-scale and linearly distributed heritage systems such as railways, canals, and defensive networks [52]. Compared with conventional HBIM applications focused on individual monuments, InfraHBIM better supports the integration of geometric and non-geometric information and the representation of historical evolution across spatially distributed assets [32, 44], and can also be applied to risk assessment, structural analysis, retrofitting, and rehabilitation [48].

Nevertheless, the effectiveness of InfraHBIM in digital representation, data integration, and cross-disciplinary collaboration remains constrained when infrastructure heritage is characterized by large spatial extents, fragmented distributions, complex historical transformations, and substantial data volumes, since object-level modelling alone is less effective in handling multi-scale spatial contexts and temporal dynamics across extensive territories. Geographic Information System (GIS) offers powerful tools for handling large-scale geospatial data, enabling spatial analysis, data integration, and visualization, while Historical GIS (HGIS) provides a suitable framework for organizing and analysing multi-source and multi-temporal historical information, including historical maps, satellite imagery, vector-based asset data, and reality-capture outputs [31, 46].

Accordingly, BIM–GIS integration has been widely applied in the management and monitoring of modern infrastructure systems [23, 37, 42] and has evolved from data-conversion experiments into a broader field supporting infrastructure planning, monitoring, asset management, and digital twin applications [24]. Most studies focus on BIM-to-GIS workflows, particularly the transformation of Industry Foundation Classes (IFC)-based models [12] into GIS environments, but major challenges remain in semantic mapping, geometry transformation, geo-referencing, conversion efficiency, and bidirectional interoperability [2, 57]. In heritage contexts, integration has progressively moved beyond technical model conversion. Earlier studies had already recognized that Historic BIM–GIS integration should support not only model management, but also maintenance, knowledge dissemination, and interactive digital representation [19]. More recent studies have expanded its scope from individual historic buildings to settlements, archaeological sites, cultural landscapes, urban districts, and infrastructure heritage [10, 18, 35, 36]. Methodologically, HBIM–GIS/HGIS integration increasingly combines historical maps, images, descriptive metadata, and multi-temporal information, while database construction, multi-phase reconstruction, and the joint use of forward modelling (FM) [11] and reverse modelling (RM) [41] have become central components of recent infrastructure heritage workflows [16, 18, 56].

Despite these advances, several limitations remain. Interoperability between HBIM and GIS/HGIS is still unstable, as model transfer often depends on intermediate formats, dedicated scripts, or platform-specific workflows [10, 16, 17, 57]. Many workflows also rely heavily on commercial software ecosystems, while open, low-cost, and long-term maintainable alternatives remain insufficiently developed [16, 36]. In addition, condition-adaptive frameworks for heritage with uneven archival documentation, physical loss, or complex intervention histories are still limited, and quantitative comparisons of alternative integration platforms remain relatively scarce [24, 25, 56]. These issues become particularly critical for corridor-scale infrastructure heritage, where dispersed assets, complex historical transformations, large territorial contexts, and heterogeneous documentary evidence must be addressed within a unified framework.

Infrastructure heritage and its associated landscape are recognized as a significant category within international heritage frameworks [51]. Accurate digital documentation of heritage structures, sites, areas, and landscapes is fundamental to conservation and to their presentation and interpretation [28]. However, such heritage is often underrepresented in conservation practice because of its large spatial extent, complex system characteristics, and continued exposure to natural and human-induced threats, which contribute to the gradual loss or transformation of original structures and spatial relationships.

To address these methodological and conservation challenges, this study proposes a corridor-oriented InfraHBIM–HGIS framework for the reconstruction and documentation of infrastructure heritage, using the Taipingling (TPL) Corridor of the Chinese Eastern Railway (CER) as a case study. The framework integrates an archival database (ADB), a geospatial database (GeoDB), InfraHBIM-based modelling, and HGIS within a unified workflow. It combines FM based on historical records with RM using point clouds derived from Structure-from-Motion (SfM) drone photogrammetry and publishes the integrated results through a WebGIS platform [53] for remote access and interactive visualization. The main contributions of this study are fourfold: (1) a corridor-oriented InfraHBIM–HGIS integration framework for infrastructure heritage characterized by large spatial extents, fragmented asset distribution, and multi-temporal evolution; (2) an operational data-linking workflow integrating ADB, GeoDB, and a previously developed 12-digit identification system to associate archival records, spatial data, and model components across multiple scales and historical stages [55]; (3) a condition-based modelling strategy that combines FM from archival sources with RM from photogrammetric point clouds to reconstruct vanished, extant, and transformed heritage assets under different data conditions; and (4) a cross-scale workflow connecting corridor-level railway alignment reconstruction, asset-level InfraHBIM development, and WebGIS-based dissemination within a single framework.

2 The Taipingling Corridor and Its Infrastructure Heritage Assets

In mountainous areas along the CER, Russian engineers developed five spiral-line systems to overcome steep topographic conditions [14] (see Fig. 1). During the construction period, temporary lines were built within these systems to transport workers and materials, and many of these routes were configured as Z-shaped switchback lines [13]. The TPL Corridor is located along the eastern section of the CER main line, a major historical railway system originally constructed between 1897 and 1903. The original historic

configuration of the corridor consists of an ascending line (AL) and a descending line (DL), located on the western and eastern slopes of TPL, the highest peak along the eastern section of the main line. Within the Qinggouzi–TPL section, the AL extends a straight-line distance of 9 km to a route length of 17 km, achieving an elevation gain of +199.36 m. In contrast, within the Zhashu–TPL section, the DL extends a straight-line distance of 6.78 km to a route length of 12.8 km, descending from 555.31 m a.s.l. at TPL Station to 406.38 m a.s.l., as shown in Fig. 2.

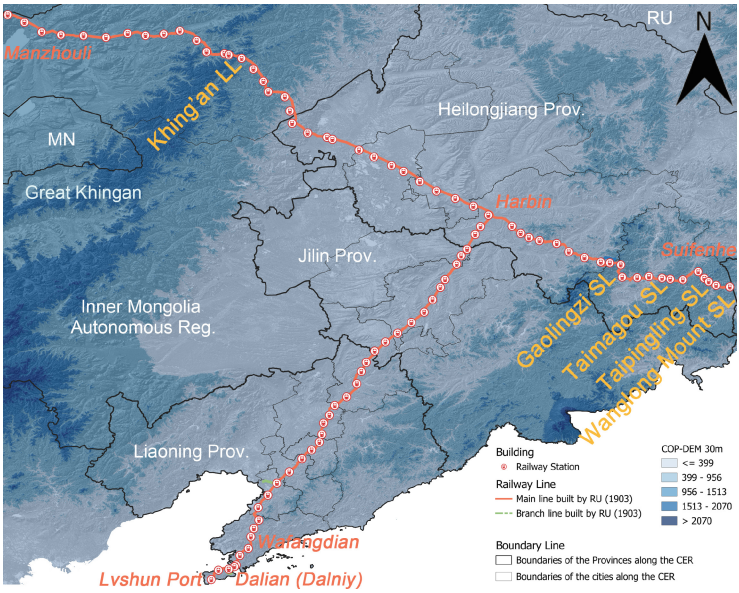


Fig. 1. Distribution of the five large-scale spiral lines along the main line of the Chinese Eastern Railway (CER) (SL = spiral line; LL = loop line).

The railway has a track gauge of 1,524 mm, a minimum curve radius of 320 m, and maximum longitudinal gradients of 15 m/km in mountainous sections and 8 m/km in flatter terrain. The Russian-built infrastructure heritage along the corridor includes four main categories with different structural scales: 15 steel plate girder bridges, 6 stone arch bridges, 14 concrete arch culverts, and 21 steel pipe culverts [14]. During the 1930s, under the administration of the South Manchuria Railway, Japanese engineers upgraded the spiral-line system to a double-track configuration and added a series of new infrastructure assets [49].

However, detailed archival records of these later interventions remain scarce. Field investigations conducted in 2021 and 2024 identified several remaining assets within the corridor. These include two stations, four bridges, and one culvert recorded in the Russian archives, as well as three Japanese concrete bridges. As an important component of the cultural heritage along the CER, this section has been exposed to continuous threats since its closure in December 2015, including climate-related factors and human interventions. Particularly significant is the recent loss of the Huli River Bridge I, which

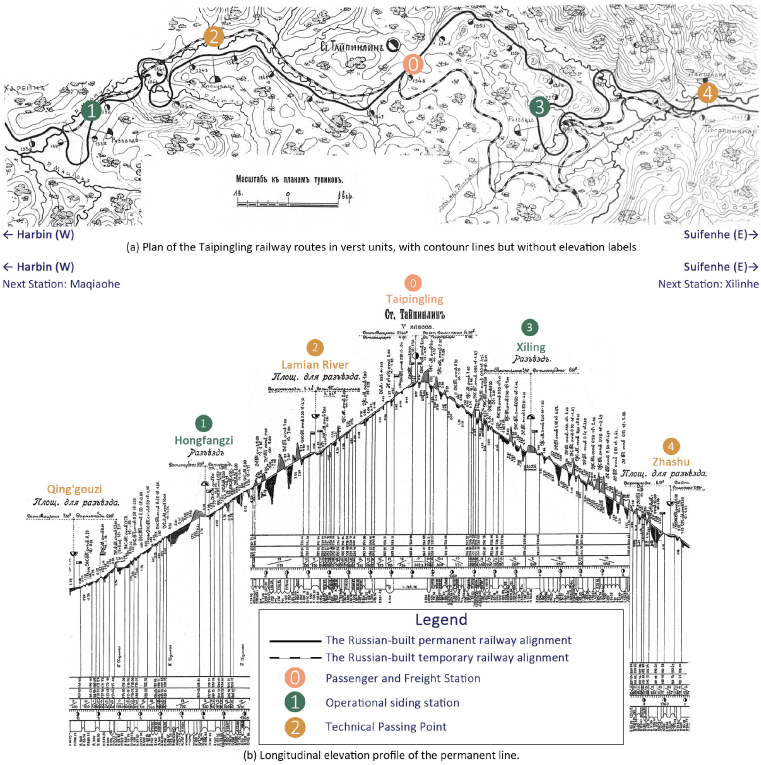


Fig. 2. Railway design drawings of the Taipingling mountainous section of the CER: (a) Plan of Taipingling railway routes in verst units, with contour lines without elevation labels; (b) Longitudinal elevation profile of the permanent line [14].



Fig. 3. Changes in the Russian-built Huli River Bridge I: (a) upstream elevation documented during the first field survey in 2021, (b) upstream elevation captured by drone in 2024, and (c) the bridge site after demolition caused by road construction in 2025.

had the longest single span along the entire line and was demolished in 2025 as part of a road renovation project (see Fig. 3). These conditions make the TPL Corridor a complex corridor-scale infrastructure heritage system characterized by dispersed assets, uneven conservation states, continued landscape transformation, and heterogeneous archival availability. These characteristics provide the basis for the multi-level reconstruction and documentation methodology presented in the following section.

3 Methodology and Workflow

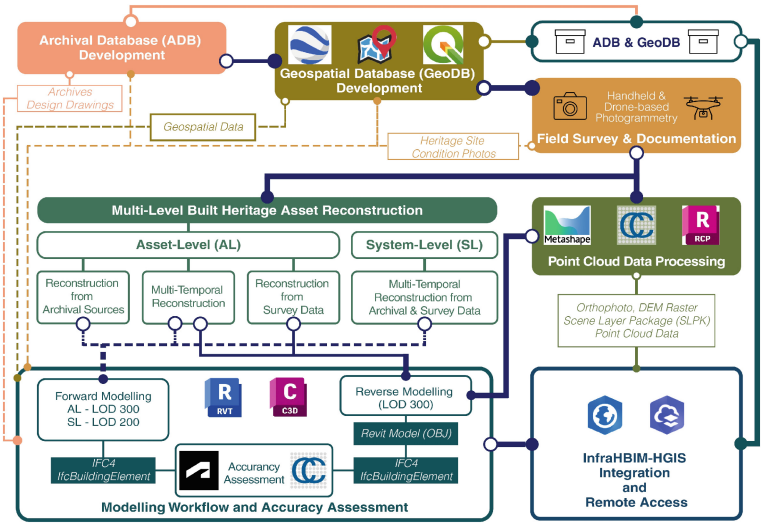


Fig. 4. The proposed workflow for integrating InfraHBIM-HGIS in this study.

This study proposes a corridor-oriented InfraHBIM–HGIS framework designed to address two interrelated problems in infrastructure heritage documentation: the reconstruction of individual assets under uneven documentary conditions and the reconstruction of railway routes and alignments at the system level. To address these challenges, the workflow integrates two complementary databases, namely ADB and GeoDB, together with two condition-based modelling strategies, FM and RM. Within this framework, HGIS serves as the common environment for linking documentary, spatial, and model-based information across temporal and spatial scales.

The workflow is organized at two complementary levels: the asset level, which focuses on the reconstruction and documentation of individual heritage assets such as bridges and culverts, and the system level, which addresses railway routes and alignments [13] in relation to the broader territorial and topographic context. Huli River Bridges II, IV, and V are used to illustrate RM-based modelling, whereas Huli River Bridge I serves as a representative FM case; railway alignment reconstruction is carried out at the system level to demonstrate corridor-scale modelling and spatial integration.

As illustrated in Fig. 4, the workflow consists of six main steps: (1) ADB development; (2) GeoDB development; (3) field survey and documentation; (4) point-cloud data processing; (5) multi-level reconstruction of built heritage assets at the asset and system levels, together with modelling workflow and accuracy assessment; and (6) InfraHBIM–HGIS integration and remote access. The following subsections describe these steps in detail.

3.1 Database Development

The development of ADB and GeoDB forms the operational data backbone of the proposed InfraHBIM–HGIS framework. ADB organizes historical and documentary evidence, including maps, engineering drawings, photographs, and descriptive records, while GeoDB provides the georeferenced spatial structure required for corridor-scale analysis, terrain interpretation, railway alignment reconstruction, and the integration of raster-, vector-, and model-based datasets. Their linkage establishes a unified and traceable data structure through which archival records, geospatial information, and InfraHBIM models can be consistently associated across multiple scales and historical stages, while field survey results contribute to the refinement and validation of both databases.

Archival Database Development
ADB was developed to systematically organize historical information related to infrastructure heritage along the corridor. It integrates multi-source archival materials, including historical maps, design drawings, engineering records, and photographic documentation collected from Russian and subsequent historical periods [3, 13, 29, 33, 40, 43, 49, 50]. Each asset was assigned a previously developed 12-digit identifier proposed by Xu et al. [55] to ensure consistent referencing and linkage across archival, geospatial, and modelling datasets (see Fig. 6). The database records both geometric-related information, such as location references and structural dimensions, and non-geometric attributes, including construction period, infrastructure type, material characteristics, and historical descriptions, thereby providing a documentary basis for GeoDB development, FM, and multi-temporal interpretation.

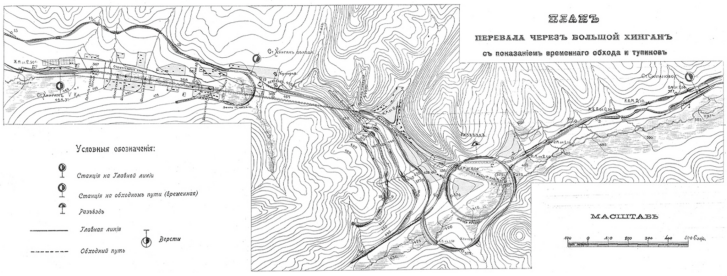
Geospatial Database Development
GeoDB was developed to organize, process, and integrate multi-source spatial data in support of analysis and reconstruction at both the asset and corridor scales. The input datasets include raster data such as satellite imagery and DEMs, vector data representing heritage asset locations, and historical spatial data extracted from georeferenced historical maps stored in the ADB. To ensure spatial consistency, all datasets were initially assigned WGS 1984 (EPSG:4326) in QGIS [45] and subsequently transformed into WGS Mercator (EPSG:3857) for visualization and data sharing in ArcGIS® Pro [21] and Online [20].

Multi-temporal satellite imagery obtained from Google Earth [25], together with field survey photographs, was used to analyze historical changes in the corridor landscape. Historical maps were georeferenced using control points derived mainly from infrastructure nodes, river confluences, and intersections between rivers and contour lines. Based on the Copernicus Global Digital Elevation Model (COP-30) [22], terrain analysis was conducted to generate contour lines at an interval of 10.67 m, consistent with historical design drawings, and to extract river networks and their spatial distribution.

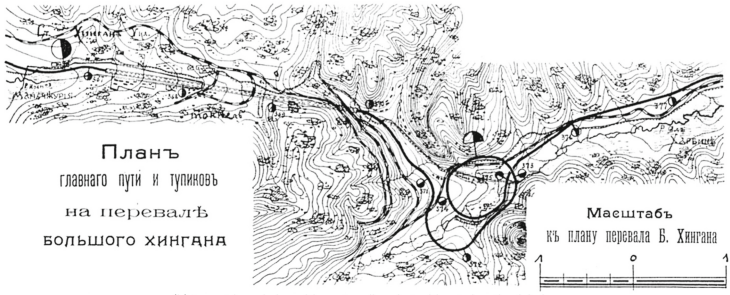
Method for Inferring Contour Intervals from Multi-Scale Historical Maps

A key challenge in this study is determining the contour interval of historical maps when elevation values are not explicitly annotated. This issue is particularly critical for the Taipingling plan (Fig. 2(a)), because terrain reconstruction and railway alignment

modelling depend on it. The inferred value of 10.67 m (5 sazhen[1]) represents a non-standard interval in modern metric systems, making direct assumption unreliable.



(a) A sazhen-based plan with contour elevation values.



(b) A verst-based plan with contour lines but without elevation labels.

Fig. 5. Plans of the Greater Khingan Range railway routes in two measurement systems, used for contour-interval inference: (a) a sazhen-based plan with contour elevation values; and (b) a verst-based plan with contour lines but without elevation labels.

To address this problem, a comparative cartographic analysis was conducted using maps from the same album. Figure 5(a) presents the 'Plan of the main railway line and switchback tracks at the Greater Khingan Range', in which the contour interval is explicitly indicated as 5 sazhen (approximately 10.67 m) [3]. Figure 5(b), depicting the same area at the same scale, does not include elevation labels; however, its contour geometry and density are consistent with those in Fig. 5(a), indicating that it was likely derived from the same interval.

Since Fig. 2(a) belongs to the same section of the album and follows the same cartographic conventions, it is reasonable to infer that the same contour interval was applied. Accordingly, the contour interval of the TPL plan is estimated to be approximately 10.67 m. Although inferred rather than directly surveyed, this value provides a historically grounded basis for terrain reconstruction under archival constraints.

These processes supported terrain interpretation, historical map georeferencing (see Fig. 6), and the reconstruction of historical railway routes. Built heritage elements, including stations, infrastructure assets, and railway alignments, were further vectorized as shapefiles and integrated into GeoDB, thereby establishing the georeferenced spatial

[1] Traditional Russian units of distance include 'verst' and 'sazhen'. One verst corresponds to 500 sazhen (≈ 1.067 km), while one sazhen is approximately 2.134 m.

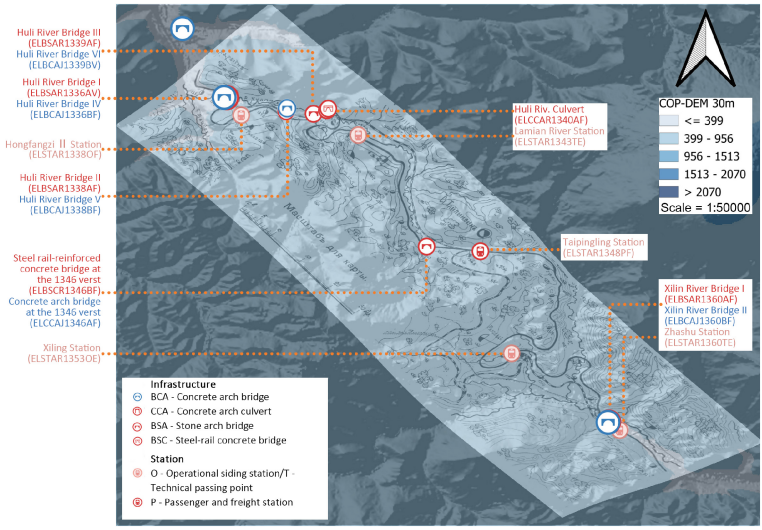


Fig. 6. Georeferenced historical map of the corridor showing the spatial distribution and identification codes of heritage assets and stations (scale 1:50,000).

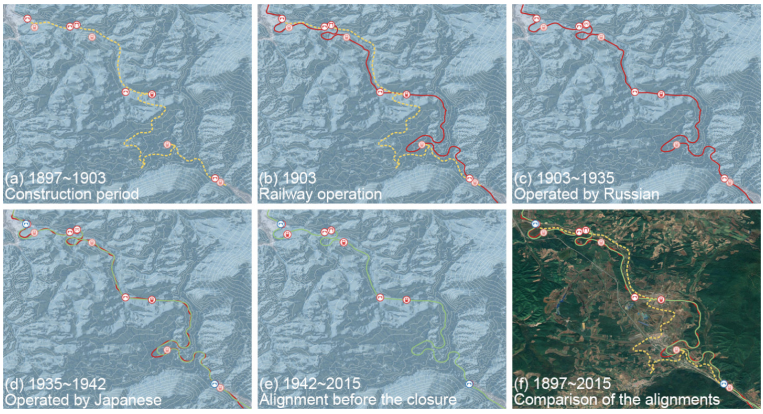


Fig. 7. Vectorized built heritage assets and railway routes within the corridor from 1897 to 2024 (a)-(e) and their comparison (f) (scale: 1:50,000).

framework required for multi-scale and multi-temporal analysis and for linking geospatial data with archival information from ADB and InfraHBIM models within the HGIS environment (see Fig. 7).

3.2 Documentation and Point Cloud Processing

Field survey and documentation were carried out based on the preliminary outputs of ADB and GeoDB, and the results further enriched and validated both databases. An initial field investigation conducted in 2021 established a preliminary record of the

existing heritage assets within the corridor. During the 2024 survey campaign, image data were collected using drone-based photogrammetry with a DJI Air 2S equipped with an FC3411 camera (8.38 mm focal length). The images were captured at a resolution of 5472 × 3078 pixels, resulting in an average ground sampling distance (GSD) ranging approximately from 0.67 to 0.94 cm/pixel, depending on flight altitude and asset extent.

Field photographs were also recorded using a handheld camera to document the current condition of the heritage assets. Due to ongoing road construction projects, certain locations were inaccessible during the survey. Consequently, several heritage assets shown in Fig. 6—including the stations, as well as ELCCAR1340AF, ELBSCR1346BF, and ELCCAJ1346AF—could not be documented. The collected image data nevertheless provided the basis for subsequent point-cloud generation and 3D modelling of the heritage assets (Fig. 8).



Fig. 8. Infrastructure heritage within the TPL Corridor documented during field investigations in 2021 and 2024.

Considering the complex topographic conditions, dispersed asset distribution, vegetation coverage, and accessibility constraints within the corridor, image acquisition was conducted using circular flight paths at appropriate altitudes to ensure sufficient coverage and overlap for 3D reconstruction (see Fig. 9). The number of images was adjusted according to the spatial extent and condition of the individual heritage assets. All datasets were referenced to WGS 84 / UTM zone 52N (EPSG:32652). Owing to the absence of ground control points (GCPs), absolute georeferencing relied on navigation-grade Global Navigation Satellite System (GNSS) data recorded onboard the drone. For this reason, the reliability of RM-based models was assessed primarily through internal photogrammetric indicators and subsequent geometric consistency evaluation rather than through external control-point-based validation.

Dense point clouds were generated using an SfM-Multi-View Stereo (MVS) workflow [26] implemented in Agisoft Metashape (version 2.2.0) [1], providing the primary geometric basis for RM-based InfraHBIM development. For the assets used in RM, ground resolution ranged from 0.67 to 0.94 cm/pix, reprojection error from 0.82 to 0.93 pix, dense point-cloud size from 3.40 to 6.41 million points, and DEM resolution from 1.34 to 1.88 cm/pix. These indicators suggest that the datasets are sufficiently dense and

internally consistent for asset-level RM, although absolute geolocation accuracy remains constrained by GNSS-only referencing.

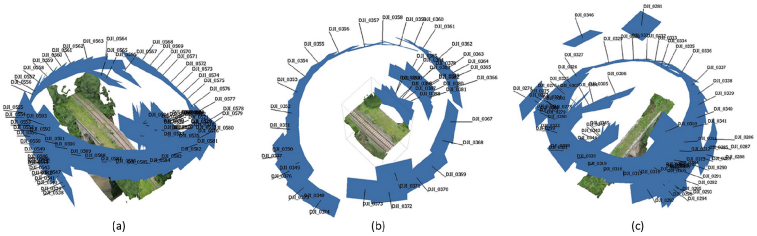


Fig. 9. Circular drone flight paths for image acquisition: (a) ELBCAJ1336BF, (b) ELBSAR1338AF and ELBCAJ1338BF, and (c) ELBSAR1339AF.

To improve usability in the HBIM environment, the initial point clouds were exported in.las format and processed in CloudCompare (version 2.11.1) [15] for slicing, denoising, filtering, and elevation-based recolouring, before conversion using Autodesk® Recap Pro® (version 2025) [6] (see Fig. 10). Asset-scale DEMs and tiled models were then generated in Scene Layer Package (SLPK) format for GIS integration and visualization. These operations improved the readability and interoperability of the point-cloud datasets without altering their underlying photogrammetric accuracy.

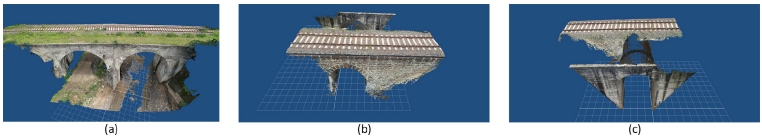


Fig. 10. Drone-based photogrammetric point clouds of (a) ELBSAR1338AF, (b) ELBCAJ1336BF, and (c) ELBCAJ1338BF.

3.3 InfraHBIM Development at the Asset-Level and System-Level

InfraHBIM Modelling Strategy for Multi-Source Data Integration and Railway Reconstruction

In this study, InfraHBIM development is structured around two complementary tasks: asset-level reconstruction of individual heritage assets and system-level reconstruction of railway routes and alignments. This structure supports both detailed object modelling and large-scale infrastructure representation, while the modelling strategy is selected according to the availability, quality, and type of evidence rather than object category alone, thereby accommodating extant, vanished, and transformed assets within the same corridor-scale heritage system.

At the asset level, modelling strategies are selected according to data conditions. FM is applied where reliable archival documentation is available but physical remains are absent or incomplete, enabling the reconstruction of lost structures from historical records. RM is adopted for well-preserved assets with sufficient point-cloud data,

enabling geometry to be reconstructed directly from survey-based evidence. In cases where assets have undergone structural transformations over time, FM and RM are combined to support multi-temporal reconstruction and maintain consistency between historical states and current conditions.

All asset models are developed in Autodesk® Revit® [7] at Level of Development (LOD) 300 [9]. Semantic information derived from ADB and GeoDB is embedded into the model components and subsequently mapped to IFC4 [12] to support interoperability between InfraHBIM and HGIS platforms (see Fig. 11(a)–(d)). In this way, the asset-level models serve not only as geometric reconstructions, but also as semantically structured information carriers linked to archival and geospatial data.

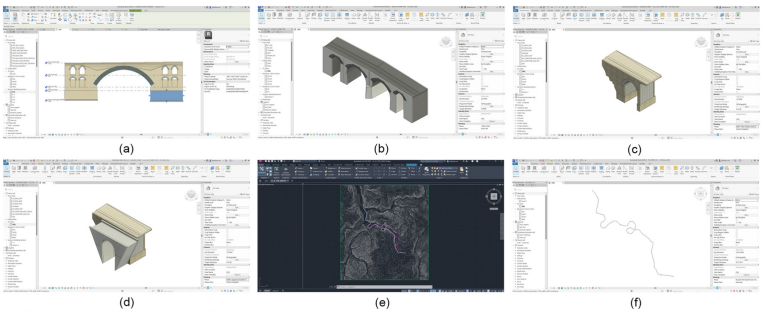


Fig. 11. InfraHBIM models of heritage assets within the TPL Corridor: (a) forward modelling of ELBSAR1336AV; (b) reverse modelling of ELBCAJ1336BF for a single historical stage; (c, d) multi-temporal modelling of ELBSAR1338AF and ELBCAJ1338BF (1897 ~ 1930s and 1930s ~ 2024); (e, f) railway alignment modelling based on the initial route extracted from georeferenced historical maps using C3D and Revit.

At the system level, railway alignment reconstruction is carried out through the combined use of Autodesk® Civil 3D® (C3D) [5] and Revit. Georeferenced railway routes, represented as shapefiles with elevation values derived from the Forest And Buildings removed Copernicus DEM (FABDEM) V1–2 [39], are imported into C3D. Using *corridor* modelling functions, railway models are generated with standardized track gauge and cross-sections at LOD 200. These models are then exported in.*dwg* format and transferred to Revit, where semantic attributes are assigned and integrated into the overall InfraHBIM environment (see Fig. 11(e) and (f)). This system-level reconstruction is not intended solely to visualize railway geometry, but to relate distributed heritage assets to their broader operational and territorial context, thereby linking corridor-scale evolution with asset-level documentation.

To ensure data integrity and modelling reliability, all IFC4 models are checked using Autodesk® Viewer® [8], while RM-based assets are further evaluated through geometric consistency assessment against the corresponding point-cloud data.

Geometric Consistency Assessment of Reverse-Modeled InfraHBIM
To evaluate the geometric consistency of reverse-modelled InfraHBIM assets, a multi-stage assessment framework was established by comparing the models with photogrammetric point clouds derived from drone-based reconstruction. Owing to the absence of ground control points and direct field measurements, the assessment relied on model-to-point-cloud comparison rather than external control-based validation.

Because photogrammetric point clouds are inherently incomplete and spatially variable, especially in occluded or poorly reconstructed areas, a two-stage filtering strategy was adopted to distinguish missing-data effects from actual geometric deviations. First, bidirectional *Cloud-to-Cloud (C2C)* distance analysis was used to identify unreliable regions and define a valid comparison domain. Then, overlap-based *Iterative Closest Point (ICP)* registration was applied within this domain to refine alignment and isolate the effective comparison area. More details are reported in Xu et al. [56].

Finally, the Multiscale Model-to-Model Cloud Comparison (M3C2) algorithm [30, 54] was used to quantify geometric discrepancies between the InfraHBIM models and the reference point clouds. By computing distances along local surface normals, this method enables robust consistency assessment under heterogeneous data conditions. The results indicate that the RM-based InfraHBIM models achieve an acceptable level of consistency within the validated comparison regions, with most deviations concentrated in localized areas affected by data incompleteness, occlusions, or modelling complexity. Overall, these results support the suitability of RM for asset-level documentation under the survey conditions of the present study.

This strategy enables flexible and condition-based modelling of infrastructure heritage, while ensuring both geometric reliability and semantic interoperability across multiple platforms and scales.

3.4 Integration of InfraHBIM and HGIS

Due to the heterogeneity of infrastructure heritage data, including documentary materials, spatial datasets, and three-dimensional models generated in different software environments, achieving unified integration and consistent representation within a single platform remains challenging. In particular, the integration of ADB, GeoDB, and InfraHBIM models requires interoperability while preserving both geometric reliability and semantic information. To address this, the study adopts a GIS-oriented platform as the central environment for organizing, integrating, and visualizing documentary, spatial, and model-based datasets within a unified HGIS framework.

The integration workflow operates through two complementary mechanisms. The first is the use of a common 12-digit identifier, which ensures consistent association between archival records, geospatial datasets, and InfraHBIM components. The second is the transfer of IFC-based semantic information into GIS attribute tables, enabling documentary, spatial, and model-based information to be queried and visualized within a single environment. Through these mechanisms, the framework supports multi-scale representation and data linkage across multiple historical stages. Rather than a simple one-way BIM-to-GIS transfer, it is conceived as a GIS-centered but cross-scale

integration framework in which InfraHBIM provides asset-level geometric and semantic reconstruction, while HGIS supports corridor-scale spatial organization, temporal interpretation, and unified access to multi-source information.

The integrated database derived from ADB and GeoDB was first imported into the HGIS environment. These datasets include: (1) raster data, such as corridor-scale DEM and DTM, asset-scale orthophotos and DEMs, and multi-temporal satellite imagery; (2) vector data, including railway alignments represented as line features and heritage assets represented as point features; and (3) archival images and documentary records linked through the common identifier. Together, they establish the geospatial and documentary basis for subsequent integration.

For the integration of built heritage models, bridge InfraHBIM models are developed in Revit with embedded geographic coordinates, while railway alignment models are reconstructed through the combined use of Civil 3D and Revit. Both types of models are exported in IFC4 format, preserving component-level geometry and semantic attributes. In parallel, point-cloud data acquired through field documentation are exported from CloudCompare in georeferenced.las format, and SLPK models generated from the processed point clouds are used to support efficient 3D visualization within the GIS environment.

All datasets are subsequently imported into ArcGIS Pro for unified organization and management. IFC files are parsed as 3D feature layers, and their component-level geometry and semantic attributes are mapped from IFC Property Sets to GIS attribute tables. This semantic transfer enables the inheritance of InfraHBIM information within the HGIS environment and supports both corridor-scale spatial analysis and asset-level information retrieval. The integrated models are represented at GIS Level of Detail (LoD) 3, which balances asset-level geometric interpretability with corridor-scale manageability.

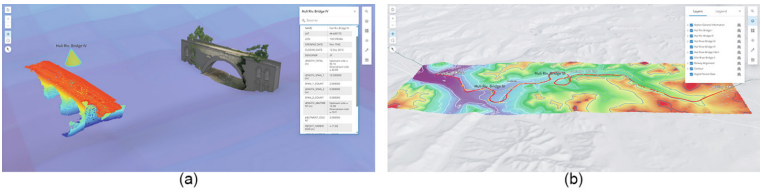


Fig. 12. Integrated results of the InfraHBIM–HGIS framework: (a) Integrated multi-source data of individual assets (ELBSAR1336AV and ELBCAJ1336BF); (b) Corridor-scale integration of built heritage assets within the Taipingling corridor (ascending line section).

Finally, the integrated results are published as Web Scenes via ArcGIS Pro and deployed on ArcGIS Online, enabling remote access, interactive visualization, and data sharing. Beyond online visualization, the WebGIS deployment allows users to navigate between corridor- and asset-level representations, retrieve associated archival materials, and access linked semantic information for individual heritage elements. In this way, the workflow establishes a unified framework for multi-scale representation, information query, and remote accessibility of infrastructure heritage (see Fig. 12).

4 Conclusion and Future Work

This study proposed a corridor-oriented InfraHBIM–HGIS framework for documenting and reconstructing infrastructure heritage characterized by large spatial extents, fragmented asset distribution, complex historical transformations, and heterogeneous data sources. Using the Taipingling Corridor of the Chinese Eastern Railway as a case study, it demonstrated the integration of archival records, geospatial datasets, InfraHBIM models, and HGIS within a unified workflow for multi-scale and multi-temporal heritage representation.

The results show that the framework supports coordinated reconstruction at both corridor and asset levels. By combining an archival database, a geospatial database, condition-based modelling strategies, and a GIS-centered integration environment, it enables the linkage of documentary, spatial, and model-based information across multiple historical stages. The combined use of forward and reverse modelling supports the reconstruction of extant, vanished, and transformed assets under different evidence conditions, while WebGIS-based deployment improves remote access, visualization, and information sharing.

Several limitations remain, including uneven archival documentation across historical phases, limited absolute georeferencing accuracy due to the absence of ground control points, incomplete field documentation caused by accessibility constraints, continued reliance on commercial software ecosystems, and validation restricted to selected assets within a single railway corridor.

Future work will extend the framework to additional corridor sections and more diverse infrastructure heritage assets, while improving reconstruction accuracy through stronger survey control where feasible. The integration of extended reality technologies will also be explored to support immersive visualization, interactive interpretation, and public dissemination of infrastructure heritage.

Acknowledgments. This work was supported by the China Scholarship Council. The authors also acknowledge the assistance of Prof. Yan Wang from the School of Architecture and Design, Harbin Institute of Technology.

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

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

Secure Microservices Architecture for ICC-Topo: Cybersecurity Applied to a Graph-Based Curricular Analytics System

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Abstract. This paper presents the design and preliminary validation of a secure microservices architecture for ICC-Topo, a graph-based curricular analytics system for higher education. The objective was to develop an initial architecture that integrates DevSecOps principles and selected OWASP controls without compromising ICC computation. The study followed a quantitative, non-experimental, cross-sectional approach framed by Design Science Research and combined STRIDE and LINDDUN risk modeling, architectural design, prototype implementation, and functional, security, and exploratory performance assessment. The main results were the integration of six core components, end-to-end verification of the principal analytical flows and key security controls, successful processing of 52 of 57 curricular meshes, and a controlled concurrent-load characterization over representative analytical scenarios. These findings provide preliminary evidence that secure curricular analytics can be operationalized in a distributed academic platform, although broader privacy validation, ASVS coverage, and advanced DevSecOps automation remain open.

Keywords: Access control · DevSecOps · higher education security

1 Introduction

The digital transformation of higher education institutions has increased dependence on platforms that process curricular information and student trajectories to support academic decision-making, institutional evaluation, and program redesign. Within this context, graph-based curricular analytics has become a useful approach for representing curricula as prerequisite networks, identifying bottleneck courses, estimating structural complexity, and analyzing academic progression [23,26,28–30,37].

However, when these analytical capabilities are deployed as distributed services, the challenge is no longer exclusively mathematical or curricular. It also becomes a cybersecurity problem. The literature on microservices shows

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 159–176, 2026.
https://doi.org/10.1007/978-3-032-30524-4_11

that functional decomposition improves modularity, scalability, and independent deployment, but it also enlarges the attack surface, multiplies APIs, increases authentication and authorization complexity, and makes it more difficult to maintain coherent security policies across services [4,8,15,17]. In academic settings, this complexity is especially sensitive because the managed data include curricular structures, histories, trajectories, and patterns that may influence institutional decisions and therefore require protection in terms of confidentiality, integrity, availability, privacy, and traceability [16,23–25].

Recent literature has advanced on several related fronts, although usually in a fragmented manner: inter-service security and threat mitigation in microservices [3,15,32], Zero Trust and differentiated protection of North-South and East-West traffic [21], API gateway hardening through JWT and rate limiting [13,22,27,36], decoupled authorization through RBAC and token-based mechanisms [5,18,34], structured evaluation with OWASP ASVS and security maturity approaches [9,35], DevSecOps as a verifiable lifecycle property [1,2,6,7,10,11,14,33], and graph-oriented educational modeling [12,20,31]. Despite these advances, a clear integration gap remains because most studies do not converge into a single architecture for the academic domain that combines graph-based curricular analytics, distributed security, access control, student privacy, and reproducible validation [15,20,23,34].

From that gap, ICC-Topo becomes justified. The research proposal is aligned with the research line of Information Technology and Information Systems and with the subline of Networks and Information Security because it designs a secure microservices architecture for a system that processes institutional academic information and incorporates secure development practices, OWASP controls, and privacy-oriented mechanisms.

The scientific problem addressed in this paper is how to design and validate a secure microservices architecture for the ICC-Topo system that integrates DevSecOps practices and selected OWASP controls while protecting academic information. Accordingly, the objective of the article is to develop and validate such an architecture without compromising ICC computation. Unlike prior studies that address curricular analytics, API security, or DevSecOps practices in a fragmented manner, ICC-Topo integrates graph-based curricular analysis, distributed academic microservices, OWASP-aligned controls, STRIDE/LINDDUN risk modeling, and observable security validation into a unified architecture for higher-education curricular analysis. Its originality therefore lies in the operational integration of these dimensions within an academic analytical environment rather than in proposing an isolated security mechanism. The main contributions are fourfold: organizing the state of the art around security-aware curricular analytics, presenting a distributed architecture with implemented controls, documenting functional, security, and exploratory performance evidence, and explicitly identifying the elements that still require consolidation for advanced validation.

2 Theoretical Background and Related Work

2.1 Curricular Analytics and Graph-Based Educational Modeling

Curricular analytics interprets curricula as structured networks in which courses and prerequisites can be represented through graph-based models. This perspective supports the identification of bottlenecks, the estimation of structural complexity, and the analysis of academic progression. Prior work has shown the value of course-prerequisite networks and related graph-based methods for understanding curricular behavior and supporting curriculum assessment and redesign [26,28–30,37]. Additional educational graph initiatives, including knowledge-graph approaches, reinforce the relevance of graph-centered representations for precise and scalable academic analysis [20,31].

2.2 Security Challenges in Microservice Architectures

Microservice architectures provide scalability, modularity, and independent deployment, yet they also introduce increased API exposure, token abuse, inter-service trust problems, access-control inconsistencies, denial-of-service risks, and greater operational complexity [4,8,15,17]. Zero Trust principles, differentiated traffic protection, and layered security have therefore become central in distributed environments [3,21,32]. API gateways are commonly used for authentication, request filtering, observability, and rate limiting, but gateway-only protection is insufficient without internal validation and authorization [19,22,27,36]. Likewise, token-based authentication requires complementary authorization mechanisms such as RBAC [13,18,34].

2.3 DevSecOps, OWASP ASVS, and Privacy-Oriented Security

DevSecOps frames security as a verifiable property of the software lifecycle rather than as a late-stage addition and supports secure design, automated verification, dependency review, scanning, and operational traceability [1,2,6,7,10,11,14,33]. In parallel, OWASP ASVS offers a structured model for assessing web and API security across architecture, authentication, cryptography, access control, data protection, logging, and API-specific controls [9,35]. Privacy is equally relevant in academic systems because educational platforms process trajectories, patterns, and potentially identifiable combinations of attributes [16,24,25].

3 Methodology and Approach

3.1 Research Design

The study adopted a quantitative, non-experimental, and cross-sectional approach in accordance with the academic proposal. Design Science Research served as the methodological framework because the main outcome was a technological artifact that had to be designed, implemented, and evaluated against a practical and scientific problem.

The process was organized into three phases. Phase I focused on the security model and risk analysis through STRIDE for application and network threats and LINDDUN for privacy analysis. Phase II addressed the design of the microservices architecture, the selection of OWASP ASVS-aligned controls, secret-management considerations, and REST communication over HTTPS/TLS. Phase III covered implementation and validation through unit testing, integration checks, API security validation, and basic performance assessment. In methodological terms, privacy was addressed in this article at the design and control-selection level, whereas formal re-identification experiments and empirical k-anonymity verification were explicitly delimited as a later validation stage.

3.2 System Context and Data Inputs

ICC-Topo was conceived to support curricular complexity analysis from curricula modeled as directed acyclic graphs. The system manages academic catalogs, authenticates users, enforces role- and permission-based access control, executes ICC analysis over curricular structures, and stores results for historical consultation.

According to the proposal, the study relied on three classes of inputs: curricular reference data for UPSE and UTEQ, aggregated academic data for analytical processing, and synthetic data for functional and security testing. In the implemented prototype, information is loaded through Excel files with the sheets `courses` and `prerequisites`. These sheets encode subjects, credits, semesters, and prerequisite relationships.

For batch validation, 57 curricular meshes were considered. Of these, 52 were processed successfully and 5 were excluded because of input inconsistencies, specifically credits lower than or equal to zero and duplicated course identifiers. In total, the batch comprised 2423 courses and 1353 prerequisites, with averages of 42.51 courses and 23.74 prerequisites per processed mesh.

3.3 Experimental Environment and Reproducibility

The validation environment corresponded to the workstation `DESKTOP-DEV-PAC`, running Microsoft Windows NT 10.0.26200.0 on AMD64 architecture, with processor identifier `AMD64 Family 25 Model 97 Stepping 2, AuthenticAMD` and 31.9 GB RAM. The deployed functional architecture integrated an Angular frontend, Java-based gateway and services using Spring Boot and Spring Cloud Gateway, a Python analytical backend with FastAPI, and PostgreSQL persistence. During consolidation, a compilation issue in `spring-gateway` associated with Lombok usage without an active dependency was corrected, and Maven compilation of the gateway was validated for the reported phase.

Reproducibility was supported through observable artifacts and versions in the workspace. The frontend `front-icc` uses Angular 18.2.x, PrimeNG 18.0.0, Chart.js 4.5.1, and TypeScript 5.5.2. The services `spring-auth` and `spring-core` use Spring Boot 3.2.4 on Java 17, whereas `spring-gateway` uses

Spring Boot 3.2.4 with Spring Cloud Gateway 2023.0.0. The analytical engine `fastapi-icc` declares FastAPI 0.104.1, Uvicorn 0.23.2, Pydantic 2.5.3, NetworkX 3.2.1, Pandas 2.1.4, and Pytest 8.3.5. Persistence relies on PostgreSQL 15-alpine as declared in `docker-compose.yml`.

The deployment structure was documented in `docker-compose.yml`, where `postgres-db`, `spring-gateway`, `spring-auth`, `spring-core`, and `fastapi-icc` were explicitly defined, together with the reverse proxy and development frontend. Reproducibility was further supported by preserved validation artifacts, including the input template `template_malla.xlsx` and the generated output files `analyze_mallas_20260327_030726.json`, `analyze_mallas_20260327_171508.json` and `load_test_analyze_demo_20260327_173644.json`. The explicit exclusion criteria for meshes were credits lower than or equal to zero and duplicated course identifiers. A stable repository release identifier was not included in the validation artifact; reproducibility therefore relies on the reported versions, declared modules, and referenced artifacts.

3.4 Risk Modeling and Security Framing

Phase I formalized the security and risk-management model. STRIDE supported the identification of threats related to spoofing, tampering, repudiation, information disclosure, denial of service, and privilege escalation. LINDDUN was applied to analyze privacy risks such as re-identification, excessive traceability, and improper disclosure of student trajectories.

The resulting prioritization focused on unauthorized access to academic information, token theft or abuse, privilege escalation, massive data extraction, denial of service against APIs, and student re-identification through combinations of attributes and queries. The formal model also considered three dominant threat profiles: an automated external attacker, a curious or malicious authenticated user, and an insider or compromised administrator. Quantitative pre-control prioritization highlighted massive data extraction and token abuse as the most relevant risks, followed by re-identification, privilege escalation, and denial of service.

3.5 Architectural Design

In accordance with the proposal, the architecture integrates the following technological components: an Angular single-page application frontend, a security and gateway layer in Spring Boot and Spring Cloud Gateway, an authentication backend in Spring Boot, an analytical backend in Python with FastAPI, and PostgreSQL as the database engine.

The repository materializes this design in five modules: `front-icc`, `spring-gateway`, `spring-auth`, `spring-core`, and `fastapi-icc`. The implemented functional flow is:

```
front-icc -> spring-gateway -> spring-auth/spring-core ->
                fastapi-icc -> PostgreSQL
```

Under this design, the frontend does not consume the analytical engine directly. Instead, `spring-core` acts as the internal consumer, thereby reducing direct exposure and increasing control over internal access.

Architecturally, the public edge is located between the browser and `spring-gateway`, whereas communication among `spring-gateway`, `spring-auth`, `spring-core`, and `fastapi-icc` corresponds to the internal service plane. This separation distinguishes North-South flows for external access and East-West flows for internal service coordination.

Figure 1 formalizes the implemented architecture, trust boundaries, and associated controls introduced in this design layer.

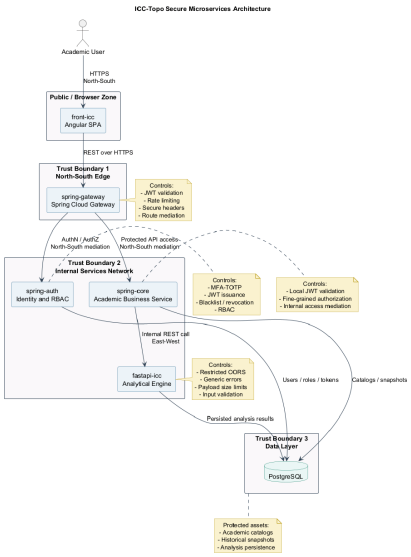

Fig. 1. Formal architecture of ICC-Topo, including components, trust boundaries, and North-South and East-West flows.

3.6 OWASP Controls, DevSecOps Orientation, and Validation Protocol

Based on the prioritized risks, the study selected OWASP ASVS Level 2-related categories for architecture, authentication, access control, session management, error handling, data protection, and API security. In parallel, Phase II established a DevSecOps framework intended to make security a verifiable lifecycle property. The framework mapped prioritized risks to ASVS categories covering architecture, authentication, cryptography, access control, data protection, logging, and API security. It also established as a reference horizon the future integration of SAST, dependency analysis, SBOM generation, container scanning, and DAST baseline testing.

The prototype implemented the following observable controls: JWT authentication with `jti`, blacklist-based invalidation in logout and refresh, JWT validation at the gateway, additional local validation in `spring-core`, granular authorization based on role, option, and action, IP-based rate limiting, secure headers at the gateway, restricted CORS in FastAPI, generic error responses in the analytical engine, temporary lockout after failed attempts, anti-DoS limits on analytical payloads, and TOTP-based multi-factor authentication for administrators.

The hardened operational parameters were the following (Table 1).

Table 1. Implemented hardening parameters

Hardening parameter	Value
Failed attempts before lockout	5
Temporary lockout duration	15 min
Login request limit	5 per 60 s
Maximum analytical request size	1 MB
Maximum number of courses per mesh	200
Maximum number of prerequisites per mesh	800

These values defined the protective thresholds adopted for the prototype and framed the subsequent validation activities.

Phase III assessed the architecture through functional testing of demo analysis, persisted analysis using `mallaId`, and analysis history retrieval, as well as CRUD validation for the Users (`Usuarios`), Menu Options (`Opciones`), Organizations (`Organizaciones`), Programs (`Programas`), and Curricular Meshes (`Mallas`) modules. Security validation included end-to-end checks of JWT blacklist, rate limiting, granular authorization in `spring-auth` and initial granular authorization in `spring-core`, functional validation of administrator MFA, and `pytest` plus Bandit execution over `fastapi-icc`. Exploratory performance evidence relied on endpoint latency measurements, a controlled gateway-facing rate-limiting check on demo analysis, and an additional concurrent-load campaign over representative analytical scenarios. Because rate limiting was configured as a protective policy, HTTP 429 responses in the burst series were treated as evidence of expected control activation rather than as system failure.

A functional flow was considered validated when it completed the expected end-to-end path and returned the corresponding system response. A security control was considered validated when its expected activation, blocking, or rejection behavior was observed under the tested condition. Performance was treated as exploratory in this phase and was assessed through basic latency observations and controlled activation of rate limiting. Accordingly, the fourth specific objective was interpreted as prototype validation through functional and operational security evidence, while advanced privacy-risk quantification was kept outside the empirical scope of the present phase.

Table 2. Prioritized STRIDE/LINDDUN risks and controls

Model	Threat	Asset	Control	Status
STRIDE	Massive data extraction	Gateway and analysis endpoints	Rate limiting, payload limits, edge control	Implemented
STRIDE	Token theft or abuse	Auth, gateway, core	JWT with `jti`, blacklist, MFA	Implemented
STRIDE	Privilege escalation	Auth and core	RBAC and backend double validation	Partial
STRIDE	Denial of service	Gateway and analytical engine	IP-based rate limiting and request-size limits	Implemented
LINDDUN	Re-identification through combined filters	Analytical service and exports	k-anonymity threshold and query restriction	Pending
LINDDUN	Linkability and disclosure	Outputs, logs, exports	Data minimization and aggregated outputs	Partial

Table 3. Validation evidence for prioritized threats

Threat	Evidence	Status
Massive data extraction	`429` triggered in load series B and login threshold observed	Implemented
Token theft or abuse	JWT blacklist validated; `challengeToken` rejected (`401`)	Implemented
Privilege escalation	RBAC validated in `spring-auth`; initial local checks in `spring-core`	Partial
Denial of service	Request-size limit configured to 1 MB; `429` activation observed	Implemented
Re-identification through combined filters	Risk modeled; empirical re-identification tests still pending	Pending
Linkability and disclosure	Individual student queries are not exposed; inference validation remains open	Partial

4 Results

4.1 Formalized Security Model and DevSecOps Framework

The first result was the formalization of the security and risk-management model, thereby fulfilling the first specific objective of the proposal. Critical assets, CIA-oriented considerations, and major threats affecting authentication, authorization, availability, privacy, and traceability were identified. The second result was the definition of a DevSecOps framework articulated with OWASP ASVS categories, which established an explicit relationship among risks, controls, and expected evidence.

Tables 2 and 3 summarize the prioritized risks, applied controls, and available evidence, preserving traceability between modeling and validation.

At the current stage, ASVS should be interpreted as an implementation matrix rather than as a closed compliance percentage. Table 4 therefore sepa-

rates what is already implemented from what remains partial or pending, thereby avoiding an overstatement of achieved maturity.

Table 4. Summarized ASVS matrix for the ICC-Topo prototype

ASVS	Control	Implementation snapshot	Status
V1 Architecture	Separation of domains and defense in depth	Gateway, auth, core, analytics, and persistence are decoupled	Implemented
V2 Authentication	JWT lifecycle, lockout, MFA	JWT with `jti`, temporary lockout, and TOTP-based MFA	Implemented
V3 Cryptography	Protection of tokens and secrets	JWT signing active; vault-based secret management pending	Partial
V4 Access control	Least-privilege authorization	RBAC by role, option, and action; local checks in core	Partial
V7 Error handling and logging	Error handling and traceability	Generic responses active; centralized traceability incomplete	Partial
V8 Data protection	Minimization and restricted outputs	Aggregated results only; formal anonymization still pending	Partial
V10 API security	Traffic abuse control	Rate limiting, restricted CORS, and payload limits	Implemented

The detailed evidence behind this matrix is provided in the risk tables and in the results on MFA, blacklist validation, rate limiting, and restricted analytical inputs.

4.2 Implemented Architecture and Functional Validation

The implemented architecture consisted of six main components: Angular frontend, gateway, authentication service, academic core, analytical engine, and PostgreSQL persistence. This separation of responsibilities materialized the third specific objective and aligned with the proposed distributed design. For the analytical path, the consolidated route was `front-icc -> spring-gateway -> spring-core -> fastapi-icc`, while authentication and permission management remained centralized in `spring-auth`. PostgreSQL supported catalogs and analytical snapshots. Table 5 links the implemented layers with their main trust boundaries and associated controls.

Functional validation showed correct operation in three main ICC-domain flows: demo analysis, persisted analysis with `mallaId`, and analysis history

Table 5. Components, trust boundaries, and associated controls

Layer or boundary	Main components	Flow type	Associated controls
Public edge	Browser and `front-icc`	North-South	Initial authentication, authenticated session, and no direct access to the analytical engine
Service perimeter	`spring-gateway`	North-South	JWT validation, secure headers, rate limiting, and route control
Identity and authorization	`spring-auth`	East-West internal	Token issuance and revocation, TOTP-based MFA, and RBAC
Academic business logic	`spring-core`	East-West internal	Additional local JWT validation and fine-grained authorization
Internal analytics	`fastapi-icc`	East-West internal	Restricted CORS, generic errors, and anti-DoS payload limits
Persistence	PostgreSQL	Internal	Support for catalogs and snapshots; advanced privacy safeguards still require formal validation

retrieval. In addition, five administrative CRUD modules were validated: Users, Menu Options, Organizations, Programs, and Curricular Meshes. The frontend supported Excel upload, template download, pre-validation of files, indicator visualization, the `iccBySemester` chart, structural graph rendering, and tabular views, confirming that the platform already operates as a curricular analytics prototype.

4.3 Observable Security Results

At the current stage, four security controls were functionally and end-to-end verified: JWT blacklist, rate limiting, granular authorization based on roles, options, and actions, and administrator multi-factor authentication. The architecture also incorporates token revocation, double JWT validation, anti-DoS limits, restricted CORS, generic responses, and temporary lockout after failed attempts.

Within the MFA flow, it was verified that administrative login could return intermediate setup and verification states, that a valid TOTP code completed authentication, and that the `challengeToken` could not be used as a final token on protected endpoints. These observations show that the implemented controls were not only configured but also operational under the tested scenarios.

4.4 Integrated Visual Evidence

Figure 2 summarizes representative interface evidence supporting authentication, analysis execution, and persistence behavior; the remaining screenshots are treated as supplementary material.

4.5 Automated Evidence

In the analytical engine `fastapi-icc`, the current automated test suite reported 9 tests passed in 1.05 s. This result supports the basic consistency of both ICC computation and the FastAPI implementation. Additionally, the local Bandit execution reported no findings, indicating the absence of evident static-security issues in the current pass. Although this result does not replace a comprehensive security evaluation, it does provide favorable technical evidence for the prototypical stage.



Fig. 2. Representative interface evidence: administrator MFA verification, curricular-mesh analysis, and persisted execution history.

Table 6. Observed latency in main endpoints

Endpoint	Requests	Min (ms)	Avg. (ms)	Max (ms)	Observation
Login	5	55.81	207.04	290.54	The next attempt returned `429`, confirming rate limiting
Demo analysis	3	15.33	108.20	288.26	First request was higher because of warm-up cost
Persisted analysis	3	17.57	77.13	194.98	Initial request was higher, then stabilized
History detail	3	15.03	87.47	228.13	Query stabilized after first access

4.6 Batch Processing and Data Quality

Batch runs performed with the Python script registered 92 attempts, of which 52 returned HTTP 200, 32 corresponded to transient HTTP 401 responses, and 8 were associated with local data-quality errors. After consolidation by mesh, 57 meshes were considered, with 52 successful cases and 5 excluded because of input inconsistencies.

The excluded meshes presented two types of issues: courses with credits lower than or equal to zero and duplicated course identifiers. This finding was not interpreted as a system failure but as evidence that input-validation mechanisms prevented the processing of defective curricular structures and protected traceability of the analysis.

4.7 Exploratory Performance Evidence

Table 6 summarizes the observed latency in the main system endpoints.

The earliest requests showed higher latency because of initialization and cache warm-up. Later runs declined toward lower and more consistent values, a behavior coherent with distributed architectures involving component startup, security validation, and persistence access.

Table 7. Controlled concurrent-load observations in the local environment

Scenario	Concurrent users	Avg. (ms)	p95 (ms)	Error rate	Req/s
Demo analysis	5	17.02	27.69	0.00	293.80
Demo analysis	10	31.88	49.80	0.00	313.20
Demo analysis	20	59.00	78.08	0.00	338.30
Persisted analysis	5	19.87	29.97	0.00	251.55
Persisted analysis	10	33.65	50.58	0.00	297.35
Persisted analysis	20	65.53	86.77	0.00	305.70
History detail	5	6.14	7.52	0.00	813.50
History detail	10	7.78	9.75	0.00	1284.15
History detail	20	10.08	12.50	0.00	1982.75

To strengthen the validation, an additional controlled concurrent-load campaign was executed in the local environment using a valid curricular mesh with 40 courses and 35 prerequisites. Three representative scenarios were evaluated: demo analysis, persisted analysis, and history-detail retrieval. For each scenario, the system was exercised with 5, 10, and 20 concurrent virtual users during a fixed 20-second window. The observed metrics included average latency, 95th-percentile latency, error rate, and throughput in requests per second.

Because the gateway-level rate-limiting policy is intentionally restrictive for abuse prevention, the concurrent campaign was configured to characterize business-flow behavior without letting that protective threshold dominate

the measurements. Accordingly, the measurements should be interpreted as exploratory but reproducible evidence of prototype behavior under controlled local concurrency, not as a full-scale production benchmark.

Table 7 summarizes the observed results.

An additional gateway-facing check on demo analysis showed stable responses under a short sequence of 10 consecutive requests, whereas a subsequent 20-request burst activated the configured rate-limiting threshold and returned HTTP `429`. These responses were therefore interpreted as expected abuse-prevention behavior rather than as service degradation.

The concurrent-load results show a consistent increase in latency as concurrency rises, which is expected in the analyzed flows, while the error rate remained at zero in all tested cases. Demo and persisted analysis exhibited higher response times than history-detail retrieval because they involve analytical execution and additional backend coordination. In contrast, the history-detail scenario showed the highest throughput and the lowest latency range, indicating that read-oriented retrieval remained comparatively lightweight in the tested environment.

Resource observations during the campaign showed that the academic core concentrated the highest operational load among the application services, whereas the analytical backend and auxiliary security services remained comparatively stable during the measured window. These findings do not yet constitute a full resource-consumption model, but they do provide initial evidence that the prototype remained operational under controlled concurrent access without functional failure in the tested scenarios.

4.8 Quantitative Synthesis

In quantitative terms, the validated prototype integrated six main components, three end-to-end ICC flows, five administrative CRUD modules, and four security controls with direct observable evidence. Batch execution considered 57 meshes, of which 52 were processed successfully and 5 were excluded because of data-quality issues. The processed set comprised 2423 courses and 1353 prerequisites, with averages of 42.51 courses and 23.74 prerequisites per mesh. In addition, the `fastapi-icc` test suite reported 9 passing tests in 1.05 s, while the enforced hardening thresholds remained fixed at 5 failed attempts before lockout, 15 min of temporary lockout, 5 login requests per 60 s, 1 MB per analytical request, 200 courses per mesh, and 800 prerequisites per mesh.

5 Discussion

The results show that the proposal moved from conceptual design to a distributed prototype with direct observable evidence. This is consistent with literature arguing that microservice security should be implemented and tested rather than stated only at the principle level [4,8,15]. The architecture aligns with prior work on gateway-mediated protection, JWT-based authentication,

RBAC, and measurable DevSecOps and ASVS practices [1,7,9,18,22,27,34–36]. Its distinguishing factor is contextual: the protected assets are curricular structures, trajectories, and institutional indicators rather than generic enterprise records [23,29,30,37].

The empirical evidence supports the applied relevance of the artifact. Processing 52 of 57 curricular meshes shows that the system goes beyond a toy scenario, while the exclusion of 5 inconsistent meshes suggests that input-validation mechanisms protected analytical integrity instead of forcing invalid computations. MFA, blacklist validation, RBAC checks, and rate limiting provide a coherent set of controls, although broader validation is still needed.

From an applied university perspective, these results also have governance implications. Separating trust boundaries between external access, identity management, academic business logic, and analytical execution reduces direct exposure of the analytics engine and improves control over curricular indicators that may inform accreditation, redesign, and institutional decision-making. In that sense, the contribution is not limited to API hardening; it also supports a more controlled handling of academic data and institutional metrics in distributed higher-education environments.

Performance evidence should still be interpreted as preliminary only. The measured latencies, the concurrent-load campaign, and the controlled rate-limiting activation provide stronger operational observations under local conditions, but they do not amount to a production-capacity benchmark or a full multi-environment resource characterization.

Table 8. Conceptual comparison between a simpler baseline and the ICC-Topo prototype

Dimension	Simpler baseline	ICC-Topo prototype	Evidence status
Analytical service exposure	Frontend may consume analytical endpoints directly	Access mediated through `spring-gateway` and `spring-core`	Implemented
Authentication and business logic	Coupled or partially shared backend responsibilities	Identity handled in `spring-auth`; business logic isolated in `spring-core`	Implemented
Token validation	Single validation point or gateway-only enforcement	Gateway validation plus additional local validation in `spring-core`	Implemented
Authorization granularity	Coarse endpoint protection	RBAC by role, option, and action	Partial
Abuse resistance	No explicit throttling or payload restrictions	IP-based rate limiting and analytical payload limits	Implemented
Administrative hardening	Password-only administration	Temporary lockout and TOTP-based MFA for administrators	Implemented
Privacy safeguards	Limited separation between query and export concerns	Aggregated outputs and restricted analytical exposure; formal anonymization pending	Partial
Validation maturity	Functionality may be demonstrated without explicit security evidence	Functional, security, and exploratory performance evidence over the prototype	Partial

5.1 Comparison with a Conceptual Baseline

Although no A/B experiment or monolithic benchmark was performed, a conceptual comparison can still be made with a simpler baseline in which the frontend consumes the analytical engine directly or in which authentication, authorization, and business logic remain coupled. Relative to that baseline, ICC-Topo introduces gateway mediation, separation between identity and business logic, additional internal validation in `spring-core`, and reduced direct exposure of the analytical service.

Table 8 shows that the improvement demonstrated at this stage is mainly architectural and related to controllability, reduced direct exposure, and observability of security controls rather than to a universal quantified reduction of risk.

5.2 Privacy, Data Minimization, and Remaining Risks

The privacy dimension must be interpreted more cautiously than the operational security dimension. The system works with aggregated results, does not expose individual student queries, and limits export to the aggregated plane, which constitutes an initial data-minimization strategy aligned with the developed LINDDUN model. However, risks of linkability, disclosure, and inference cannot be considered closed solely because of functional restriction. Formal validation of k-anonymity, measurement of re-identification risk, and verifiable suppression or anonymization techniques remain pending tasks.

5.3 Threats to Validity

Internal validity is conditioned by the fact that most of the evidence comes from functional testing, operational control validation, and exploratory performance measurements in a local environment. External validity is moderate because the results rely on 57 curricular meshes and on a specific academic context. Construct validity also requires caution because the observed security reflects activation of selected controls, not comprehensive certification against the full ASVS catalog or all LINDDUN scenarios. Additional limitations include warm-up effects, transient `401` responses during batch runs, bounded concurrent-load scenarios, and the lack of empirical privacy-risk quantification.

5.4 Limitations and Future Work

The study still has clear limits. Although the current version includes a controlled concurrent-load campaign with latency, percentile, throughput, and initial resource observations, the evidence comes from a local environment and should not be interpreted as a production-capacity benchmark. Pending elements therefore include multi-environment performance replication, deeper per-service resource profiling, an evidence-based ASVS compliance percentage, formal re-identification and k-anonymity testing, CI/CD security automation, and reproducible SAST, SCA, and DAST reports.

6 Conclusions

The study made it possible to develop a secure microservices architecture for ICC-Topo, aligned with the academic proposal and grounded in an explicit sequence of risk modeling, control selection, prototype implementation, and initial validation. The integration of frontend, gateway, authentication, academic business logic, analytical engine, and persistence indicates that the project already has a technological base for graph-based curricular analytics. In that sense, the work fulfills the general objective and the first three specific objectives through explicit risk modeling, DevSecOps and OWASP framing, and implemented architectural separation with verifiable controls.

The main empirical contribution lies in connecting prioritized risks, implemented controls, and verifiable evidence across three ICC flows, five administrative CRUD modules, MFA, JWT blacklist, rate limiting, batch processing, automated testing of the analytical engine, and controlled concurrent-load observations. This evidence also supports fulfillment of the fourth specific objective at the level of functional, security, and exploratory performance validation. Nevertheless, the scope must remain realistic: ASVS coverage, formal privacy validation, and advanced security automation still require consolidation. Consequently, the present contribution should be understood as an implemented prototype with a clear methodological path toward a more complete validation phase. The study also demonstrates that security-aware curricular analytics can move beyond conceptual discussion toward an operational distributed prototype with integrated cybersecurity controls for higher-education environments.

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

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Deep Learning-Based Acoustic Event Detection in IoT Edge Devices

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Abstract. Acoustic event monitoring in high-variability scenes requires edge-aware intelligence that preserves privacy while operating under memory and compute constraints. We present an integrated IoT-to-edge workflow that combines ESP32-C6 acquisition, timestamped local storage, and multi-stage data curation to train acoustic classifiers from field recordings. We benchmark CNN, TCNN, GRU, LSTM, and attention-based CRNN models on 16 kHz mel-spectrograms, reaching up to 95.6% Macro-F1 and 95.3% accuracy. Results show that CRNN/LSTM maximize discrimination, whereas TCNN provides stronger probability reliability. This study is a laboratory validation setting (TRL 2–3: pre-deployment): no real-time inference has yet been executed on the ESP32-C6 platform. The study focuses on reproducible edge-aware offline experimental evaluation. These findings support informed pre-deployment model selection in real-world IoT scenarios, where reliability and resource efficiency must be jointly optimized.

Keywords: Internet of Things · Deep Learning · Edge AI · Acoustic Event Detection · Smart Environments

Nomenclature

Acronym	Definition
CNN	Convolutional Neural Network
CRNN	Convolutional Recurrent Neural Network
GRU	Gated Recurrent Unit
LSTM	Long Short-Term Memory
TCNN	Temporal Convolutional Neural Network
IoT	Internet of Things
ESP32	Espressif Systems 32-bit Microcontroller

1 Introduction

IoT acoustic sensing systems must characterize speech, impacts, alerts, and background noise under high scene variability, intermittent connectivity, and limited edge resources, ideally without continuous raw-audio offloading. Prior work

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 177–194, 2026.
https://doi.org/10.1007/978-3-032-30524-4_12

shows that recording conditions strongly affect generalization [25,30], while IoT and edge-computing studies emphasize local processing for latency and resilience [2,3,34,35]. Communication-centric MEC analyses further detail orchestration constraints in heterogeneous networks. In practice, these constraints define a multi-objective design space where accuracy, memory footprint, latency, and reliability must be co-optimized rather than tuned independently [5,24,36,39].

Unlike prior works that evaluate models in isolation on benchmark datasets, this paper contributes a reproducible, leakage-safe, calibration-aware evaluation framework grounded in real IoT acquisition. The main contribution is an integrated IoT-to-edge workflow that bridges real-world data acquisition with calibration-aware model selection under deployment constraints.

This work applies three techniques: (1) adaptive firmware-triggered acquisition and multi-stage curation with leakage-safe partitioning; (2) a unified comparative evaluation of CNN, TCNN, GRU, LSTM, and CRNN under discrimination, calibration, and complexity criteria; and (3) a pre-deployment selection protocol based on auditable run artifacts and trade-off analysis. This study links real-world acoustic acquisition with edge-aware model selection in an end-to-end pipeline. The contribution focuses on integration and evaluation rather than new architectures. Specifically, the evaluation corresponds to technology readiness level (TRL) 2–3 (laboratory validation / proof-of-concept): experiments are offline in a laboratory validation setting rather than on embedded fielded inference. We emphasize that "edge-aware" in this study refers to constraint-informed evaluation design, not validated embedded inference on the ESP32-C6.

1.1 Edge AI and IoT Architectural Perspective

The proposed system follows a layered Edge AI architecture where each layer solves a distinct function under resource constraints: (i) *sensing layer* for event-triggered acquisition and local persistence, (ii) *edge analytics layer* for lightweight filtering and feature-oriented preprocessing, and (iii) *modeling layer* for offline training and periodic model refresh. This decomposition is consistent with current edge-intelligence design recommendations [34,35] and broader convergence analyses between deep learning and edge systems [14].

In this framework, we view edge operation as orchestrating heterogeneous compute roles rather than running the largest model on the smallest device. The study therefore focuses on integration and evaluation: we compare model families under an edge-aware feasibility protocol using a real acquisition-to-training pipeline. Full on-device inference on the ESP32-C6 remains future work; the present results provide offline, laboratory validation.

We hypothesize that CRNNs yield better discrimination in constrained edge settings because they capture local transients (convolutions) and temporal context (recurrent layers) while keeping a modest footprint.

2 Related Work

Recent acoustic-event literature shows three stable findings relevant to this paper: (i) spectrogram-based deep models consistently outperform handcrafted features in multi-class sound recognition [28,31]; (ii) temporal modeling (CRNN

and recurrent variants) improves robustness in non-stationary scenes [1,6]; and (iii) edge deployment requires joint analysis of discrimination, calibration, and model size rather than accuracy alone [5,34–36]. Our study focuses on this integrated perspective with field-recorded data and leakage-safe evaluation.

From a methodological standpoint, two additional technical aspects remain underemphasized in many prior pipelines: domain-shift sensitivity and confidence quality. Cross-dataset evidence indicates that performance can degrade notably when recording conditions, microphones, or scene priors differ from training assumptions [9,25,30]. In parallel, calibration studies show that modern deep classifiers may produce overconfident probabilities even when top-1 accuracy is high, which directly impacts threshold-based alerting in IoT operation [13,26,29,40]. These findings motivate our use of leakage-safe splits and explicit calibration reporting as first-class evaluation criteria rather than secondary diagnostics.

Recent progress in audio representation learning has shifted toward large-scale pretraining and transferability. AudioSet-scale supervision and pretrained audio networks improve robustness under dataset shift [10,16,23], while transformer-based models report strong cross-benchmark performance in environmental sound analysis [7,11,12,21]. In self-supervised settings, CPC and wav2vec-family approaches support low-label adaptation in acoustic tasks [4,17,33,41]. Cross-domain architectural transfer has also influenced audio modeling practice: residual and channel-attention mechanisms improve feature reuse [15,20,22], mobile-oriented designs improve efficiency under constraints [8,18,19,32,37,38].

However, despite advances in large-scale pretraining, these approaches are rarely evaluated within fully integrated IoT-to-edge acquisition pipelines under real-world constraints. This motivates the methodological design presented in Sect. 3.

Table 1 summarizes representative prior studies in comparison with our approach. As observed, previous works focus primarily on controlled benchmark datasets such as ESC-50 and UrbanSound8K [30], whereas our study extends evaluation to real-world field-acquired data under IoT constraints. Additionally, prior works do not explicitly address edge-awareness and calibration reliability jointly, which are central to our methodology.

2.1 Model Families Considered in This Study

The model families compared in this paper cover complementary inductive biases: local spectral pattern extraction (CNN), recurrent temporal memory (GRU/LSTM), hybrid spectro-temporal modeling (CRNN), and temporal convolution dynamics (TCNN).

3 Methodology

This section describes IoT acquisition, dataset assembly and partitioning, feature extraction, model implementations, and evaluation protocol. We emphasize reproducibility and auditable experimental artifacts.

Table 1. Representative comparison between prior literature and this study.

Work	Dataset/Task	Model Family	Reported Result	Edge
Piczak (2015) [28]	ESC-50, environmental sound classification	CNN	64.5% accuracy (reported)	No
Salamon and Bello (2017) [31]	UrbanSound8K, augmented ESC setting	CNN + augmentation	73.7% accuracy on US8K (reported)	No
This work	Field AED with mixed real events	CNN, TCNN, GRU, LSTM, CRNN	95.6% Macro-F1 (best model) with calibration analysis	Partial

3.1 IoT Edge Acquisition and Adaptive Signal Processing

Each sensing node uses ESP32-C6 DevKitC v1.4, INMP441 digital microphone, NEO-6M GPS synchronization, and SPI microSD logging. Audio is captured at 32 kHz and stored as 16-bit PCM WAV. Figure 1 shows the wiring architecture used in field collection.

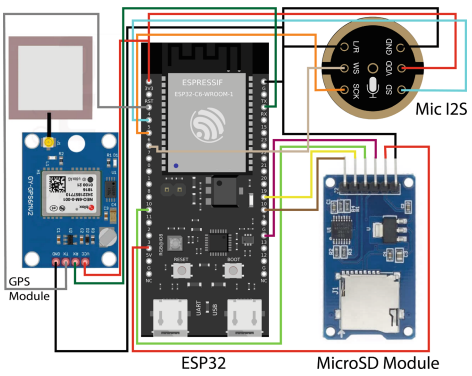

Fig. 1. Hardware architecture of the ESP32-C6 acoustic sensing node integrating I^2S microphone, SPI storage, and GPS synchronization. *Key takeaway: Autonomous edge acquisition with local persistence enables offline feature extraction and model training without raw-audio offloading.*

Triggering is based on adaptive short-term energy:

$$\tilde{x}[n] = \frac{x[n]}{2^{15}}, \quad \mathrm{RMS}_k = \sqrt{\frac{1}{N}\sum_{n=1}^{N} \tilde{x}_k[n]^2}, \quad L_k = 20\log_{10}(\mathrm{RMS}_k + \varepsilon) \tag{1}$$

$$B_k = \alpha B_{k-1} + (1-\alpha)L_k, \quad \Delta_k = L_k - B_k \tag{2}$$

with $\alpha = 0.92$, threshold $\theta = 3.5$ dB, pre-buffer $T_p = 2$ s and recording window $T_r = 6$ s.

Equation (1) computes RMS energy and converts it to a logarithmic level L_k for robust amplitude tracking. Equation (2) constructs an exponential moving

baseline B_k, so $\Delta_k = L_k - B_k$ measures deviation from background noise. The trigger fires on positive deviations to detect transient events while suppressing steady noise. This simple, streaming-friendly method avoids spectral transforms and reduces unnecessary transmission and storage in constrained IoT nodes.

Algorithm 1. Adaptive Edge Acoustic Triggering

```
Acquire audio block and compute L_k, B_k, and Δ_k
if Δ_k > θ and cooldown is satisfied then
    Append pre-buffer + current segment to WAV file
    Save timestamp and event metadata in event_log.csv
end if
```

3.2 Dataset Assembly and Partitioning

The curated corpus contains 6,400 clips across seven classes: car_horn, children, dog, ball, siren, ambient, and people. Source material combines proprietary field recordings with selected UrbanSound8K samples [30]. We applied balancing and targeted augmentation and used the high-frequency ratio R_{hf} to preserve child-vocalization spectral content. Specifically, targeted augmentation was applied to the real field recordings collected in educational environments to improve representation for classes that are frequent in school settings; augmentation procedures follow common practices in environmental-sound augmentation [31]. We note that several classes required additional augmented examples due to scarcity of natural samples, and that most proprietary recordings originate from a single institutional context, which constrains geographic and demographic generalization and should be considered when interpreting results [9,25].

Inclusion criteria: (i) event-labelled clips with unambiguous annotations; (ii) intact audio files without clipping or corruption; (iii) segments that pass the VAD filter (see Sect. 5.4) and with a minimum event duration after VAD of 0.5 s; and (iv) retention of spectral content indicated by R_{hf}. Exclusion criteria: corrupted files, clips with ambiguous or conflicting labels, recordings dominated by silence or non-informative noise, and event types judged irrelevant to the target educational context. These curation rules follow common dataset-assembly best practices [25,30] and are intended to reduce label noise and dataset leakage. We selected classes that are commonly present in educational environments due to their high prevalence and occurrence frequency; additional samples from UrbanSound8K were added when appropriate, while classes outside the scope of the educational/use-case context were discarded to keep the taxonomy task-relevant.

Table 2 provides descriptive statistics of the curated dataset, including class distribution, median duration, and signal intensity. These values highlight relevant variability across classes, particularly in duration and RMS levels, which motivates robust spectro-temporal feature extraction and class-aware training (Fig. 2).

Table 2. Descriptive statistics by class for the curated final dataset.

Class	Files	Median Duration [s]	Median RMS [dBFS]
car_horn	800	2.00	−23.3
childrens	1000	4.00	−31.5
bark_dog	1000	4.00	−25.5
kick_ball	1000	1.00	−26.0
siren	1000	4.00	−27.2
background_ambient	1000	4.00	−25.4
people	600	2.00	−36.2

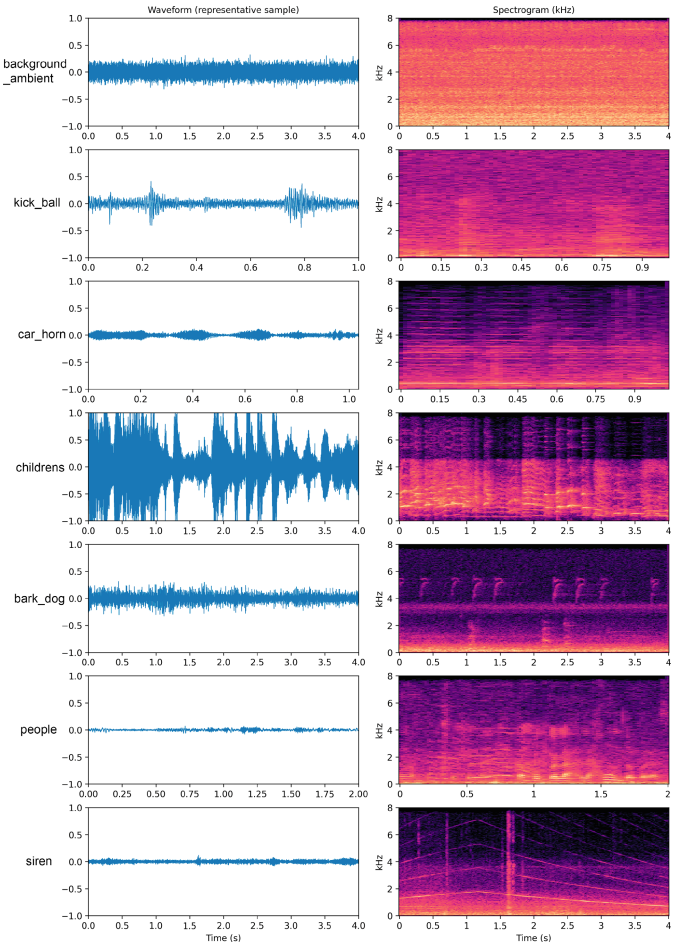

Fig. 2. Representative waveform and spectrogram examples for each target class in the curated dataset. *Key takeaway: Distinct spectro-temporal signatures across classes (e.g., ball transients vs. siren sweeps) motivate hybrid temporal modeling with attention mechanisms.*

The panels show qualitative differences used by downstream classifiers: ambient scenes present low-amplitude, broadband energy; *ball* events appear as brief, high-amplitude transients concentrated at higher frequencies; *car_horn* exhibits sustained tonal energy at lower frequencies; *children* vocalizations display longer-duration harmonic structure with variable pitch and energy; *dog* events present mid-frequency impulsive signatures; *people* clips are lower-energy speech-like segments; and *siren* shows strong narrowband sweeps. These distinctions motivate spectro-temporal representations and inform why hybrid models (CRNN, LSTM) can improve discrimination. If the figure prints in grayscale, note the relative time–frequency energy patterns (vertical intensity) and transient duration (horizontal extent) as the main visual cues.

Leakage-Safe Group Split in Training Workflow. To prevent contamination, splits are generated by group keys (`source_clip_id`, `device_id`, `session`) instead of individual clips. Groups are partitioned into train/validation/test = 70/15/15 with fixed seed, and augmentation is applied only to the training subset.

3.3 Deep Learning Stack

Each model (CNN, TCNN, GRU, LSTM, CRNN) is trained with the same protocol: 128-bin mel features, Adam optimizer (1×10^{-3}), class weighting, early stopping, and held-out test evaluation. Reported outputs include discrimination metrics (Macro-F1, Weighted-F1, Macro-Precision, Macro-Recall), ranking metrics (ROC-AUC, PR-AUC), and calibration error (ECE), together with model size indicators.

For each model family we follow a short, repeatable pipeline: load balanced manifest, map class indices, extract unified multi-channel features (mel, cepstral, temporal derivatives), split groups into train/validation/test as defined in Sect. 3.2, convert to batched tensors, and train with Adam (lr 1×10^{-3}), categorical cross-entropy, class weighting, and early stopping. After training, the notebook evaluates the held-out test set, records discrimination and calibration metrics, exports artifacts, and saves the final checkpoint.

Algorithm 2. Leakage-Safe Group Train/Validation/Test Split (Implemented Protocol)

1: **Input:** Manifest D with $(filepath, classID, source_clip_id, device_id, session)$
2: **Input:** Random seed $s = 42$
3: **Output:** Disjoint sets $(D_{train}, D_{val}, D_{test})$
4: Build group key $g = (source_clip_id, device_id, session)$
5: Aggregate one representative class label per group for stratification
6: Split groups into train/temp (70/30) with fixed seed s
7: Split temp groups into val/test (50/50) with fixed seed s
8: Assign each sample to the split of its group key g
9: Verify: no group appears in more than one subset

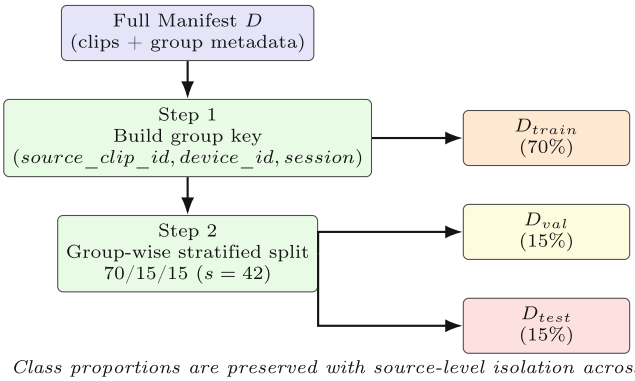

Fig. 3. Illustrative scheme of the implemented leakage-safe split policy: group-wise class-stratified partitioning (70/15/15). *Key takeaway: Group-level partitioning with source isolation prevents data contamination and ensures reproducible validation metrics under realistic deployment constraints.*

Under this protocol, class balance is preserved across subsets and experiments remain reproducible through fixed random seed while grouping by source context is enforced, which mitigates leakage risk from highly related clips when interpreting validation and test metrics (Fig. 3).

To address leakage-related concerns explicitly, all experimental results reported in Table 5 and Figs. 4, 5, 6 and 7 were obtained exclusively using the proposed split protocol (Sect. 3.2). No clip-level random splits were used.

Model Construction by Notebook (Layer Definition). Before presenting the common training flow, each notebook defines a specific network topology while preserving a shared design principle: a compact front-end for robust spectro-temporal representation and a softmax output layer for multi-class inference.

- **CNN baseline:** uses an EfficientNetB0 backbone without classification head (global average pooling output), followed by a dense projection block and final softmax layer.
- **TCNN:** stacks temporal convolutional blocks with convolution, batch normalization, ReLU activation, max-pooling, and dropout; features are aggregated with global average pooling and mapped through dense layers to softmax outputs.
- **GRU-attention:** applies a convolutional front-end (three Conv-BN-ReLU-pooling stages), reshapes features into temporal sequences, processes them with bidirectional GRU units, and applies an attention layer before dense classification.
- **LSTM-attention:** follows the same convolutional front-end and sequence reshaping strategy, replacing GRU with bidirectional LSTM recurrent units and attention-guided pooling before the softmax classifier.

– **CRNN-attention:** combines convolutional feature extraction, bidirectional recurrent encoding, and an attention-based aggregation head, ending in dense and softmax layers for final class probabilities.

Notebook-Based Training Workflow. During training we applied on-the-fly time–frequency augmentations inspired by SpecAugment to increase variability and robustness in model optimization [27].

Algorithm 3. Unified Training Pipeline per Model Notebook

Input: Balanced audio manifest and model family $m \in$ {CNN, TCNN, GRU, LSTM, CRNN}
Output: Trained model and exported metrics artifacts
Load balanced metadata and remap class indices
Extract fixed-size acoustic feature tensors
Build stratified train/validation/test splits
Instantiate architecture corresponding to m
Compile with Adam optimizer and categorical loss
Train with class weighting and early stopping
Evaluate on test split and compute summary metrics
Export metrics for table generation
Save final model weights and experiment artifacts

4 Experimental Results

This section reports empirical results from the offline leakage-safe protocol across five deep learning architectures. We present ablation analysis of preprocessing and augmentation contributions, domain generalization tests to characterize dataset-shift sensitivity, and unified comparative evaluation highlighting the discrimination-calibration-efficiency trade-off space. All experiments use the same train-validation-test partitioning with independent acquisition sets to exclude data leakage.

4.1 Ablation Study

To assess the contribution of each preprocessing and augmentation stage described in Sect. 3, an ablation study was performed using the best-performing architecture (CRNN). Table 3 shows that removing Voice Activity Detection (VAD) significantly reduces performance, highlighting the importance of excluding silent segments for transient sound events. Likewise, data augmentation and the proposed high-frequency ratio (R_{hf}) make a measurable contribution to preserving high Macro-F1 scores.

These ablation results indicate that pipeline design choices are not cosmetic preprocessing steps but primary determinants of downstream discrimination performance.

Table 3. Impact of pipeline components on classification performance: ablation study.

Configuration (CRNN)	Macro-F1
Full Pipeline (Baseline)	0.952
- w/o Augmentation	0.914
- w/o VAD Filtering	0.887
- w/o R_{hf} Modulation	0.931

4.2 Domain Generalization

A critical requirement for edge-aware evaluation in audio classification is robustness against environmental shifts. Table 4 provides explicit domain generalization results, demonstrating how a model trained exclusively on proprietary data degrades when exposed to the UrbanSound8K domain [30]. Conversely, the mixed training regime recovers performance significantly.

Table 4. Domain generalization performance exhibiting model robustness across source datasets.

Training Source	Evaluation Target	Macro-F1
Mixed (UrbanSound + Proprietary)	Balanced Test Set	0.952
Proprietary Only	UrbanSound8K Only	0.814
Mixed	UrbanSound8K Only	0.925
Mixed	Proprietary Only	0.961

4.3 Model Comparison

Models are evaluated on a held-out test set produced by the defined split protocol in Sect. 3.2, representing all seven classes without source-group contamination across subsets. To avoid metric inflation and improve methodological clarity, we restrict reporting to standard multi-class metrics: Macro-F1, Weighted-F1, Macro-Precision, Macro-Recall, classwise ROC/PR behavior, and calibration diagnostics (ECE with calibration-curve analysis). While full on-device deployment is left for future work, models are instead compared through verifiable complexity indicators: parameter count, serialized model size (MB), and profiling artifacts (CPU latency/memory).

This constitutes a broad comparative evaluation across five model families under a unified protocol.

To strengthen reproducibility, we implement: (i) an explicit split manifest keyed by `source_clip_id`, `device_id`, and `session`; (ii) domain-generalization test manifests with UrbanSound-only and proprietary-only partitions when

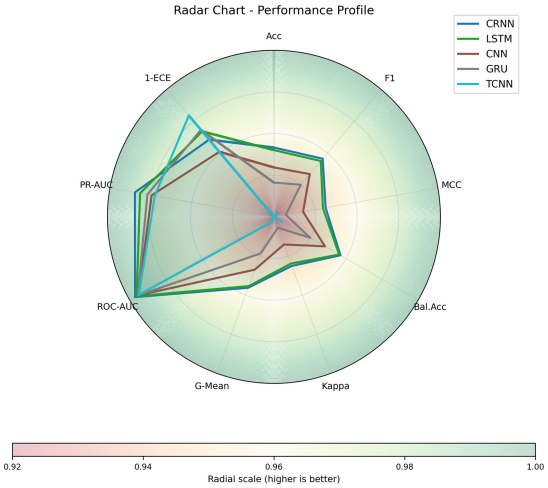

Fig. 4. Radar performance profile for the five models. Calibration is expressed as $1 - \text{ECE}$ (higher is better), and efficiency is represented by FP32 model size (MB). *Key takeaway: CRNN/LSTM dominate discrimination axes; TCNN excels in calibration efficiency.*

origin metadata is available; (iii) a basic edge-validation protocol for CPU latency/memory profiling; and (iv) an ablation pipeline (without-VAD, without-R_{hf}, without-augmentation) driven by run artifacts.

Table 5 presents the consolidated quantitative comparison across the five architectures under the same leakage-safe evaluation protocol.

Table 5. Comparison of standard multi-class metrics across all evaluated models.

Model	Acc	Macro-F1	Weighted-F1	Macro-P	Macro-R	ROC-AUC(m)	PR-AUC(m)	ECE
CRNN	0.9531	0.9563	0.9532	0.9559	0.9569	0.9971	0.9879	0.03150
LSTM	0.9521	0.9550	0.9521	0.9542	0.9562	0.9962	0.9854	0.02672
CNN	0.9437	0.9468	0.9434	0.9458	0.9483	0.9953	0.9799	0.04241
GRU	0.9365	0.9401	0.9364	0.9413	0.9402	0.9955	0.9818	0.02552
TCNN	0.9187	0.9228	0.9181	0.9232	0.9245	0.9950	0.9782	0.01885

Interpretation of Table 5. Macro-F1 and Weighted-F1 quantify discrimination; ROC-AUC(m) and PR-AUC(m) capture ranking quality; ECE reflects probability reliability (lower is better). Two regimes emerge: CRNN/LSTM for peak discrimination, TCNN for calibration-oriented operation.

To complement Table 5 with a multi-metric perspective, Fig. 4 visualizes the models across discrimination, calibration, and efficiency axes.

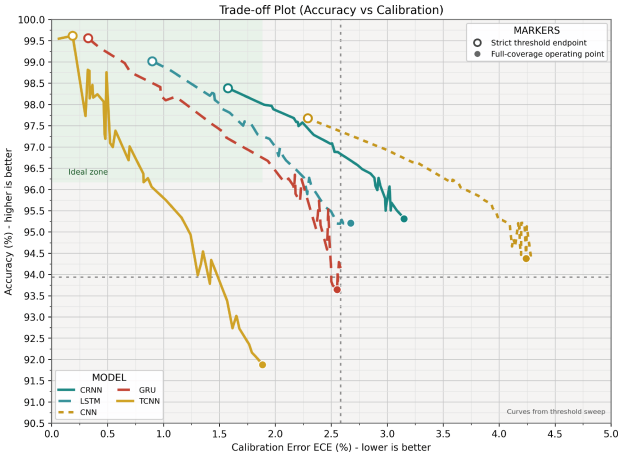

Fig. 5. Trade-off between Macro-F1 and ECE for the five models. Marker size is proportional to parameter count; distinct marker shapes and line styles were chosen for black-and-white readability. *Key takeaway: CRNN maximizes discrimination (95.6% Macro-F1); TCNN maximizes calibration reliability (ECE 0.01885).*

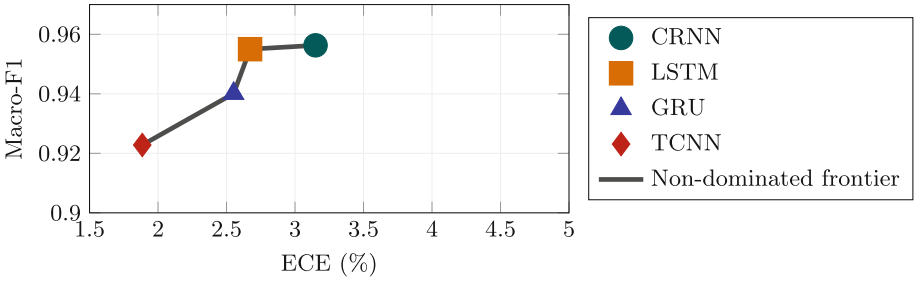

Fig. 6. Trade-off frontier between Macro-F1 and ECE. Each marker represents one model, and the line joins the non-dominated solutions in order of decreasing Macro-F1. *Key takeaway: Only CRNN, LSTM, GRU, and TCNN are non-dominated candidates; selection depends on application risk tolerance parameter α.*

Interpretation of Fig. 4. Each spoke represents one metric family; larger radius indicates stronger performance. CRNN and LSTM dominate discrimination axes, while TCNN excels in calibration efficiency.

To make the discrimination-calibration compromise explicit in two dimensions, Fig. 5 maps Macro-F1 against ECE with marker size proportional to model scale and highlights the trade-off frontier among the evaluated models.

Interpretation of Fig. 5. The axes expose the accuracy–calibration frontier directly. Lower calibration error trades off against peak discrimination; operating points should lie on the non-dominated frontier. For deployment, practitioners

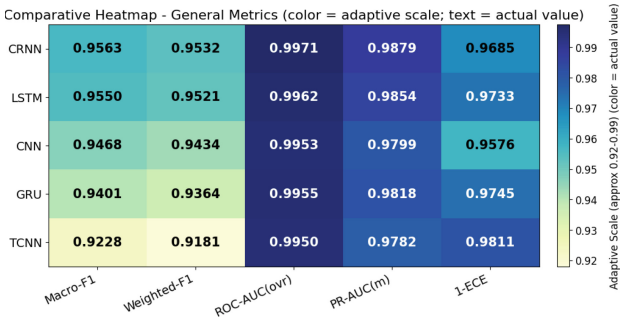

Fig. 7. Comparative heatmap across Macro-F1, Weighted-F1, ROC-AUC (macro), PR-AUC (macro), and 1 − ECE. Colors indicate min-max normalized scores, and annotations show raw values. *Key takeaway: CRNN and LSTM dominate discrimination metrics, while TCNN exhibits superior calibration—no single architecture is optimal across all objectives.*

select a utility function $U(\alpha) = \text{MacroF1} - \alpha \times \text{ECE}$ where $\alpha \in [0, 1]$ encodes risk preference: $\alpha = 0$ prioritizes discrimination, $\alpha = 1$ prioritizes calibration.

Interpretation of Fig. 7. Rows represent the five models and columns represent standard metrics. Color intensity encodes normalized quality on [0,1], while annotations preserve raw values for traceability. This joint view confirms that ranking behavior is stable across plots and tables, and that no single architecture simultaneously dominates discrimination, calibration, and size.

5 Discussion

5.1 Accuracy-Efficiency Trade-Off and Performance Analysis

The experimental results show a clear multi-objective trade-off between classification performance, calibration reliability, and computational consumption. CRNN's superior performance (95.6% Macro-F1) is attributed to its hybrid inductive bias, while LSTM offers similar discrimination with lower complexity, and TCNN provides a compressed profile with more reliable confidence (ECE 0.01885). GRU and CNN models obtained lower discrimination in our experiments and are therefore less competitive on this dataset. This is not a single-model dominance result: higher Macro-F1 typically demands more memory and may worsen calibration, while lower ECE often trades off peak discrimination.

5.2 Computational Complexity Under Edge Constraints

Computational complexity is a critical factor for edge deployment. CRNN requires the largest parameter count and memory, while TCNN and CNN offer substantially smaller footprints. Convolutional models incur cost proportional to kernel size, channel depth, and feature-map dimensions; recurrent/attention

models scale with sequence length but capture temporal context more effectively. CRNN/LSTM occupy the high-discrimination region with higher resource demands, while TCNN offers an operating point with lower resource consumption and superior calibration. Since this manuscript does not claim final embedded deployment, complexity claims remain bounded to auditable artifacts; hardware-specific throughput conclusions are deferred to future full deployment experiments.

5.3 Generalization, Domain-Shift, and VAD Limitations

The multi-stage manifesting process improves traceability and reproducibility. While the 6,400-clip dataset is simple compared to large-scale reference benchmarks, it reflects controlled, traceable acquisition under real IoT constraints, prioritizing experimental validity over scale. Domain-shift risks include: (i) *geographic specificity*—recordings collected in a single Ecuadorian institution may not represent diverse acoustic conditions, which may limit external validity in unseen environments; (ii) *voice-cohort homogeneity*—children vocalizations lack broader demographic variability; (iii) *event scarcity*—ball and siren events required additional augmentation of the real recordings, limiting naturally recorded samples. VAD filtering ($\tau_v \in [0.15, 0.55]$) improves consistency but can discard events in crowded scenes, reducing multi-speaker context representation.

5.4 Calibration and Confidence Implications

Although models achieved strong discrimination, the calibration analysis reveals that predictive confidence requires caution. CRNN's recurrent and attention-driven structure tends to generate sharper softmax distributions, leading to overconfident predictions, particularly for low-frequency classes like siren. By contrast, TCNN exhibits lower ECE (0.01885), suggesting more reliable confidence estimates suitable for downstream decision logic (threshold-based alarms, abstention mechanisms, two-stage verification pipelines) at the edge.

5.5 Comparison with Prior Work

Previous studies in acoustic event detection, such as those reported by [30,31], commonly achieve accuracy levels between 90% and 95% on the UrbanSound8K dataset under controlled experimental conditions. In our case, the best-performing CRNN model reached a Macro-F1 score of 95.6% with an overall accuracy of 95.3% on a domain-specific seven-class dataset.

While these results are competitive, direct comparison should be approached carefully due to differences in class taxonomy, dataset composition, and validation protocols. In particular, our dataset was specifically curated for the target application context, which differs from general-purpose urban sound benchmarks.

6 Conclusion and Future Work

6.1 Summary and Practical Recommendations

We present a pragmatic IoT-to-edge evaluation workflow with three outcomes: (1) a reproducible acquisition and curation pipeline with source-wise partitioning and VAD verification; (2) a leakage-safe evaluation protocol reporting discrimination, calibration, and complexity metrics; and (3) an application-oriented selection procedure based on the Pareto trade-off frontier. This positions the framework as a practical bridge between controlled model evaluation and real-world edge deployment constraints.

Key findings: CRNN produces the highest discrimination (95.6% Macro-F1) at moderate footprint; TCNN yields the lowest ECE and more reliable probabilistic outputs. To pick a deployment model, practitioners select a trade-off parameter α in $U(\alpha) = \text{MacroF1} - \alpha \times \text{ECE}$ and maximize $U(\alpha)$ over the non-dominated set (Fig. 6). Prefer discrimination-oriented models when false negatives are costlier; prefer calibration-oriented models when false alarms or human-verification costs dominate.

6.2 Limitations and Future Directions

Generalization and Transfer Learning: Future work will validate model robustness across geographically and architecturally diverse recording sites. Techniques such as domain adversarial training, source-free domain adaptation, or federated learning could mitigate geographic specificity while preserving privacy. Exploring transfer from large-scale multilingual speech datasets (if publicly available) is also warranted.

Multi-label and Overlapping Events: The current 7-class single-label formulation does not capture scenarios with simultaneous sirens and crowd noise. Extending the pipeline to multi-label or hierarchical classification (e.g., presence of 'siren' + presence of 'crowd') would improve ecological validity in real-world settings.

Feature Extraction Optimization: Optimizing mel-spectrogram extraction and intermediate representations could reduce network and storage footprint by a factor of $\sim$10 in future data-collection pipelines.

Concluding Remarks. This work demonstrates that reproducible acoustic event modeling can be achieved with low-cost IoT hardware when acquisition, curation traceability, and multi-objective model evaluation are designed as a single system.

Data Availibility Statement. Code and documentation will be released on Mendeley Data. The **IoT-AED** dataset and manifests are available at https://doi.org/10.17632/dg5k9pwv4d.1.

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

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Lightweight Side-Channel-Resistant True Random Number Generator Design for FPGA-Based Edge-AI Platforms

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Abstract. Random number generators are fundamental components in modern cryptographic systems, secure communications, and hardware security modules. Although pseudorandom number generators (PRNGs) are widely used due to their efficiency and low cost, they are inherently deterministic and unsuitable for high-security applications requiring true unpredictability. True random number generators (TRNGs) exploit physical entropy sources to generate non-deterministic random sequences. In addition, side channel analysis (SCA) attack techniques will be introduced to enhance the necessary TRNG in hardware security, especially with IoT devices. This paper aims to describe about the TRNG design for FPGA as a hiding countermeasure technique against SCA, and to simulate again an SCA attack for an unprotected AES algorithm.

Keywords: Field-programmable gate array (FPGA) · True Random Number Generator (TRNG) · Random Number test · Side Channel Analysis (SCA)

1 Introduction

The Internet of Things (IoT) has transformed industries and daily lives through increased connectivity of devices. The expansion of IoT devices has led to increased security concerns, necessitating strong protection measures for sensitive data and critical infrastructure. In contrast to invasive techniques that require a physical breach of a device, contemporary cryptographic attacks often employ side-channel monitoring. This methodology exploits the 'leakage' of physical manifestations such as power consumption, electromagnetic radiation, or timing variations that are produced during computational processes. By analyzing these unintentional emissions, adversaries can non-intrusively reconstruct sensitive cryptographic keys or embedded security parameters without compromising the device's structural integrity [30]. The traditional IoT framework is

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 195–212, 2026.
https://doi.org/10.1007/978-3-032-30524-4_13

structured into three layers, namely application, network, and perception layer. Each tier of the IoT architecture faces unique security threats that the application layer is vulnerable to SQL injection [20] and phishing attack [17], the network layer is susceptible to state-based [13] and AI-based [15], and the perception layer is targeted by physical-world disruptions such as RF jamming [9] and side-channel attacks [14]. However, the scope of this paper is limited to the Power Analysis Attacks (PAAs) model, a form of side-channel attack (SCA); in this paper, we will focus on Correlation Power Analysis (CPA).

The main contributions of our paper can be summarized in three folds.

1. We introduced our efficient FPGA-based TRNGs hardware core to enhance security level for edge AI platforms.
2. We investigate on Side-Channel Analysis attack may occur on edge devices
3. We analyze our experiment results based on the NIST and AIS tests for TRNGs quality

In order to increase resistance against side channel attacks, random number generators (RNGs) are essential security tools that leverage physical phenomena to produce randomness, which is vital for cryptographic functions such as authentication and key generation [5]. Beyond encryption, they are utilized in circuit simulation and as masking agents to defend against side-channel attacks [32]. To initiate a challenge-response sequence, an integrated circuit transmits a unique, unpredictable "nonce" to a secure server, typically generated by an on-chip hardware True Random Number Generator (TRNG) that produces a fresh binary combination for every session. An efficiency hardware TRNG design needs to be unpredictability, a modern TRNG is expected to be compact, fast, self-testable, and easily synthesizable. A good design of TRNGs must pass through the statistical test suites of the National Institute of Standards and Technology (NIST) and the BSI. This paper focuses on the BSI statistical test rather than the NIST test.

The rest of the paper is organized as follows. Section 2 discusses related work in the literature. Section 3 discusses the key considerations for designing a TRNG. Section 4 presents the simulation of CPA on unprotected AES algorithms and the hidden countermeasure AES algorithm. We design our own hardware TRNGs with the BIS statistical test in Sect. 5. Finally, we conclude our paper in Sect. 6.

2 Background and Related Work

As these vulnerabilities threaten the integrity of cryptographic systems, the development of robust countermeasures has gained prominence. A crucial component of secure cryptographic implementations is the True Random Number Generator (TRNG), which is essential for generating unpredictable keys and nonces. Designing an efficient and secure TRNG on FPGAs presents unique challenges, particularly in achieving high throughput while maintaining low resource utilization and resilience against side-channel attacks [35]. Effective TRNG designs

must leverage various sources of entropy to enhance randomness and ensure compliance with stringent security standards, such as FIPS 140 and Common Criteria EAL5 [21]. In the context of Edge AI, where devices operate in resource-constrained environments, the need for lightweight and efficient cryptographic solutions becomes even more critical. Edge AI integrates intelligence directly into devices on the network edge, allowing real-time processing while addressing privacy concerns and minimizing latency [10]. As such, the implementation of secure cryptographic mechanisms, including TRNGs, is paramount to protect sensitive data processed in these distributed systems. The evolution of security measures in edge computing environments requires adaptive and proactive strategies to counter emerging cyber threats. This landscape highlights the importance of establishing a secure and reliable foundation for cryptographic applications on FPGA-based Edge AI platforms, balancing the trade-offs between security, resource efficiency, and usability in a dynamic environment [7].

Early FPGA-based True Random Number Generators (TRNGs) predominantly rely on ring oscillator (RO) jitter, where multiple free-running oscillators are combined to extract entropy for cryptographic applications. However, these RO-based designs can suffer from correlation and layout-dependent bias, motivating the use of spatially distributed oscillators and on-chip post-processing such as XOR mixing or hashing to meet standard randomness tests [1].

Metastability-based TRNGs have been proposed as an alternative or complementary entropy source, exploiting unstable latch or flip-flop states to generate high-quality random bits on commercial FPGAs. Recent work demonstrates hybrid entropy sources that combine RO jitter with metastability and use automatic phase tuning or dedicated FPGA primitives (e.g., CARRY chains, clock managers) to enhance throughput and statistical quality for hardware security applications [11,19].

The side-channel vulnerability of FPGA TRNGs has been increasingly investigated, with studies showing that power and electromagnetic analysis can reveal internal behavior or bias in RO-based and coherent-sampling TRNGs. To address this, several authors propose SCA-resistant RO structures such as Galois Ring Oscillators, dynamic partial reconfiguration, and run-time monitoring to detect or mislead ongoing attacks while preserving overall system functionality [2,6,12].

In parallel, FPGAs have emerged as key platforms for edge-AI acceleration, where security primitives must coexist with AI workloads under tight power and resource constraints. Recent industrial and academic reports highlight the need for integrated low-overhead security blocks—including TRNGs—within FPGA-based edge-AI systems, but comprehensive designs that explicitly co-optimize entropy quality, side-channel resistance, and AI performance are still limited, leaving significant room for novel architectural contributions [16,24].

3 TRNG Design: Key Considerations

3.1 Hiding and Masking Countermeasure Against Power Analysis Attack

Investigation of the power consumption of individual AES components reveals that the S-box within the SubBytes stage is the most power-intensive element, accounting for 75% of total power usage in a 1-round-per-cycle loop architecture [30]. Because the S-box is responsible for three-quarters of the power drain, it is the most critical area for applying Hiding or Masking countermeasures. Optimizing the efficiency of the S-box or masking its signature is the most effective way to secure the entire AES engine. Following [30], an AES design without a countermeasure is called "unprotected" to enhance the necessity of countermeasures technique. The countermeasure techniques are defined into two categories that are Hiding and Masking techniques.

The hiding countermeasure technique is used to obscure the relationship between the device's operations and its emissions. Hiding uses two different vertical (amplitude) and horizontal scales (time) to achieve the goal. The vertical scale aims to ensure uniform or randomized power consumption in each clock cycle. In this approach, each operation of the cryptography core consumes an identical level of power in every clock cycle, independent of the input or data values. However, horizontal hiding disrupts the temporal alignment of leakage points. In this approach, the device is designed so that its power consumption varies randomly, meaning that a different amount of power is drawn in each clock cycle. Consequently, the operations of the cryptographic algorithm are executed at varying time instants during each run.

The masking countermeasure technique is to mitigate leakage by dividing sensitive intermediate values into independent shares. This ensures that the power consumption of the device does not depend on the intermediate values being processed. A key advantage of this approach is that its implementation at the algorithm level does not alter the overall power profile of the cryptographic device. Masking countermeasures can be applied at both the algorithmic and circuit levels.

3.2 Random Number Generator Architecture for Countermeasure

In order to design good TRNGs, it is necessary to understand the concept of random numbers. Random numbers are essential for most cryptographic applications, as they are used to generate session keys, signature parameters, nonces, challenges, and blinding or masking values to protect against implementation attacks. If the random number generators (RNGs) used for these purposes are weak, they can severely compromise the security of cryptographic systems. This risk highlights the importance of conducting reliable and reliable security evaluations of RNGs to ensure their suitability for cryptographic use. Therefore, [23] proposed a classification of RNGs to satisfy the hiding or masking countermeasures required in hardware security techniques.

DRNGs, also known as deterministic random number generators or PRNGs (pseudo-random number generators), take a short truly random sequence called a seed—typically obtained from an entropy source—and deterministically extend it into a very long sequence of seemingly random bits. In contrast, PTRNGs (physical true random number generators) rely on genuine physical noise sources, such as dedicated hardware or measurements from physical experiments, to produce randomness. NPTRNGs (non-physical true random number generators) also aim to generate true randomness, but do so without dedicated hardware, instead extracting entropy from non-physical noise sources like system data or user interactions. Figure 1 describes the classification of Random Number Generators.

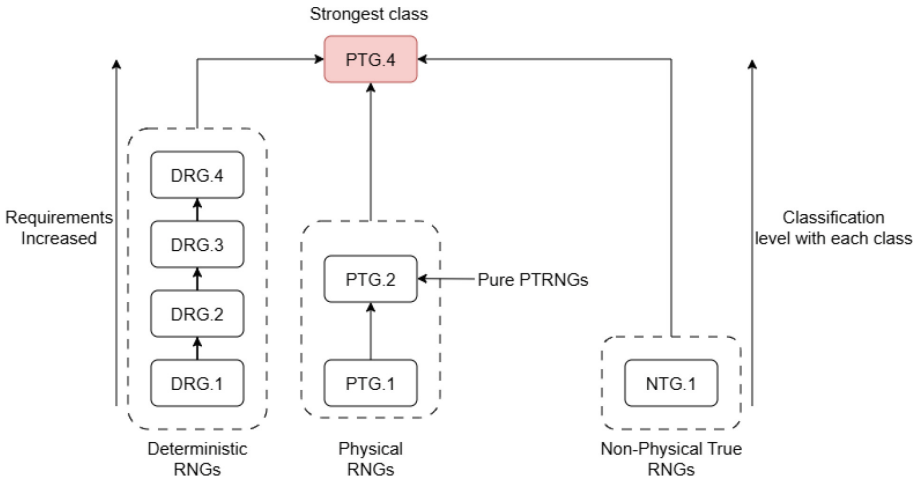

Fig. 1. New AIS 20/31 - Functionality classes of AIS 20/31 [23]

In order to achieve ideal TRNGs, a statistical test suite known as AIS-31 has been developed to evaluate the quality of RNG designs. The AIS-31 standard consists of two procedures, A and B. Procedure A includes six groups of tests designed to verify statistically inconspicuous behavior in the output sequence, while Procedure B includes three groups of tests applied to the internal random bits of the generator. Table 1 presents a detailed description of these tests.

Table 1. AIS-31 statistical tests

No.	Purpose	Requirement
Test 0	Disjointedness test	Subsequent members are pairwise different
Test 1	Monobit test	The number of ones must be between 9,654 and 10,346
Test 2	Poker test	Distribution of 4-bit tuples checked for 15° of freedom
Test 3	Runs test	Runs of 1, 2, 3, 4, 5, and 6 ones (zeros) are checked for expected occurrences
Test 4	Longest run test	No single run can be larger than 34
Test 5	Auto-correlation test	The overlap of the bit stream in the latter half of the sequence is compared to the sequence with the largest overlap in its first half
Test 6	Uniform distribution test	6a: Monobit test to ensure the number of ones is between 25–75% 6b: A special case of Test 7 with a width of 2
Test 7	Homogeneity test	Collect 10,000 occurrences of runs less than the given width and check for the expected transition probabilities. 7a: Test with a width of 3 7b: Test with a width of 3
Test 8	Entropy test	Accumulate the nearest predecessor distance between byte values in a 256,000 + 2,560 bit sequence, and calculate the empirical entropy

3.3 Correlation Power Analysis

[18] proposed Differential Power Analysis (DPA) attacks, which can recover secret keys by analyzing detailed cryptographic operations and statistically examining their power consumption traces. Later, [3] also introduced Correlation Power Analysis (CPA), which uses Pearson's correlation coefficient to improve the performance of power analysis attacks. The most widely used leakage models are Hamming-based, including the Hamming Weight (HW) and Hamming Distance (HD) models. These models often appear in leakage from software running on small microcontrollers and from medium-scale cryptographic implementations on FPGA and ASIC platforms [31].

The power consumption model transition is described in Table 2. The Hamming Weight (HW) model assumes that only bits with a value of 1 contribute significantly to power consumption, meaning that the number of ones in the data determines the leakage. In contrast, the Hamming Distance (HD) model focuses on bit transitions, where both changes $0 \rightarrow 1$ and $1 \rightarrow 0$ result in similar power consumption. Therefore, HW emphasizes the static value of bits, while HD captures dynamic switching activity between states.

Table 2. Power Consumption Models Transition

Transitions	Hamming Weight	Hamming Distance
$0 \rightarrow 0$	0	0
$0 \rightarrow 1$	1	1
$1 \rightarrow 0$	0	1
$1 \rightarrow 1$	1	0

Under a brute-force attack, an attacker would need to try up to $2^{128} \approx 3.4028 \times 10^{38}$ possible keys, which is computationally infeasible. However, in a CPA attack (chosen-plaintext), the attacker only needs $16 \times 2^8 = 4096$ key guesses to recover the secret key. Let N be the number of bytes in plaintext, D the number of measured traces,K the number of hypothetical keys, and T the number of samples. The main steps of CPA are described in Fig. 2.

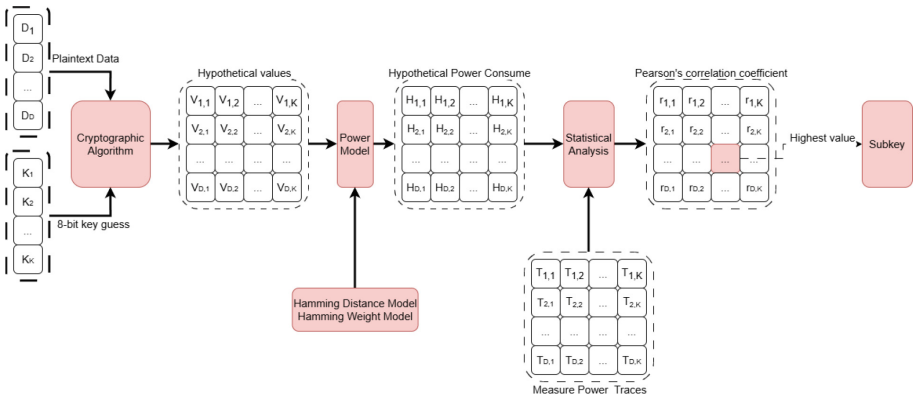

Fig. 2. Main steps of CPA

An intermediate value of the encryption algorithm is first selected. This value must depend on both the secret key and a known variable. Next, a matrix of hypothetical intermediate values V is computed. Let $d_m \in \{0, D-1\}$ denote one byte of the m-th plaintext input, and let $k_i \in \{0, K-1\}$ represent the i-th key hypothesis. The potential output of the S-Box in the first round is then calculated using Eq. 1.

$$v_{m,i} = S(d_m \oplus k_i) \tag{1}$$

Therefore, a matrix of hypothetical intermediate values V is defined. This matrix is then mapped to a hypothetical leakage matrix H using HD or HW power models to estimate the power consumption of the device. If the attacker has additional knowledge about the target device, such as the netlist, more

accurate electromagnetic (EM) simulations of the algorithm can be performed. Improved EM simulations reduce the number of EM traces required to recover the secret key.

Finally, the hypothetical leakage matrix H is compared with the measured power trace matrix T of size $D \times T$. The results of this comparison are stored in a matrix R, which has dimensions $K \times T$. Each comparison between h_i and t_j can be performed using various statistical methods. Each element $r_{i,j}$ in R represents the correlation result between h_i and t_j, and a higher value of $r_{i,j}$ indicates a stronger match.$r_{i,j}$ is calculated using Eq. 2.

$$r_{i,j} = \frac{\sum_{m=0}^{D-1}(h_{m,i} - \overline{h_i})(t_{m,j} - \overline{t_j})}{\sqrt{\sum_{m=0}^{D-1}(h_{m,i} - \overline{h_i})^2 \sum_{m=0}^{D-1}(t_{m,j} - \overline{t_j})^2}} \tag{2}$$

4 Simulation SCA Attack

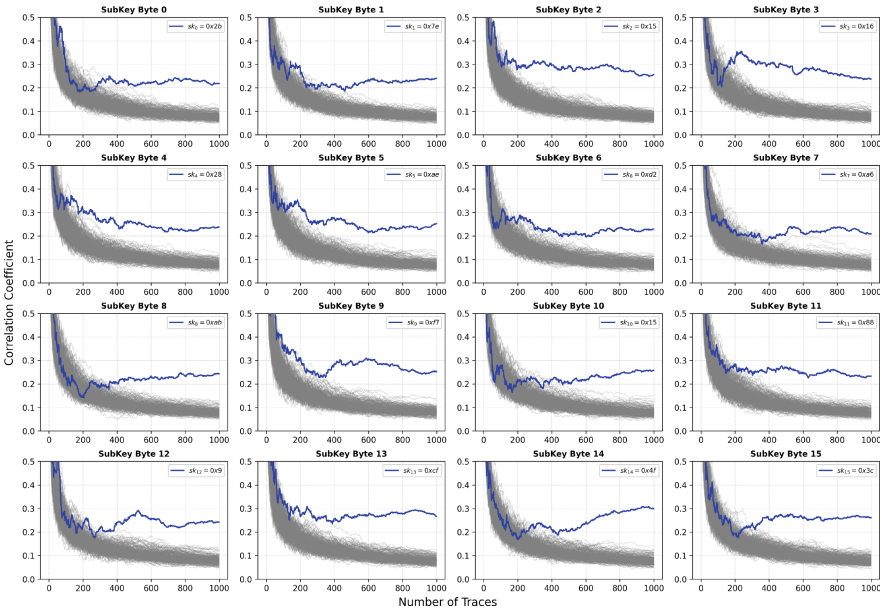

Fig. 3. Attack on simulated "unprotected" AES

Figure 3 illustrates the results obtained from the CPA attack performed on the unprotected implementation of AES. It can be observed that the correct subkey is clearly distinguishable after approximately 1000 traces. This conclusion is drawn based on the Pearson correlation coefficient, where the correct key hypothesis produces the highest correlation value compared to all other candidates. As the number of traces increases, the correlation corresponding to the

true key gradually separates from the incorrect hypotheses, eventually emerging as the dominant peak. This shows that, without any countermeasure, the secret key can be efficiently recovered with a relatively small number of measurements.

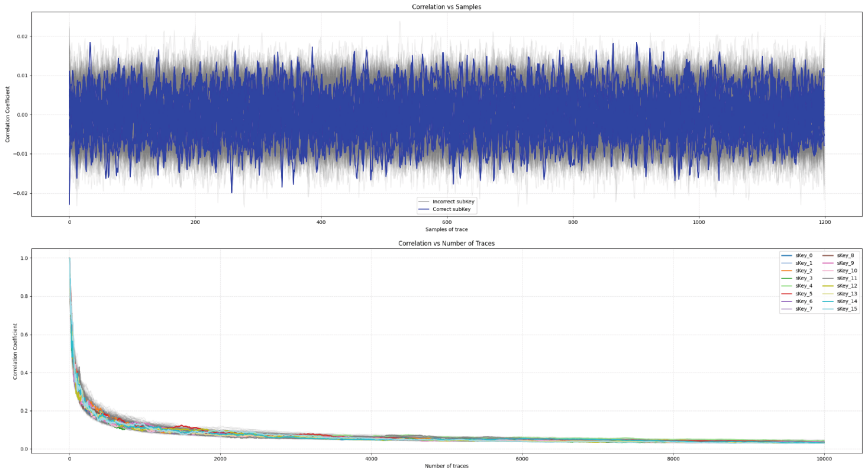

Fig. 4. Attack on simulated hiding countermeasure AES

In contrast, when a hiding countermeasure is incorporated into the simulation, the attack performance is significantly degraded. As shown in Fig. 4, the correlation values of the correct key hypothesis remain indistinguishable from those of the incorrect hypotheses for a much larger number of traces. Even as the number of collected traces increases, the separation between the correct and incorrect key candidates is substantially reduced. The results indicate that the secret key is not reliably exposed until approximately 10,000 traces are used.

5 Lightweight FPGA-Based TRNGs for Edge-AI Platforms

5.1 FPGA Implementation

In this section, we concentrate on the design of TRNG sources intended to hide countermeasures on target devices. Based on our investigation and analysis, we propose a TRNG architecture that combines both a Ring Oscillator (RO) and a Ring Generator (RG). The work in [25] introduced a TRNG jitter sampler that integrates an RO stage as an entropy source with an RG stage. Figure 5 illustrates the overall concept of this TRNG architecture.

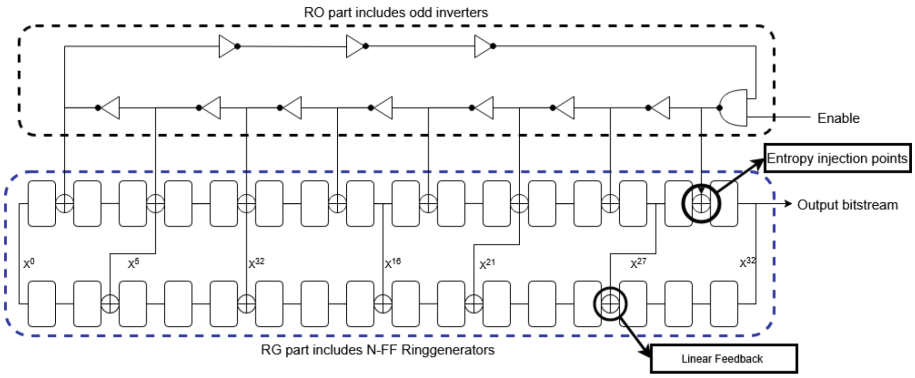

Fig. 5. The core ring-generator-based TRNG with the characteristic polynomial $f(x) = x^{32} + x^{27} + x^{21} + x^{16} + x^{10} + x^5 + 1$

The RG stage is implemented using a Linear Feedback Shift Register (LFSR) structure, while the RO stage consists of a chain of odd-numbered inverters to inject entropy into the RG stage. In our design, an inverter is replaced with a NAND gate, allowing the injection of entropy into the RG stage to be enabled or disabled.

Depending on the XOR gate configuration, LFSR.can be categorized into two types: (a) Fibonacci LFSR and (b) Galois LFSR. In our work, the RG structure is optimized by using a Galois configuration arranged in a ring topology. This optimization is motivated by the critical path limitations associated with the Fibonacci structure and the fan-out issues present in the conventional Galois form.

In this section, a 7-inverter RO generates raw random bits from its jitter, which are then fed into a 64-bit linear feedback shift register (LFSR) defined by the polynomial in Eq. 3.

$$f(x) = x^{64} + x^{52} + x^{39} + x^{26} + x^{14} + x^7 + 1. \tag{3}$$

The LFSR whitens the RO output, spreading entropy across 64 bits and producing a uniform, maximal-length random sequence suitable for TRNG applications. The design is implemented on the Xilinx Artix-7 FPGA chip using the Digilent Arty A7-100T.

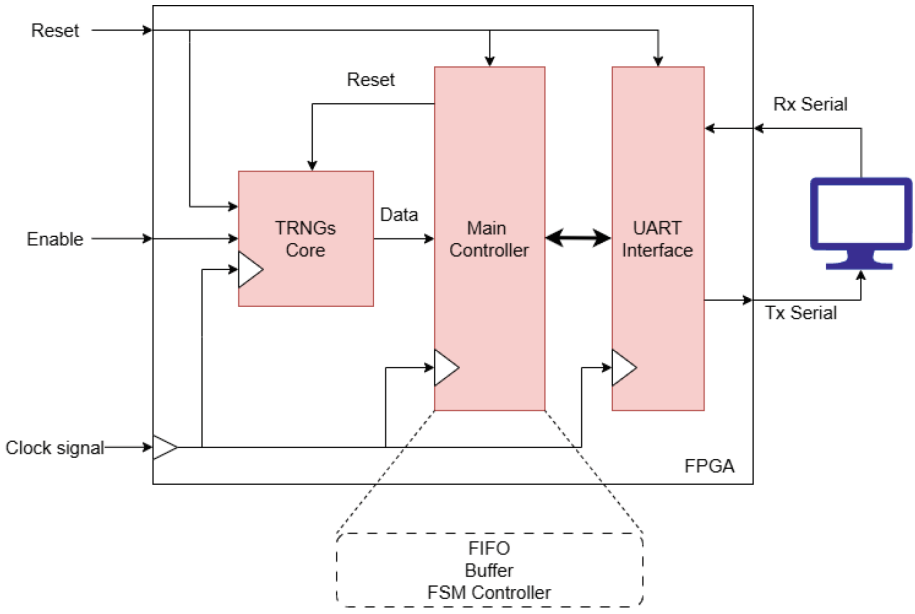

Fig. 6. Hardware implementation

Figure 6 shows the architecture of the design. The implementation uses a total of 10 LUTs and 64 FFs, which uses around 8 SLICEs, making it a lightweight and efficient TRNG source suitable for integration into our next AES core design. We declare the Enable signal as the trigger signal for the RO block to generate entropy, since the first inverter stage is implemented as an AND gate. The oscillation frequency depends on the total number of inverters configured in this experiment, which consists of one NAND gate and ten inverter stages.

The initial validation of the random source involves assessing key statistical properties of the proposed TRNG immediately after start-up, to account for potential correlations in the generated sequences. A preliminary dataset of 1 million bits was analyzed before applying the official standard tests. Among common RNG evaluations, the autocorrelation test is often the most challenging, so following [22], we examined the correlation between each bit and its lagged values. The acceptance threshold for this test is a maximum correlation coefficient of 0.3, indicating the degree of dependence between a variable and its past values [4,33]. As shown in Fig. 7, the observed autocorrelation coefficients are close to zero, indicating that the generated bits are largely independent. This low autocorrelation further suggests that correlation-based attacks would be ineffective against the proposed TRNG upon start-up. Finally, Fig. 8 illustrates the spatial distribution of 1 million bits arranged on a 1000×1000 grid from the start-up dataset.

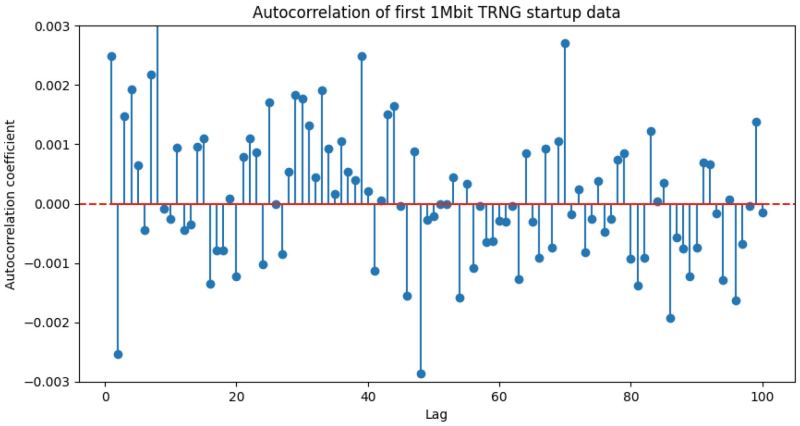

Fig. 7. Auto corelation test

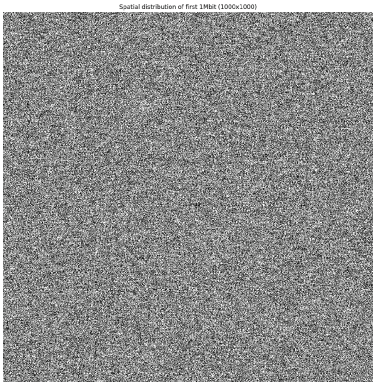

Fig. 8. Distribution of raw data

The results indicate that our TRNG design satisfies all the requirements for a TRNG. In future work, we plan to integrate this design with an AES core, where it can serve as a hiding countermeasure within the system. Table 3 presents the utilization of post-implementation resources of our FPGA design. The LUT usage is higher than in previous designs due to the inclusion of an additional controller and a UART interface.

5.2 Experimental Results

We obtain the bit sequences from the FPGA and then transmit them to the PC through the UART interface. Additionally, the sampling clock rate for the TRNG source was reduced by half to 50 MHz to ensure that the TRNG achieves reliable and stable performance. The results show that we passed all the test from AIS-31 with an ideal entropy TRNG approx 0.998 perbit with the collection data. In

Table 3. FPGA Resource Utilization

Resource	LUT	FF	IO	DSP
Utilization	196	222	7	0
Available	63400	126800	210	0
Utilization %	0.31%	0.18%	3.33%	0%

addition to the AIS-31 tests, there are additional evaluations from NIST, namely SP800-22 and SP800-90B [28].

Table 4 exploits the destination of each test for the TRNG design. According to [26], the latest version of SP800-22 does not provide meaningful results for this evaluation, as it requires a very large input size of approximately 100 million bits. Therefore, in our context, we focus exclusively on the AIS-31 and SP800-90B tests, since the TRNG is intended for cryptographic applications. Table 5 presents the results of the AIS-31 test for the proposed design, while Table 6 summarizes the results of the SP800-90B test.

Table 4. Evaluating test for TRNG

Standard	Focus	Type of Test
AIS-31	TRNG quality	Health and statistical
SP800-22	Statistical randomness	15 statistical tests
SP800-90B	Entropy estimation	Entropy estimation and health test

In Table 5, a more recent NIST suite, SP800-90B, evaluates whether an entropy source is suitable for secure cryptography by estimating its minimum entropy. This assessment includes IID and non-IID tests. Passing the IID test indicates that the source can be reliably used in cryptographic applications. The proposed TRNG exhibits high-quality entropy, confirming its suitability for cryptographic algorithms. In the NIST test, the p-value (Chi square) in a sequence greater than or greater than 0.01 is a good random sequence. Therefore, the results in Table 5 indicate that our TRNGs design achieves the entropy source test as a high quality entropy estimation source.

On the other hand, Table 6, the AIS-31 test, developed by the German BSI, serves as a guide for evaluating RNGs in cryptographic applications and complements the NIST SP800-90 suite. AIS-31 consists of nine tests (T0–T8). To confirm that the sequences are disjoint, preventing repeated cycles in the 16-state ring generator. The tests T1-T5, applied to 257 data segments, achieve a pass rate of 100. Since we use the Python code of AIS-20 provided, the result of T6-T8 only shows pass or fail results. Therefore, T6–T8 assess the entropy of the source and all criteria are satisfied, indicating a high-quality random output. These tests provide good TRNGs development quality.

Table 5. SP800-90B IID test

Test	Default	Value
IID Permutation	Pass	Pass
Chi-square Independence	Pass	0.14021
Chi-square goodness of fit	Pass	0.609907
Length of the longest repeated substring	Pass	Pass
Restart	Pass	Pass
Min. entropy per byte	7.972135	7.972135

Table 6. AIS-31 statistical tests result

No.	Purpose	Results
Test 0	Disjointedness test	257/257
Test 1	Monobit test	257/257
Test 2	Poker test	257/257
Test 3	Runs test	257/257
Test 4	Longest run test	257/257
Test 5	Auto-correlation test	257/257
Test 6	Uniform distribution test	Pass
Test 7	Homogeneity test	Pass
Test 8	Entropy test	7.998013

Table 7 presents the performance of our proposed TRNGs compared to recent FPGA-based designs. By transferring entropy from the RO part to the RG part, we can generate a 64-bit sample in just 64 clock cycles at 50 MHz. The throughput can be calculated using the formula where fmax is our clock system design, n is the number of bit-lengths of the generated random number, and latency is the number of cycles taken to generate the block random number as shown in Eq. 4.

$$\text{throughput} = \frac{n \times f_{\max}}{\text{latency}} \tag{4}$$

Our design achieves higher throughput with lower hardware cost than the approaches reported in [8] and [27], and also has lower hardware cost compared to [29]. Each SLICEs of FPGA contains 4 LUTs and 8 Flip Flops. In [27], the authors only proposed the parameters of SLICEs, therefore we estimate their design based on the Xinlinx Datasheet. Although throughput does not reach the design levels [34], our design successfully passes the AIS-31 test due to the efficient spreading of entropy in the RG part. In edge AI platforms, we focus on lightweight design rather than high-throughput design.

Table 7. Comparison of TRNG Designs on FPGA Platforms

TRNG Design	FPGA Family	Resource Cost	Throughput [Mbps]
TROT [8]	Artix-7	32LUTs/55FFs	25
DC-TRNG [27]	Spartan6	64 SLICEs (50 LUTs)	14.3
DD-cell [29]	Artix-7	256 LUTs/256FFs	225
JL-TRNG [34]	Spartan6	56 LUTs/19FFs	100
This work	Artix-7	10LUTs/64 FFs	50

6 Conclusion

In conclusion, this paper has highlighted the critical role of TRNG in strengthening hardware security, particularly in the context of cryptographic systems and resource-constrained IoT devices. Although PRNG offer efficiency and low implementation cost, their deterministic nature makes them vulnerable in high-security applications where unpredictability is essential. TRNGs, by using physical entropy sources, provide genuine randomness that significantly enhances security robustness. The study demonstrated the design and implementation of a TRNG in FPGA as a hiding countermeasure against side-channel analysis (SCA) attacks. By introducing true randomness into cryptographic operations, the proposed approach reduces information leakage and mitigates the effectiveness of power- and timing-based attacks. Furthermore, the simulation of an SCA attack in an unprotected AES implementation emphasized the practical risks associated with inadequate protection mechanisms. In general, integrating TRNG-based countermeasures into FPGA-based cryptographic systems represents a promising strategy to improve resistance against side-channel threats. Future work may focus on optimizing entropy sources, improving statistical performance, and evaluating the design against advanced SCA techniques to further enhance hardware-level security.

Acknowledgement. This research is funded by Vietnam National University - Ho Chi Minh City (VNU-HCM) under grant number: A2025-20–01.

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

Modeling Wind Turbine Operational States from SCADA Data Using Hidden Markov Models

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Abstract. People need to act quickly to stop climate change. Wind energy is a big step toward making energy systems that are better for the environment. But it's hard to keep wind turbines working well because they are very complicated systems that have to deal with bad weather and mechanical problems. A Supervisory Control and Data Acquisition (SCADA) system is used by wind farms to keep an eye on the turbines' health in real time. Even with this kind of system, it's hard to find important patterns across time, especially when it comes to how turbines break down. This is because SCADA data doesn't have a lot of time resolution and there aren't enough failure and non-failure classes. This article looks at how to use Hidden Markov Models (HMMs) to model and categorize the operational states of wind turbines using SCADA data from a real wind farm. The proposed method regards standard operation and various pre-failure conditions as concealed states. This method lets the model find temporal dependencies by using sequences from past data. We use a maximum likelihood-based method to pick features so that the model can figure out which SCADA variables are most important for each turbine component being tested. The proposed methodology is assessed across six operational states, encompassing normal operation and the pre-failure conditions of the chosen components. The macro F1 score ranges from 0.78 to 0.89, with an average of 0.83, showing that the method used correctly identifies temporal patterns related to component degradation.

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 215–230, 2026.
https://doi.org/10.1007/978-3-032-30524-4_14

Keywords: Wind Energy · Hidden Markov Models · Fault Detection · Predictive Maintenance

1 Introduction

Wind and solar energy are two of the most important components of the global transition to less polluting energy systems. Their growth helps reduce greenhouse gas emissions and promotes the diversification of the energy mix. Thus, it is clear that they are aligned with global sustainability goals, such as the UN Sustainable Development Goals, especially SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) [3,7].

In the last few years, there have been a lot more wind farms, especially. But it's still hard to make sure that wind turbines work right. These turbines are subject to a wide range of mechanical and environmental conditions, which quickly wear down parts like gears, generators, and bearings. These parts are very important. If they break, they can cause big service interruptions and high maintenance costs. This is why wind farms need to be watched in real time [12].

As mentioned earlier, modern wind farms use Supervisory Control and Data Acquisition (SCADA) systems to continuously collect large volumes of operational data. Although they are often used to monitor turbine performance and provide information to detect faults in data and improve predictive maintenance, they still have significant limitations, primarily due to low temporal resolution, noise, and a large imbalance between normal operation and fault events.

In recent years, various machine learning and statistical approaches have been proposed to address these problems, including support vector machines, regression-based models, and deep learning methods [13,24]. Some of these approaches have shown promising results; however, they ultimately require large labeled datasets, are affected by class imbalance, and, in most cases, hinder interpretability, resulting in models with high accuracy but that do not allow for a true understanding of the problem, particularly in complex systems such as wind turbines.

Hidden Markov Models (HMMs) are a classical statistical technique that provides an interesting probability-based framework for modeling system activities as transitions between hidden states. They were designed to model sequential processes and temporal dependencies in time series data. So, HMMs make it possible to model how the parts of a wind turbine wear down over time under different operating conditions [19,25]. This quality makes them a good way to find patterns in how wind turbines work over time.

There have been a number of studies that looked into using HMMs to keep an eye on wind turbines by looking at both vibration signals and operational data [21,30]. But most of the studies that are already out there use high-frequency vibration measurements or simple experimental setups, which makes them less useful in real-world situations where only SCADA data is available. Conversely, as previously noted, utilizing SCADA data introduces further challenges, especially owing to reduced sampling rates and the challenges in identifying subtle degradation patterns.

Thus, this study evaluates the use of Hidden Markov Models for the multi-class classification of wind turbine operational states using real SCADA data. The proposed approach models normal operation and multiple pre-failure conditions as hidden states and aims to identify temporal degradation patterns from sequential operational data.

The main contributions of this work are as follows. First, we evaluate the use of Hidden Markov Models for the multi-class classification of wind turbine operational states using SCADA data. Second, we employ a feature selection strategy based on maximum likelihood estimation to identify variables associated with component degradation. Third, we present an experimental evaluation of the proposed approach that accounts for multiple pre-failure processes affecting key turbine components.

The remainder of this paper is organized as follows. Section 2 introduces the theoretical foundations of Hidden Markov Models, including their main algorithms and the feature selection approach adopted in this work. Section 3 reviews related studies on wind turbine fault detection and condition monitoring. Section 4 describes the proposed methodology. Section 5 presents and discusses the experimental results. Finally, Sect. 6 concludes the paper.

2 Theoretical Background

Hidden Markov Models (HMMs) are probabilistic models widely used to represent sequential processes in which the underlying system states are not directly observable but can be inferred from observed data [6,19]. In this framework, the system evolves over a finite set of hidden states, generating observations according to state-dependent probability distributions, which makes HMMs suitable for modeling time-series data and dynamic systems.

Formally, an HMM is defined by the parameter set $\lambda = (A, B, \pi)$, where A denotes the state transition probability matrix, B represents the emission probability distributions associated with each hidden state, and π is the initial state probability vector.

The transition probability matrix $A = \{a_{ij}\}$ defines the probability of transitioning from state S_i to state S_j:

$$a_{ij} = P(q_{t+1} = S_j \mid q_t = S_i) \tag{1}$$

where q_t denotes the hidden state at time t. The emission distribution B defines the probability of observing o_t given the current hidden state.

Figure 1 illustrates the structure of a Hidden Markov Model. The hidden states, denoted by q_1, q_2, q_3 (in yellow), represent latent system conditions and evolve over time according to the transition probabilities a_{ij}. Each state generates observable variables o_1, o_2, o_3 (in blue) according to emission probability distributions $b_i(o_t)$, which specify the likelihood of an observation given the current state.

Three fundamental computational problems are typically associated with HMMs [19]: (i) the *evaluation problem*, which consists of computing the likelihood of an observation sequence given a model; (ii) the *decoding problem*, which

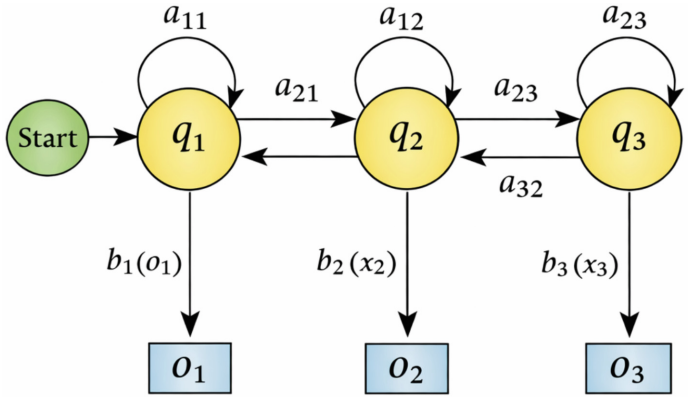

Fig. 1. Conceptual representation of a Hidden Markov Model showing hidden states, transition probabilities, and observation variables.

aims to determine the most probable sequence of hidden states; and (iii) the *learning problem*, which involves estimating the model parameters that maximize the likelihood of the observed data.

2.1 Algorithmic Formulation

The likelihood of an observation sequence $O = (o_1, o_2, \ldots, o_T)$ is computed using the Forward algorithm [14]. The forward variable $\alpha_t(i)$ represents the joint probability of observing the partial sequence up to time t and being in state S_i:

$$\alpha_t(i) = P(o_1, o_2, \ldots, o_t, q_t = S_i \mid \lambda) \tag{2}$$

It can be computed recursively as:

$$\alpha_{t+1}(j) = \left(\sum_{i=1}^{N} \alpha_t(i) a_{ij} \right) b_j(o_{t+1}), \tag{3}$$

where N denotes the number of hidden states.

For state decoding, the Viterbi algorithm is used to determine the most probable sequence of hidden states [5]. The Viterbi variable $\delta_t(i)$ is defined as:

$$\delta_t(i) = \max_{q_1, \ldots, q_{t-1}} P(q_1, \ldots, q_t = S_i, o_1, \ldots, o_t \mid \lambda) \tag{4}$$

and is computed recursively as:

$$\delta_{t+1}(j) = \max_i \left[\delta_t(i) a_{ij} \right] b_j(o_{t+1}). \tag{5}$$

Model parameters are estimated using the Baum–Welch algorithm, a special case of the Expectation–Maximization (EM) framework, which iteratively updates the model parameters to maximize the likelihood of the observed data [28].

2.2 Feature Selection

In this work, the likelihood computed by the Forward algorithm is used as a criterion for evaluating the relevance of individual SCADA variables. For each variable, an observation sequence is constructed and its likelihood $P(O \mid \lambda)$ is computed under the corresponding HMM.

This likelihood tells us how well the model captures the time-related structure of the variable. Variables that produce elevated likelihood values are regarded as more informative for depicting degradation patterns and are consequently chosen for model development.

This strategy adheres to the maximum likelihood principle [22], which is fundamental to parameter estimation and model evaluation in HMMs.

HMMs have been extensively utilized in the analysis of sequential data for tasks including speech recognition, activity recognition, and signal processing [15,18,23]. When it comes to monitoring wind turbines, they offer a natural way to use SCADA time-series data to model changes between different operational states, such as normal operation and degradation states.

This study utilizes Hidden Markov Models to represent the temporal progression of operational states in wind turbine components through SCADA measurements. The next section explains how the proposed model was built and trained.

3 Related Work

In recent years, a significant amount of research has been conducted on how to use data-driven methods, leveraging SCADA data and sensor readings, to identify problems and monitor the integrity of wind turbines. The growing volume of operational data from wind farms has led to increased use of machine learning, along in conjunction with probabilistic models, in developing models able of detecting anomalous operational patterns and supporting predictive maintenance strategies. This section is a narrative review of the literature on using Hidden Markov Models (HMMs) to find problems and figure out what state a wind turbine is in, with a focus on SCADA-based methods.

3.1 Search Methodology

We used the Elicit platform [1] for literature search. This tool does a semantic search on big academic platforms like OpenAlex and Semantic Scholar [2]. Elicit goes beyond keyword searches to do a contextualized retrieval of studies. This improves search coverage and gets rid of biases that can happen in traditional searches. To this end, we formulated the subsequent research question:

> "How effectively can Hidden Markov Models applied to SCADA data classify normal and pre-failure operational states in wind turbine components?"

[1] elicit.com.

The search returned an initial set of 500 candidate papers. These studies were screened based on their abstracts using the following inclusion criteria:

- Application of Hidden Markov Models as the principal method;
- Using SCADA data;
- Focus on wind turbine components or systems;
- Classification of operational states (normal, anomaly, or pre-failure);
- Empirical validation with quantitative performance metrics;
- Use of real-world data (excluding purely simulated studies);
- Publication in peer-reviewed venues;

After the search results from the Elicit platform were returned, 16 studies were selected for in-depth analysis. Subsequently, a manual review was conducted to confirm the selection and ensure compliance with the inclusion criteria.

At this point, two studies were identified in a different language (a Korean version of another paper already included and another in Portuguese), and another was excluded because it didn't use Hidden Markov Models.

Consequently, the final collection comprised 13 distinct studies included in this review. Figure 2 shows a summary of the whole process of choosing literature.

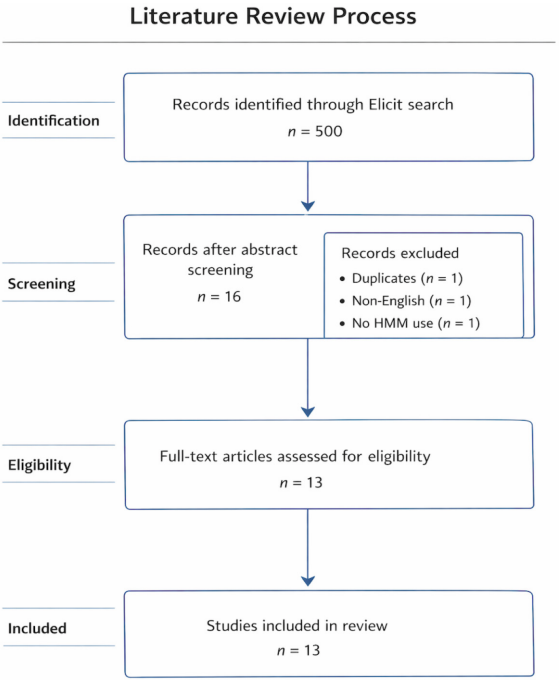

Fig. 2. Overview of the literature review process, including Elicit-based screening and subsequent manual validation

3.2 More About Included Studies

The selected studies examine various components of wind turbines, with a focus on bearings, gearboxes, and generators. The kind of data used is a big difference. Numerous studies use high-frequency sensor data, particularly vibration signals, which provide richer temporal information and enable more comprehensive characterization of mechanical dynamics. For instance, Shin et al. [21], and Zhao et al. [30] used HMMs on vibration-based measurements and obtained very good classification results. Another use of HMMs was presented by Jang et al. [9], who investigated their use to monitor rotating machinery operating under varying conditions.

Several studies use traditional HMM formulations to model degradation processes [11], a variant using an adaptive approach is presented in [10]. In this adaptive approach, the authors demonstrate its ability to make predictions at multiple stages. To demonstrate that a hybrid probabilistic approach can efficiently handle complex system dynamics, the authors Sasaki [20] present the HMM with probabilistic principal component analysis (PPCA).

Another line of research is based on the analysis of SCADA data, aiming to model real-world operational situations, but faces additional challenges such as lower temporal resolution (e.g., 5 or 10-min intervals), higher noise levels, and severe class imbalance, as demonstrated by Windmann et al. [26] and Poyraz et al. [17]. These authors examined anomaly detection using SCADA data in manufacturing environments, demonstrating the practical effectiveness of these methods. Another proposal, still in this context, was made by Yang et al. [29]. The authors propose a dynamic HMM with real-time updates to improve adaptability to changes in environmental conditions, thus advancing this line of research.

Furthermore, some studies indicate that results in SCADA-based environments are often more limited. Parekh et al. [16] report that standard HMMs may fail under severe class imbalance, highlighting the importance of data preprocessing and modeling choices. In this context, Chesterman et al. [4] highlight the diversity of modeling strategies and the challenges associated with assessing the normal behavior of operational wind farms.

Other works like Herp et al. (2017) [8] examine state transition dependencies using a Bayesian framework based on Hidden Markov Models (HMMs), whereas Leahy et al. (2016) employ Support Vector Machines (SVM) as a non-HMM benchmark for SCADA-based fault detection, providing a valuable point of reference for comparison.

The performance varies substantially across studies, someone achieve F-measures above 0.9 when using high-frequency data and carefully engineered preprocessing frameworks [27]. In contrast, studies based on SCADA data often report lower performance or increased sensitivity to noise and imbalance [Omitted for review].

Another important point is how to define operational states. There are several ways to define pre-failure conditions, including thresholds, historical maintenance records, and anomaly detection. The time frame for pre-failure states is often not clearly defined, making it difficult to compare studies.

As presented, several extensions of HMMs have been proposed to address the limitations of standard HMM formulations. They consist of degradation-aware models, adaptive HMMs with dynamic parameter modifications, and composite methodologies that integrate y probabilistic mechanisms. Table 1 summarizes the studies included in this review.

Table 1. Summary of the 13 studies included in the literature review

Study	Data Type	Component	HMM Variant	Notes
Zhao et al. (2009) [30]	Vibration	Bearings	HMM + fuzzy quantization	Robust to outliers
Jang et al. (2012) [9]	Vibration	Gearbox	Standard HMM	Rotating machinery monitoring
Windmann et al. (2015) [26]	SCADA	General	Standard HMM	Industrial dataset
Leahy et al. (2016) [13]	SCADA	Multi-component	Non-HMM (SVM)	Included for comparison
Herp et al. (2017) [8]	SCADA	General	HMM-related (Bayesian)	State transition modeling
Sasaki et al. (2017) [20]	Sensor (strain)	Blades	HMM + PPCA	Hybrid probabilistic model
Shin et al. (2018) [21]	Vibration	Bearing, Gearbox, Generator	Standard HMM	High performance (F1 up to 0.918)
Poyraz et al. (2018) [17]	SCADA	General	Standard HMM	Power curve-based detection
Jiang et al. (2023) [10]	Sensor	Bearings	Adaptive degradation HMM	Multi-step prediction
Chesterman et al. (2023) [4]	SCADA	General	Not specified	Comparative review/implementation
Jiang et al. (2024) [11]	Sensor	Bearings	Degradation HMM	Reliability modeling
Parekh et al. (2025) [16]	SCADA	Multi-component	Standard HMM	Failed under class imbalance
Yang et al. (2025) [29]	SCADA	Multi-component	Dynamic HMM	Real-time adaptation

3.3 Discussion

The reviewed literature indicates that Hidden Markov Models provide a suitable probability structure for modeling time relationships in wind turbine operational data. Their ability to represent sequential transitions between latent states makes them particularly appropriate for capturing degradation processes and intermediate operating conditions.

However, the effectiveness of HMM-based approaches varies substantially with data features. Studies based on high-frequency sensor data generally show higher performance, as these signals provide detailed temporal information that supports the identification of degradation patterns. In contrast, SCADA-based approaches face additional challenges, including lower temporal resolution, higher noise levels, and pronounced class imbalance, which can significantly affect model performance.

Furthermore, several studies show that standard HMM formulations may be insufficient when applied directly to raw SCADA data. As a result, extensions such as degradation-aware models, adaptive HMMs, and hybrid probability-based approaches have been proposed to improve robustness plus predictive effectiveness. Nevertheless, these approaches often introduce additional complexity and may rely on assumptions that are not always compatible with realistic contexts.

Another limitation seen across the literature concerns the definition and labeling of pre-failure states. Different studies use heterogeneous criteria, such as threshold-based methods. In particular, the study stresses scenarios in which

only low-frequency operational data are available and where preprocessing, along with feature selection, is central to identifying degradation patterns.

In this context, the present work assesses the use of standard Hidden Markov Models for multiclass classification on SCADA data under realistic conditions. In particular, the study stresses scenarios in which only low-frequency operational data are available and where preprocessing along with feature selection are central to identifying degradation patterns.

4 Methodology

This study investigates the use of Hidden Markov Models (HMMs) for the multi-class classification of operational states in wind turbine components, using SCADA data, with a particular focus on modeling pre-failure states. Figure 3 describes the methodology used with four main steps: data acquisition, time-series construction and feature selection, HMM modeling, and performance evaluation.

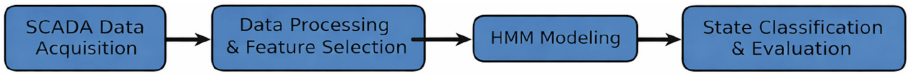

Fig. 3. Overview of the proposed methodology.

4.1 Dataset

The experiments used a publicly available wind turbine dataset [1], comprising SCADA measurements from turbines operating in a wind farm. The dataset comprises 79 operational variables and a failure log that records past faults affecting different parts of the turbine. The dataset exhibits common features of real SCADA data, including noise, missing values, and an imbalance between normal and failure conditions.

4.2 Data Processing and Temporal Sequence Construction

The SCADA data are modeled as multivariate time series, in which each observation comprises multiple operational variables recorded simultaneously.

To capture temporal behavior, the time series were segmented into subsequences of 2000 observations. Considering the SCADA sampling interval, each subsequence corresponds to a fixed temporal window preceding a failure event.

Subsequences representing normal operation were extracted from periods without recorded failures. Pre-failure sequences were defined as the observations immediately preceding each failure event.

Each sequence τ_i is associated with one of the following operational states:

- S_1: normal operation
- S_2: gearbox pre-failure
- S_3: generator pre-failure
- S_4: generator bearing pre-failure
- S_5: hydraulic group pre-failure
- S_6: transformer pre-failure

In this context, pre-failure states are interpreted as transitional stages associated with the progression of anomalies toward failure.

Initially, each subsequence is represented by a matrix of size 2000×79, corresponding to the number of time steps and measured variables.

4.3 Feature Selection

Due to the high dimensionality and potential redundancy of SCADA variables, a feature selection step was performed.

Each variable was evaluated individually using the likelihood produced by the HMM. For each variable, sequences corresponding to normal operation and the respective pre-failure condition were used to estimate model parameters and compute the log-likelihood.

The likelihood is used as a proxy to assess how well each variable captures the statistical structure of the degradation process. Variables with higher likelihood values were selected to compose the final feature subset.

After this step, each subsequence is represented by a matrix of size 2000×5.

4.4 HMM Modeling

The *hmmlearn* library was used to implement the HMM model in Python, with multivariate Gaussian emission distributions and diagonal covariance matrices.

The model was configured with six hidden states, corresponding to the previously defined operational conditions $(S_1, ..., S_6)$. Model parameters were estimated using the Baum–Welch algorithm, and state decoding was performed using the Viterbi algorithm.

To reflect the progressive nature of degradation processes, a left-right topology was adopted, restricting transitions to the same state or to the next state.

4.5 Model Evaluation

The dataset was divided into training and testing subsets using a 70–30 split, resulting in eight test sequences τ_i.

Model performance was assessed using confusion matrices and the macro-averaged F1-score, which provides a balanced evaluation across all classes, particularly in the presence of class imbalance.

For each class c, precision and recall are defined as:

$$\text{Precision}_c = \frac{TP_c}{TP_c + FP_c} \tag{6}$$

$$\text{Recall}_c = \frac{TP_c}{TP_c + FN_c} \tag{7}$$

where TP_c, FP_c, and FN_c denote the number of true positives, false positives, and false negatives for class c, respectively.

The F1-score for each class is computed as:

$$F1_c = 2 \cdot \frac{\text{Precision}_c \cdot \text{Recall}_c}{\text{Precision}_c + \text{Recall}_c} \tag{8}$$

The macro-averaged F1-score is then obtained as the arithmetic mean across all classes:

$$F1_{\text{macro}} = \frac{1}{C} \sum_{c=1}^{C} F1_c \tag{9}$$

where C is the number of classes.

This metric was selected due to its sensitivity to class imbalance, as it assigns equal weight to each class regardless of its frequency.

The adopted split does not explicitly enforce temporal separation between training and testing sequences, which may influence generalization performance.

5 Results and Discussion

This section presents the results, in which the first part analyzes the feature selection process. The second part presents the classification performance on the test samples using HMM.

The feature selection procedure identified one representative variable for each monitored component based on the maximum likelihood criterion described in the methodology. Table 2 summarizes the selected features.

Table 2. Selected features for each component.

Component	Selected Feature
Gearbox	Average ambient temperature [°C]
Generator	Minimum average generator rotation speed [rpm]
Generator Bearing	Average absolute wind direction [m/s]
Hydraulic Group	Average controller-center temperature [°C]
Transformer	Active generator power [Wh]

The selected variables appear to capture the relationships with the monitored components. From this selection, some characteristics can be interpreted based on what occurs in the physical operation of the turbine; an example is the relationship between the generator's rotational speed and the active power,

while others capture less clear operating conditions that may influence component degradation. This suggests that the probability-based selection procedure can identify variables that encode relevant temporal patterns, even when the relationship with the component is not explicitly causal.

Based on historical failure events, the time series were divided into subsequences that formed training and test subsets, in a 70%–30% ratio, resulting in eight test samples τ_i. Each sample contains subsequences associated with the six operational states described previously.

The classification performance was evaluated using confusion matrices and macro-averaged F1-scores. Table 3 shows the results for the test sample τ_1. We obtained a model that achieved a macro F1-score of 0.85.

Table 3. Confusion matrix for test sample τ_1.

	S_1	S_2	S_3	S_4	S_5	S_6
S_1	1938	62	0	0	0	0
S_2	0	2000	0	0	0	0
S_3	0	705	1295	0	0	0
S_4	0	0	0	1076	924	0
S_5	0	0	0	0	1972	28
S_6	0	0	0	0	0	2000

The model achieved perfect classification for gearbox pre-failure (S_2) and transformer pre-failure (S_6), indicating that the selected features provide strong discriminatory signals for these components. In contrast, higher confusion was observed between generator-related states (S_3 and S_4). This behavior suggests that the degradation patterns of these components exhibit similar temporal signatures within the selected feature space, making them harder to distinguish.

For the second test sample τ_2, the model achieved a macro F1-score of 0.89, as presented in Table 4.

Table 4. Confusion matrix for test sample τ_2.

	S_1	S_2	S_3	S_4	S_5	S_6
S_1	2000	0	0	0	0	0
S_2	0	1954	46	0	0	0
S_3	0	0	2000	0	0	0
S_4	0	0	0	2000	0	0
S_5	0	0	0	861	1139	0
S_6	0	0	0	0	330	1670

The results for τ_2 show improved class separability compared to τ_1, although some confusion persists in states associated with hydraulic and transformer systems (S_5 and S_6). This variability across samples indicates that classification performance is influenced by the specific characteristics of each failure event and the associated temporal patterns.

The remaining test samples produced consistent results, as summarized in Table 5.

Table 5. Macro F1-score

Sample	Macro F1-score
τ_3	0.80
τ_4	0.78
τ_5	0.78
τ_6	0.87
τ_7	0.80
τ_8	0.84

Overall, the model achieved macro F1-scores ranging from 0.78 to 0.89, with an average of approximately 0.83 across the eight test samples. These results indicate that the HMM-based approach is able to capture temporal patterns associated with degradation processes in wind turbine components using SCADA data.

In general, the results obtained indicate that HMMs tend to achieve moderate results when using data from SCADA. These results corroborate what is indicated in the literature, where high-frequency data are better learned by HMMs, while medium or low-frequency data show less expressive results, especially as in the case of this work, where there is a significant imbalance between the classes.

Particularly, although some classes show higher misclassification rates, especially those associated with generator-related components. The results demonstrate that HMMs provide a coherent and interpretable probabilistic framework for modeling sequential operational behavior, making the technique quite interesting to support predictive maintenance strategies in wind power systems, especially in scenarios where only SCADA data is available.

6 Final Remarks and Future Work

The relevance of wind energy as a component in reducing greenhouse gas emissions and achieving climate goals has grown amidst the transition to sustainable energy systems. In this sense, maintaining wind turbines in efficient operation is of paramount importance to ensure an efficient energy supply.

This work evaluates the use of Hidden Markov Models (HMMs) for multiclass classification of operational states in wind turbine components of the Portuguese

company EDP, using SCADA data. The modeling used allows the representation of temporal degradation patterns in the turbines' operational data.

The results of experiments on a publicly accessible dataset indicate that the HMM-based method can distinguish between various operating conditions and identify temporal relationships in SCADA time series. The assessed test samples had macro F1 scores ranging from 0.78 to 0.89.

Finally, the data demonstrate that HMM provides a reliable, probability-based framework for emulating the sequential operational behavior of wind turbines in practical conditions, based on SCADA data. The findings also highlight the effects of class imbalance and low temporal resolution on classification performance.

Further work on this project will investigate integrated models that combine HMMs with other machine learning techniques and will extend the proposed method to include additional turbine components. In addition, it is believed that the robustness and predictive performance of the models can be improved by combining SCADA data with complementary monitoring sources, such as vibration measurements and meteorological data.

Acknowledgment. This work was supported by FCT - Fundação para a Ciência e Tecnologia, I.P., by projects: CeDRI, UID/05757/2025 (DOI: 10.54499/UID/05757/2025) and UID/PRR/05757/2025 (DOI: 10.54499/UID/PRR/05757/2025); SusTEC, LA/ P/0007/2020 (DOI: 10.54499/LA/ P/0007/2020). Specifically, the financial assistance of the FCT grant CETP/0003/2022 (DOI 10.54499/CETP/0003/2022) towards this research is hereby acknowledged. Additionally, the authors would like to thank the following Brazilian Agencies: FAPERJ, CAPES, and CNPq. DB thanks Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ) for the financial support through the grants E-26/210.798/2024 and E-26/204.262/2025.

Declaration of Generative AI in Scientific Writing. During the preparation of this work, the authors used Elicit to assist with the literature review and Grammarly for English-language refinement. Following the use of these tools, the authors reviewed and edited the manuscript as necessary and assume full responsibility for its content.

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A Comparative Study of Hyperparameter Optimization Methods for Soil Organic Carbon Stock Prediction Using Machine Learning

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Abstract. To understand how carbon moves in soil, we need to know how it is stored there, the called soil organic carbon (SOC). This knowledge is fundamental given that it facilitates the formulation of climate change mitigation policies. More and more people are using machine learning models for this task because they are able to uncover nonlinear and complex relationships among environmental variables. However, getting improved accuracy models requires carefully choosing their hyperparameters, which is often a hard, time-consuming task. This article analyzes the influence of different optimization strategies on hyperparameter identification for machine learning models used to estimate SOC in Brazilian soils. Data from approximately 3,404 Brazilian soil profiles, originating from different biomes, were used. The optimization methods evaluated were grid search, random search, and successive partitioning, using different tree-based models. The results indicate that hyperparameter optimization significantly affects model performance, with slight predictive superiority for the Gradient Boosting method using Grid Search.

Keywords: Soil Organic Carbon · Machine Learning · Hyperparameter Optimization · Environmental Modeling

1 Introduction

Attempting to determine soil organic carbon stocks (SOCS) is essential for understanding and combating climate change, since soil represents one of the

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 231–242, 2026.
https://doi.org/10.1007/978-3-032-30524-4_15

largest carbon reservoirs in terrestrial ecosystems [5]. Soil carbon dynamics determine how much carbon is stored or released to the atmosphere, directly affecting atmospheric CO_2 concentrations and thereby influencing aspects of global warming. In countries such as Brazil, where the agricultural sector accounts for a significant portion of the economy, a more accurate estimate of SOCS is particularly relevant, not only to improve land management practices but also to ensure compliance with international commitments, such as the United Nations Sustainable Development Goals (UN SDGs), especially SDG 13 (Climate Action) [4].

Despite its importance, estimating SOC content is a complex task due to the intrinsic heterogeneity of soils, the large geographic area typically monitored, and the temporal variability of carbon levels driven by human activities and weathering [18]. Another complicating factor in estimating SOCS is the use of traditional measurement methods, known as direct methods, which are typically expensive, labor-intensive, and prone to measurement errors during sampling, processing, and laboratory analysis [1]. As a result, large-scale, high-resolution monitoring of soil carbon is significantly limited.

To address these challenges, indirect measurement methods have been increasingly adopted. These methods use indirect data, such as environmental and soil variables, which are easier to obtain and are combined with statistical or machine-learning techniques to estimate SOCS [8,9]. In this context, classical methods such as pedotransfer functions based on regression models or kriging operators are commonly used. However, the performance of these methods is often limited, as they require linearity assumptions and must be calibrated for each region studied [7,15].

As an alternative to traditional indirect measurement methods, machine learning (ML) models have been widely used in recent years. They have emerged as powerful tools for approximating complex, nonlinear relationships and for handling large, heterogeneous datasets [10]. However, the performance of these models depends not only on data quality but also on the appropriate selection of their hyperparameters [19]. This process involves high computational costs, which can affect the model's accuracy and generalization [6].

Thus, hyperparameter optimization is a step that requires careful attention in the data-driven modeling workflow [20]. Although classical techniques, such as *grid search*, *random search*, and *successive halving*, are commonly employed, there are still few comparative studies evaluating their impact on machine learning models, and even fewer when it comes specifically to SOCS estimation for Brazilian soils.

In this study, we aim to fill this gap by systematically comparing three hyperparameter optimization strategies (*grid search*, *random search*, and *successive halving*) across three machine learning models: Decision Tree, Random Forest, and Gradient Boosting. The main contribution of this study is to conduct an empirical comparative evaluation of the effects of different optimization strategies on the predictive performance and computational efficiency of SOCS estimation models.

The remainder of this paper is organized as follows. Section 3 presents related work. Section 2 reviews the theoretical background on machine learning and hyperparameter optimization. Section 4 describes the dataset and methodology. Section 5 presents and discusses the results. Finally, Sect. 6 concludes the paper and outlines directions for future research.

2 Theoretical Background

This section describes aspects of soil's role in the global carbon cycle, the use of machine learning models to describe complex environmental processes, and the impact of hyperparameter optimization on predictive models' performance.

2.1 Global Carbon Cycle

The global carbon cycle describes the continuous exchange of carbon between Earth's major reservoirs, including the atmosphere, oceans, biosphere, and lithosphere [2,3]. Soil is one of the largest terrestrial repositories of carbon. It stores organic carbon in many forms, such as humified organic matter, plant residues, and microbial biomass. The interactions between biological, chemical, and physical processes, like mineralization, decomposition, and stabilization, are what control how soil carbon moves. These processes happen at different times and places, which makes soil carbon different from other types of carbon. Human activities like intensive farming, cutting down trees, and changing how land is used can throw this balance off, which releases more CO2 and makes climate change worse. To understand how carbon moves around and make soil sustainability strategies easier to use, it's important to get an accurate estimate of SOC.

2.2 Machine Learning Techniques

Machine learning (ML) offers a wide range of tools to assist in identifying or determining subtle relationships between predictor variables and target variables, particularly in domains characterized by high variability, noise, and nonlinear effects, such as soil systems [13]. The goal of supervised learning is to derive a mapping $f : \mathcal{X} \rightarrow \mathcal{Y}$ from labeled data, where $\mathcal{X}$ represents the input feature space (variables characterizing the soil, such as sediment, texture, etc.) and $\mathcal{Y}$ denotes the target variable (SOCS). To obtain the learned mapping, we minimize the loss function $\mathcal{L}(y, \hat{y})$ over the training data. This means it performs well on samples we have not seen before.

Here, we focus on tree-based ensemble models due to their trustworthiness and strong performance on tabular environmental datasets, where feature associations together with nonlinearity are prevalent.

Decision Trees (DT) partition the feature space recursively by selecting splits that minimize a given impurity measure, typically the reduction of variance in

regression problems. At each node, the algorithm selects the feature and threshold that maximize the decrease in prediction error. Formally, the split is chosen to minimize:

$$\sum_{i \in R_1} (y_i - \bar{y}_{R_1})^2 + \sum_{i \in R_2} (y_i - \bar{y}_{R_2})^2,$$

where R_1 and R_2 are the resulting regions after the split. Although Decision Trees are highly interpretable and can detect nonlinear relationships, they usually exhibit high variance and are sensitive to small changes in the data, resulting in overfitting.

Random Forest (RF) tackles this shortcoming by constructing an ensemble of decision trees using bootstrap aggregation (bagging). Each tree is trained on a random subset of the data, and at each split, a random subset of features is considered. The final prediction is obtained by averaging the outputs of all trees:

$$\hat{f}(x) = \frac{1}{T} \sum_{t=1}^{T} f_t(x),$$

where T is the number of trees. This process reduces variance whilst holding low bias, thereby increasing generalization performance. Key hyperparameters, such as the number of trees, the maximum tree depth, and the number of features considered at each split, critically affect model results.

Gradient Boosting (GBoost) follows a different paradigm by building models sequentially rather than independently. Each new learner is trained to minimize the residual errors of the current ensemble, typically using gradient descent in function space. The model is updated as:

$$f_m(x) = f_{m-1}(x) + \gamma_m h_m(x),$$

where $h_m(x)$ is a weak learner fitted to the negative gradient of the loss function and γ_m is the learning rate. This progressive refinement enables the model to detect complex patterns and interactions with high accuracy. However, Gradient Boosting is more sensitive to hyperparameter choices–such as learning rate, number of estimators, and tree depth–and may overfit without proper regularization.

Overall, tree-based models are particularly suitable for SOCS estimation because they naturally handle nonlinear associations, high-order interactions, and heterogeneous distributions of characteristics, which are commonly observed in soil datasets. Additionally, they are relatively robust to scaling issues and can accommodate mixed types of predictors, making them fitting for environmental modeling tasks.

2.3 Hyperparameter Optimization

Hyperparameters are predefined configuration parameters that control a model's learning process, such as tree depth, the number of estimators, and the learning rate. Unlike model parameters, hyperparameters are not directly learned from data and must be optimized to balance bias and variability.

Formally, hyperparameter optimization can be defined as:

$$\lambda^* = \arg\min_{\lambda \in \Lambda} \mathcal{L}(f_\lambda),$$

where λ represents a set of hyperparameters, Λ is the search space, and $\mathcal{L}$ is a validation loss function.

In this study, three optimization strategies are considered:

Grid Search (GS) performs an exhaustive evaluation over a predefined grid of hyperparameter combinations. Although simple and deterministic, it leads to an exponential computational cost with the number of parameters.

Random Search (RS) samples hyperparameter configurations from predefined distributions. It is more efficient in high-dimensional search spaces, as it explores a wider set of configurations with fewer evaluations.

Successive Halving (SH) is a resource-efficient approach based on iterative elimination. It starts by evaluating many configurations with limited computing resources and progressively allocates more resources to the most promising candidates. This strategy diminishes computational cost while preserving competitive performance.

Selecting an appropriate optimization strategy is particularly important in SOCS estimation, where model effectiveness is highly sensitive to hyperparameter settings.

2.4 Evaluation Metrics

Model performance is assessed using two regression metrics [17]:

Mean Absolute Error (MAE):

$$\text{MAE} = \frac{1}{n_{\text{test}}} \sum_{i=1}^{n_{\text{test}}} |e_i| \tag{1}$$

Root Mean Squared Error (RMSE):

$$\text{RMSE} = \sqrt{\frac{1}{n_{\text{test}}} \sum_{i=1}^{n_{\text{test}}} e_i^2} \tag{2}$$

where $e_i = \hat{y}_i - y_i$ represents the prediction error for sample i. These two metrics are interesting because, while the MAE is less sensitive to outliers, the RMSE penalizes larger errors more severely, making it useful for assessing whether the model remains stable under observations with high variance.

The k-fold cross-validation ($k = 5$) was used both during model training and hyperparameter optimization to prevent overfitting. The idea behind this procedure is to partition the dataset into k approximately equal, mutually exclusive subsets (folds). At each iteration, one fold is used as the validation set, while the remaining $k - 1$ folds are used for training. This process is repeated k times, so that each fold is used exactly once for validation.

The overall performance is then obtained by averaging the evaluation metric across all folds:

$$\hat{\mathcal{L}} = \frac{1}{k} \sum_{j=1}^{k} \mathcal{L}_j,$$

where $\mathcal{L}_j$ represents the loss computed on the j-th validation fold.

The use of cross-validation provides a more robust estimate of model performance than traditional holdout strategies, in which a single split is made between training and testing, as it reduces the variance caused by the data split and allows all samples to be used for both training and validation, making it even more valuable in scenarios with limited data availability. In addition to these advantages, it is important to consider that when dealing with heterogeneous datasets, such as soil datasets, spatial variability and non-uniform distributions could otherwise distort the evaluation.

In hyperparameter optimization, cross-validation is used to guide the selection of model configurations by evaluating each candidate set of hyperparameters across multiple folds. This prevents overfitting to a specific subset of the data and leads to more reliable and generalizable models.

It is important to avoid data leakage during model evaluation. Data leakage occurs when information from the validation set is inadvertently used during training, leading to overly optimistic performance estimates. In this study, cross-validation is applied strictly during training, ensuring that each validation fold remains unseen during model fitting.

Furthermore, because the dataset may exhibit inherent structure and potential ordering effects, cross-validation helps mitigate biases arising from a single data split. However, it is acknowledged that in datasets with possible spatial or regional dependencies–such as soil data–additional validation strategies (e.g., spatial cross-validation) could further improve the robustness of performance estimates. This aspect is considered a direction for future work.

3 Related Work

This section reviews related studies on estimating soil carbon stock using machine learning techniques. A search conducted on Google Scholar using the query (“Carbon stocks” AND “machine learning” AND “hyperparameter” AND (“Brazil” OR “Brazilian”)) limited to publications from 2019 onward returned 14 studies. Notably, prior to 2018, only two studies were identified, none of which focused on Brazilian soils.

Among the 14 studies, four used data from China, one focused on landfills, and another addressed image classification using convolutional neural networks. Two studies used machine learning to analyze the impact of straw on soil carbon and phosphorus stocks. Two others used remote sensing and machine learning for Italian soils.

Safanelli (2020) [12] developed a cloud platform for estimating soil carbon stocks in Brazilian and European soils using machine learning and remote sensing data, employing *grid search* for hyperparameter tuning.

Barbosa *et al.* (2023) [11] applied machine learning and remote sensing to estimate both soil carbon and nitrogen stocks, also using *grid search* for hyperparameter optimization.

Santos *et al.* (2023) [14] used satellite vegetation data and machine learning to estimate soil carbon stocks in Brazil, again using *grid search*.

Thus, no prior studies were found comparing different hyperparameter optimization techniques for machine learning models applied to soil carbon estimation in Brazilian soils.

4 Methodology

This section describes the proposed methodology, including the dataset used and the workflow adopted for training machine learning models with hyperparameter optimization.

4.1 Dataset

The dataset used in this study is based on the work of [16] and is extended with additional information on geographical regions according to the classification of the Brazilian Institute of Geography and Statistics (IBGE). To ensure consistency between training and testing subsets, the dataset was reorganized prior to the experiments.

The complete dataset consists of 3,404 records, covering all five geographical regions of Brazil (North, Northeast, Central-West, Southeast, and South). The database was compiled from 69 different sources of publications on soil data in Brazil. This range of sources makes certain that our database is more representative and reliable, allowing a more robust modeling process.

The variables used in this study are described in Table 1.

4.2 Modeling Pipeline

The proposed training pipeline is summarized in Fig. 1, which presents an overview of the main stages: *(i)* Dataset, *(ii)* Preprocessing, *(iii)* Model Training, *(iv)* Hyperparameter Optimization, and *(v)* Performance Evaluation.

Three machine learning models were evaluated: Decision Tree (DT), Random Forest (RF), and Gradient Boosting (GBoost). For each model, three hyperparameter optimization techniques were applied, as described in Sect. 2.3: *Grid Search*, *Random Search*, and *Successive Halving*.

The input data correspond to the training subset described in Sect. 4.1. A preprocessing stage was applied to ensure that the data were suitable for machine learning.

The first step is to choose features based on Pearson's correlation. We only kept variables that had an absolute correlation with the target variable ($SOCS$) that was greater than 0.1. This process makes the problem less complex by getting rid of features that don't add much predictive value.

Table 1. Definition of variables used in the model.

Variable	Description
$SOCS$	Soil organic carbon stock
ds	Soil bulk density
$sand$	Proportion of sand particles in the soil
$silt$	Proportion of silt particles in the soil
$clay$	Proportion of clay particles in the soil
pH	Soil pH in water
sb	Base saturation
al	Aluminum content
h	Hydrogen content
SOC	Soil organic matter content
$Espessura$	Soil thickness

The next step is to use a normalization method on all of the numbers. This process makes sure that all variables are in the same numerical range. This stops differences in magnitude between variables from affecting the learning process, which makes the training algorithm converge faster. We decided to use the rescaling method, which is also called *min-max* normalization, in this study.

Finally, the three tree-based machine learning models were used with each of the three hyperparameter optimization strategies, yielding evaluations under the same experimental conditions, thereby allowing for a fair comparison of the impact of each strategy on predictive performance.

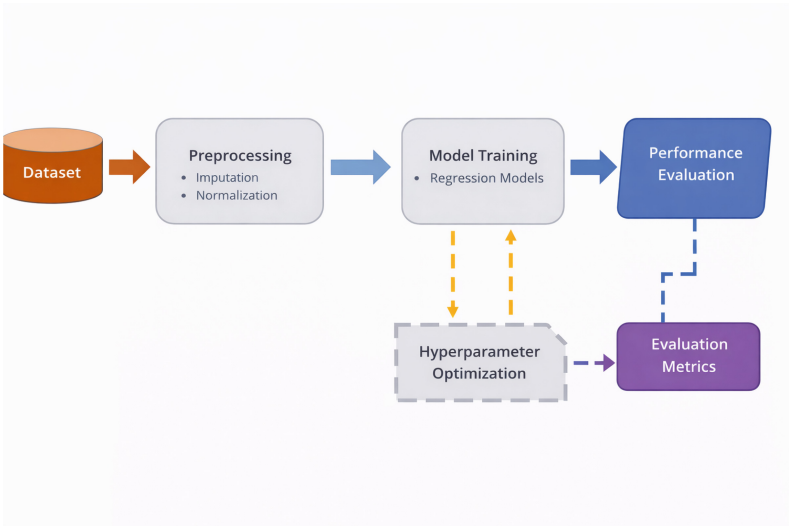

Fig. 1. Overview of the proposed machine learning pipeline.

5 Results

The experiments were conducted using computational routines implemented in Python version 3, on a Dell Inspiron machine equipped with an Intel Core i7-1255U CPU at 3.20 GHz, 10 cores, and 16GB of RAM. The libraries used were *pandas*[1] version 1.5.3, *numpy*[2] version 1.24.2, and *scikit-learn*[3] version 1.2.2. The dataset was split into 80-20% for training and testing, preserving the original order of the data. The hyperparameter optimization methods evaluated were *Random Search* (RS), *Successive Halving* (SH), and *Grid Search* (GS), all combined with cross-validation (k-*Fold* = 5).

Figure 2 presents the correlation among the variables. It can be observed that hydrogen (h), soil thickness ($Espessura$), and soil organic matter are highly correlated with soil organic carbon stock ($SOCS$), while variables such as pH (pH), silt proportion ($silt$), and clay proportion ($clay$) show low correlation. Additionally, it is important to note that the variables related to sand ($sand$) and clay ($clay$) proportions are significantly correlated, suggesting that only one of them may be sufficient for model construction.

Table 2 presents the results considering the evaluation metrics (RMSE and MAE). In terms of MAE, the best result (0.36) was achieved by the Gradient Boosting model (GBoost) using the *Random Search* (RS) technique. This result indicates that the model performs well in minimizing the average absolute prediction error.

Regarding RMSE, the best value (0.93) was also obtained with the GBoost model, using the *Grid Search* (GS) technique for hyperparameter tuning. Considering both metrics, the combination of GBoost with GS achieved the best overall performance, with RMSE and MAE of 0.93 and 0.37, respectively.

Overall, the results indicate that hyperparameter optimization is essential for improving the performance of machine learning models for soil carbon stock prediction.

6 Final Considerations

Accurate estimation of soil organic carbon (SOC) stocks is a crucial step toward understanding and mitigating climate change. Soil carbon plays a key role in the global carbon cycle, as it directly influences atmospheric carbon dioxide concentrations. In Brazil, where the agricultural sector accounts for a significant portion of the national economy, understanding soil carbon dynamics is particularly relevant, as it can support international commitments, such as the United Nations Sustainable Development Goals (SDGs), especially SDG 13, while contributing to sustainable economic development.

As shown, machine learning models have been useful for soil studies due to their ability to handle large datasets and to identify complex relationships among

[1] https://pandas.pydata.org/.
[2] https://numpy.org/.
[3] https://scikit-learn.org/stable/.

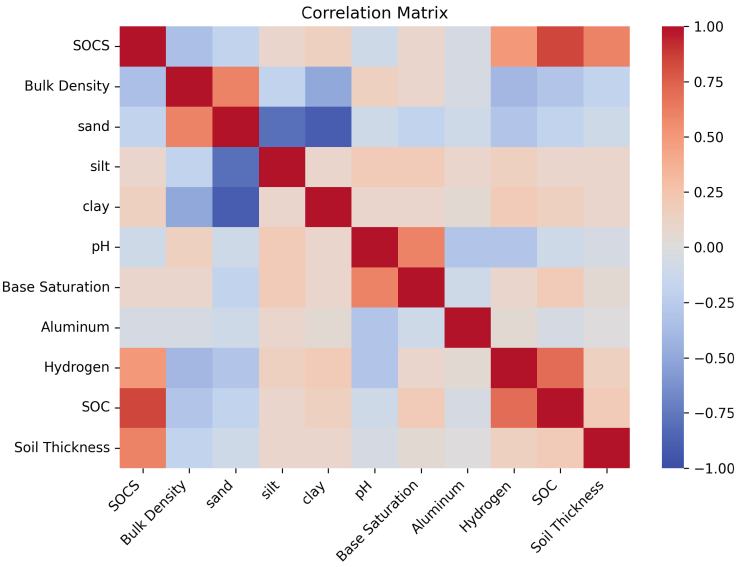

Fig. 2. Correlation matrix of the variables used in the study, highlighting the relationships between soil properties and soil organic carbon stock (SOCS).

Table 2. Performance of machine learning models under different hyperparameter optimization strategies.

Target	Model	Method	RMSE	MAE	Time	Key Hyperparameters
SOCS	RF	RS	0.98	0.50	10 s	$n_iter = 500$, $cv = 5$
	RF	SH	1.14	0.50	10 s	$cv = 5$
	RF	GS	0.94	0.45	10 s	$cv = 5$
	GBoost	RS	0.95	0.36	3 s	$n_iter = 500$, $cv = 5$
	GBoost	SH	0.95	0.41	3 s	$cv = 5$
	GBoost	GS	**0.93**	**0.37**	3 s	$cv = 5$
	DT	RS	1.52	0.50	1 s	$n_iter = 500$, $cv = 5$
	DT	SH	1.54	0.59	1 s	$cv = 5$
	DT	GS	1.58	0.50	1 s	$cv = 5$

variables. These characteristics help create more accurate prediction models, aiding our understanding of the country's soils. However, as noted, achieving good predictive performance from the model often involves a nearly manual process of parameter tuning. Thus, optimization methods for parameter tuning, such as those presented here, are highly relevant for improving model performance and making more accurate predictions.

The results obtained here highlight the importance of hyperparameter optimization in estimating soil carbon. Experiments comparing different optimiza-

tion strategies show that the chosen method can have a significant impact on both the model's accuracy and the speed at which it runs.

This suggests exploring other methods for optimizing hyperparameters in future work, such as Bayesian hyperparameter tuning and population-based metaheuristics, including Genetic Algorithms and the Biased Random Key Genetic Algorithm (BRKGA).

In addition, the integration of remote sensing data will be investigated to improve the models' predictive capacity and enable more accurate large-scale assessments of soil organic carbon. These extensions are expected to improve both the model's effectiveness and scalability in environmental monitoring applications.

Acknowledgments. This work has been funded by national funds through FCT Fundação para a Ciência e a Tecnologia, I.P., through project UIDB/05037/2025 with DOI 10.54499/UIDB/05037/2025. Additionally, the authors would like to thank the following Brazilian Agencies: FAPERJ, CAPES, and CNPq. DB thanks Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ) for the support through the grants E-26/210.798/2024 and E-26/204.262/2025.

Declaration of Generative AI in Scientific Writing. During the preparation of this work, the authors used Grammarly for English-language refinement. Following the use of these tools, the authors reviewed and edited the manuscript as necessary and assume full responsibility for its content.

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Blockchain-Enabled Implementation of Supply–Demand Matching for Local Electricity Markets

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Abstract. This work introduces a permissioned blockchain architecture to support a Supply–Demand Matching strategy for local peer-to-peer (P2P) electricity markets. The strategy computes time-varying bilateral coefficients that favour trades between households whose surplus and deficit profiles are temporally aligned. Market clearing is formulated as a decentralised optimisation problem and solved using the Alternating Direction Method of Multipliers (ADMM). The proposed blockchain layer records bilateral proposals at each iteration, preserves an immutable audit trail, and enables verifiable agreement on final trades, while keeping raw generation and load data off-chain to protect household privacy. The design includes a chain-code API, a lightweight on-chain data model for trading proposals and iteration summaries, and endorsement and identity policies tailored to residential deployments. The approach is evaluated on the case-study platform, with blockchain performance assessed by chain-code execution time. Results show that a permissioned ledger can effectively coordinate the Supply–Demand Matching mechanism with acceptable latency while providing auditability, tamper resistance, and exposing only aggregated, non-sensitive information on-chain.

Keywords: Peer-to-Peer electricity markets · Permissioned Blockchain · ADMM-based Distributed Optimization

1 Introduction

The growing penetration of renewable distributed energy resources (DERs), together with the extensive deployment of smart meters, home energy management systems, and behind-the-meter storage, is reshaping the operation of low-voltage networks. In this context, local peer-to-peer (P2P) electricity markets

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 243–259, 2026.
https://doi.org/10.1007/978-3-032-30524-4_16

have emerged as a promising mechanism for enabling prosumers and consumers to trade electricity directly within a community. Such schemes can increase self-consumption, enhance local flexibility, and keep economic value within the local area [8–10,14]. Compared with conventional centralised market structures, P2P approaches are better suited to explore spatial and temporal complementarities among households and can also support a more refined coordination between generation surpluses and consumption deficits [9,10,25]. Nevertheless, their practical deployment still faces major challenges related to transaction trust, privacy preservation, settlement integrity, and scalable coordination across multiple participants [9,25,28].

Blockchain technology has been widely investigated as a suitable infrastructure for local electricity trading because it can provide a tamper-resistant ledger, transparent transaction recording, and automated execution through smart contracts [13,15,20,27]. In particular, and according with [13,15,20], permissioned blockchain architectures are especially attractive for residential energy communities when compared with public blockchains, considering that they enable controlled participation, identity management, and lower computational overload, while preserving auditability and distributed trust. Most existing blockchain-based electricity trading approaches focus primarily on transaction logging, payment settlement, or auction execution, and often treat the blockchain layer as a stand-alone coordination mechanism rather than as an integral component of the market-clearing process [13,15,20,27]. From this view, connecting blockchain-based coordination with optimisation-driven matching mechanisms remains an open challenge. As a result, the challenge of coupling blockchain-based coordination with optimisation-based matching mechanisms remains insufficiently addressed.

From another perspective, market-clearing formulations based on distributed optimisation have shown strong potential for local electricity trading, especially when the objective is to match supply and demand while accounting for temporal complementarity. Among these methods, the Alternating Direction Method of Multipliers (ADMM) has become a widely adopted solution strategy because, as stated in [26], it decomposes the global clearing problem into local sub-problems that can be solved in parallel, enforcing consensus through iterative coordination. This makes ADMM well-suited to P2P electricity markets, where each household retains autonomy over local decisions but still participates in a globally consistent clearing process [26,28]. However, when such distributed mechanisms are implemented in practice, the coordination layer must also guarantee traceability of proposals, verifiable agreement, and protection of sensitive data [9,13,20].

The present study addresses these challenges by proposing a permissioned blockchain architecture to implement a Supply–Demand Matching strategy for local P2P electricity markets. The proposed strategy constructs time-varying bilateral coefficients that prioritise energy trades between households whose surplus and deficit profiles are temporally aligned, thereby strengthening local matching quality and improving the effectiveness of decentralised market clearing. The clearing problem is solved using ADMM, while the blockchain layer

records, in a lightweight on-chain format, per-iteration bilateral proposals, consensus-related summaries, and final trade outcomes. Raw consumption and generation data remain off-chain, limiting exposure of sensitive information and preserving household privacy. The proposed architecture further defines a chaincode interface, on-ledger data structures, and identity and endorsement policies suitable for residential deployments [13,15,26,27].

The main contributions of this work are threefold. First, it introduces a blockchain-enabled coordination architecture tailored to a decentralised Supply–Demand Matching mechanism for local energy communities [9,10,20]. Second, it demonstrates how a permissioned ledger can support iterative market clearing with immutable auditability and verifiable settlement while minimising on-chain data exposure [13,15,20,27]. Third, it evaluates the feasibility of the proposed design through a case study and blockchain execution analysis, showing that the architecture can support decentralised coordination with acceptable latency and operational transparency [13,20,27].

The remainder of this paper is organised as follows. Section 2 reviews the relevant literature on local electricity markets and peer-to-peer electricity trading. Section 3 presents the case study and describes the residential energy community under consideration. Section 4 details the proposed methodology, including the market-clearing and trading mechanisms. Section 5 introduces the blockchain implementation architecture and technological infrastructure. Section 6 presents the results and feasibility analysis. Finally, Sect. 7 concludes the paper and outlines future research directions.

2 State of the Art

The transition toward decarbonised and decentralised electricity generation systems has accelerated the deployment of distributed renewable generation, smart metering infrastructures, home energy management systems, and behind-the-meter storage. These developments are reshaping the operating model of low-voltage distribution networks, which are increasingly evolving from passive infrastructures into active environments populated by heterogeneous prosumers, flexible loads, and opportunities for local balancing. Within this setting, local peer-to-peer (P2P) electricity markets have gained attention as a promising way to enable direct electricity exchanges among community members, so that local surplus generation can be matched with nearby demand. Such arrangements can enhance self-consumption, lessen dependence on the upstream grid, improve the use of local flexibility, and keep economic benefits within the community [3,16,18,19].

The literature on local electricity markets also reveals a gradual shift from conceptual market formulations towards frameworks that are much more focused on real-world implementation. Earlier studies, such as [3,16–18], were mainly concerned with theoretical market structures, prosumer participation incentives, and bilateral trading mechanisms. However, recent works have examined practical solutions for settlement, transaction verification, and market coordination.

A consistent finding is that local electricity markets are most effective when they explicitly exploit both spatial and temporal complementarities among participants. In practice, trading is not only about balancing total energy volumes, but also about aligning generation and consumption patterns over time. This is especially relevant in residential contexts, where the temporal mismatch between photovoltaic surplus and household demand strongly influences the local exchange.

A second and growingly important line of research relates to the use of blockchain as a trust and coordination layer for these markets. Blockchain has been widely proposed because it provides a tamper-resistant ledger, distributed transaction recording, and programmable execution through smart contracts. In local electricity trading, these characteristics are attractive because they preserve the traceability of offers, bids, and settled trades while reducing reliance on a central, trusted intermediary. Permissioned blockchain architectures are particularly well-suited to residential energy communities, as they support controlled membership, identity management, and lower computational overhead than public blockchain systems, while still ensuring auditability and resistance to unauthorised data manipulation [3,12,19,21].

Despite this promise, most blockchain-based local electricity market solutions still focus on transaction logging, settlement automation, or auction execution, rather than on a close integration with the market-clearing logic itself. In many proposals, blockchain functions primarily as a record-keeping layer, while the actual matching of supply and demand is performed by an external optimisation engine. Although this separation is understandable from a computational perspective, it also highlights an important gap in the literature: the coordination mechanism and the market-clearing algorithm are often developed independently, even though they are functionally interdependent in real deployments. Consequently, there remains limited work on architectures that combine blockchain-based verifiability with optimisation-based clearing within a unified design [5,19,21].

In parallel with blockchain research, distributed optimisation has become a central tool for solving local market-clearing problems in decentralised energy systems. Among the available methods, the Alternating Direction Method of Multipliers (ADMM) has received significant attention due to its ability to decompose a global optimisation problem into smaller local sub-problems that can be solved in parallel, while enforcing consensus through iterative coordination. This makes ADMM particularly attractive for P2P electricity markets, where each household or agent can solve its own local problem using private information, and only aggregated or consensus-related variables need to be exchanged across iterations. The method therefore aligns well with the privacy and autonomy requirements of decentralised energy communities [1,11,29].

In the context of electricity trading, ADMM-based formulations have been used to coordinate dispatch decisions, match supply and demand, and enforce network or market constraints in a distributed way. However, while these approaches are algorithmically elegant, they do not by themselves solve the

issues of trust, traceability, and settlement integrity. In practice, an ADMM-driven market-clearing process still requires a reliable coordination layer capable of storing iteration-level proposals, identifying the evolution of consensus, and producing an auditable record of the final trade outcome. This is precisely where blockchain can complement distributed optimisation: ADMM can handle the numerical market clearing, while blockchain can provide the immutable coordination and verification infrastructure needed for deployment in real communities [11,23,29].

Another important aspect addressed in the literature is privacy. Local electricity markets require the exchange of information that may reveal sensitive behavioural patterns, such as occupancy, appliance use, or regularity in lifestyle. Since raw generation and consumption profiles are highly sensitive, many implementations avoid placing them directly on-chain and instead rely on aggregated, hashed, or off-chain representations. This design choice is especially relevant in residential environments, where confidence in the platform depends not only on economic efficiency but also on data minimisation and alignment with privacy expectations. Accordingly, recent blockchain-based market designs increasingly adopt lightweight on-chain structures, off-chain data storage, and selective disclosure mechanisms to limit exposure of household-level information [7,12,19,22].

Another major constraint relates to scalability. Local electricity markets may require repeated bargaining or iterative clearing among participants, which can create significant communication and computational overload. In blockchain-based systems, this challenge is intensified by ledger update latency, endorsement procedures, and consensus costs. For this reason, recent studies are proposing permissioned architectures, hybrid off-chain/on-chain workflows, and compact transaction payloads to preserve operational feasibility [7,19]. On the whole, the literature suggests that blockchain is most effective when used as a lightweight coordination and verification layer, rather than as the component that performs all optimisation directly on-chain [6,18].

From the above, and synthesising, blockchain-enabled local electricity markets are progressing towards more practical and deployable architectures, although several open issues remain, as follows: the integration of market clearing with blockchain-based coordination, the design of efficient permissioned infrastructures, privacy preservation without loss of auditability, and scalable algorithms that can operate under residential communication and computational constraints. Distributed optimisation methods such as ADMM provide a strong mathematical basis for decentralised matching, while blockchain contributes trust, immutability, and verifiable settlement [6,16]. The combination of these two paradigms appears particularly promising for local P2P electricity markets, especially when the trading mechanism is designed to exploit temporal complementarity between local surplus and deficit profiles.

3 Case Study

This chapter introduces the case study adopted in this work, providing a platform to evaluate the performance of the previously introduced decentralised P2P

trading strategy. The case study consists of a synthetic residential community of ten households, including consumers and prosumers, but without storage systems. The deliberate exclusion of energy storage reflects current market realities, where installed residential battery systems remain comparatively costly and their adoption is limited, so modelling without storage better represents the present-day majority of households while remaining readily extensible for future studies. The analysis focuses on quantifying P2P trade volumes, grid import/export, self-consumption, and procurement cost. This scenario enables assessment of both economic efficiency and operational impacts on the local distribution network, which will be presented in the following chapters.

3.1 Synthetic Dataset Description

The case study is based on a real dataset from a single residential household, spanning nearly five years (2014–2020) [24]. The full dataset contains 201,604 observations recorded at 15-minute intervals. For this study, synthetic profiles for ten households are generated by scaling the original household data using predefined factors. This approach introduces diversity across households while preserving the temporal structure, statistical variability, and seasonal characteristics of the source data, thereby providing realistic representations of both consumption and generation profiles and supporting community-level analysis. A representative day, 19 August 2020, was selected to maintain computational tractability while preserving realistic intra-day dynamics. With its 15-minute temporal resolution, this dataset offers detailed information on electricity consumption and distributed renewable generation, forming a solid basis for modelling dynamic household energy behaviour, with particular emphasis on three main variables: electricity consumption, residential wind generation, and residential solar photovoltaic (PV) generation.

3.2 Grid Topology

The community is composed of ten households, connected to the low-voltage grid in a radial configuration via a point of common coupling (PCC) on the low-voltage side of a distribution transformer in the utility grid. Among the ten households, five are modelled as prosumers, equipped with solar photovoltaic panels and small wind turbines, while the remaining five operate solely as consumers. Figure 1 depicts the prosumers with solar panels, representing households with photovoltaic generation, while the wind turbine icon denotes households with wind energy conversion systems. The blue lines indicate the traditional grid connections linking all participants to the transformer and subsequently to the utility electricity grid.

3.3 Preprocessing and Operational Assumptions

All time series were analysed at their native 15-min resolution in order to capture short-term fluctuations in both demand and generation. The evaluation considers

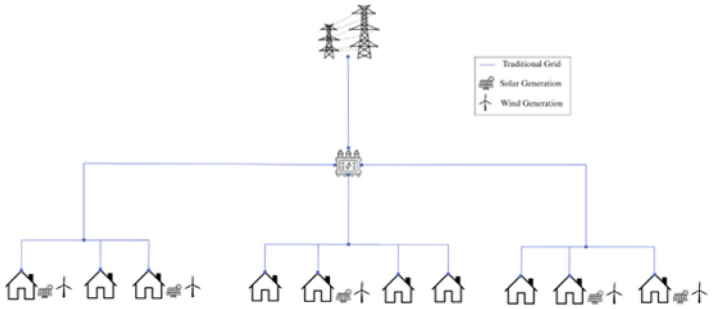

Fig. 1. Topology and distribution of households.

a single daily horizon. Prior to the analysis, the dataset was inspected for missing or corrupted entries; missing values were handled so as to preserve data integrity, and all series were retained at the original 15-min granularity to ensure temporal alignment between load and generation profiles. These preprocessing steps ensure that subsequent comparisons across households and scenarios are conducted on a consistent and reliable basis.

For simplicity, the case study uses fixed grid purchasing and selling prices rather than dynamic tariffs. The grid purchasing price was set at €0.18/kWh, while the grid selling price was defined as 20% of the purchasing price, corresponding to €0.036/kWh. This simplification serves two purposes. First, it removes the confounding effects of hourly or seasonal price variability, allowing the analysis to isolate the impact of P2P trading strategies on grid interaction and household costs. Second, the selected values are representative of realistic retail and feed-in tariff magnitudes, while the asymmetric relationship between purchasing and selling prices reflects common market conditions in which exported energy is remunerated at a substantially lower rate than imported energy. Consequently, the use of fixed prices facilitates a transparent evaluation of the mechanisms under study and highlights the distributional effects of P2P energy exchanges without adding the complexity of tariff design.

4 Methodology

This chapter describes, in a reproducible manner, the methodology adopted in this study. It integrates the mathematical modelling of the peer-to-peer (P2P) electricity trading problem, the bilateral matching strategies under analysis, the decentralised formulation solved via an optimisation algorithm, the Alternating Direction Method of Multipliers (ADMM), implementation details, and evaluation metrics.

4.1 Mathematical Model of the P2P Problem

This study considers a residential energy community composed of a set of nodes N, indexed by $i = 0, 1, ..., N$. Although a node can represent a household or a

building within the distribution network, this study focuses solely on households. All households are connected to the main grid and can inject/withdraw power through that connection. Their electricity demand is characterised by a load profile. The baseload demand of household i at timestep t is denoted as $P^l_{i,t}$, and is assumed to be deterministic. The power withdrawn from and injected into the grid is denoted as $p^g_{i,t}$ and is associated with corresponding tariffs for energy purchased from and sold back to the grid. These tariffs are fixed on timestep t for all households in the community. In P2P trading, each household can exchange a net amount of power with other households in the network. The net power exchange is denoted by $p_{i,t}$. A positive value indicates surplus power, i.e., power available for export, while a negative value represents residual demand, i.e., power that must be imported.

4.2 Mathematical Formulation of ADMM for Bilateral Trading

In this study, a P2P market model is employed as a particular instance of the unified formulation presented in [4]. This model assigns a unique bilateral trading coefficient to each trade, ensuring that every transaction is weighted by its specific characteristics. It is assumed that all households on the network act as rational, non-strategic market participants. The primary objective is to minimise the overall costs for all households (denoted by N) over a given time horizon T. These costs encompass both the expenses (or revenues) associated with withdrawing power from or injecting power into the grid, as well as those arising from bilateral electricity trading among households.

Each household independently optimises its own sub-problem, and the individual solutions are then reconciled to satisfy the global coupling constraints. After solving its local sub-problem, each household produces its own optimal local trading quantity schedule. Consensus between households is achieved when both parties propose equal values for their bilateral trades, a condition ensured by the ADMM algorithm at convergence, which is guaranteed under convexity assumptions of the optimisation problem [4]. Importantly, the decentralised setup preserves agent privacy; locally measured series (generation, demand) remain private and are not shared across the network.

4.3 Bilateral Trading Strategy

To aggregate all bilateral trading coefficient values between any household and its peers in the network, a matrix of bilateral trading coefficients, Γ, should be defined. This matrix is used to indicate preferred trading partners and enable product differentiation. According to the formulation, lower values of $y_{ij,t}$, indicate a higher preference for trading between households i and j. In this approach, a Supply-Demand Matching strategy for defining the matrix Γ is proposed, being inspired by the work presented in [2]. In this study, the strategy is implemented as a time-varying matrix Γ to capture temporal and economic complementarity between households. A time-varying approach produces dynamic matching

patterns and requires recomputation and coordination at each scheduling interval, potentially affecting traded volumes, sensitivity to forecast errors, and the computational/communication burden of ADMM coordination.

In this strategy, the bilateral trading coefficients, $y_{ij,t}$, are determined by matching households' power demand and surplus power generation [2]. It privileges temporal and economic complementarity between households. Households are preferentially paired when one's surplus production temporally matches another's demand. The principal objective is to maximise local utilisation of renewable generation and minimise aggregate imports from the main grid by promoting trades that increase system-level self-consumption. Analysis under this strategy, therefore, focuses on traded volumes aligned with generation profiles, reductions in grid dependence, sensitivity to forecasting errors, and distributional outcomes that arise from temporal complementarity. To implement these assumptions in the bilateral trading coefficients, several steps are followed:

1. The expected net budget matrix P^{net} is determined, containing the net power of all households across all time steps.
2. From this matrix, two additional matrices, P^{buy} and P^{sell}, are defined, representing the amount of net power each household intends to buy or sell at each time step.
3. Each row of P^{buy} and P^{sell} is normalised with respect to the maximum deficit and surplus values in that row.
   Normalisation ensures that preference values are comparable across households with different scales, bounds the bilateral coefficients within a predefined range (i.e., $[0, \chi]$), and preserves the temporal patterns of surplus and deficit while converting absolute energy quantities into relative trading preferences.
4. Subsequently, the matrices $\Gamma^{(b,\text{rel})}$ and $\Gamma^{(s,\text{rel})}$ are constructed.

The matrices $\Gamma^{(b,\text{rel})}$ and $\Gamma^{(s,\text{rel})}$ represent the relative willingness of households to buy or sell energy, expressed through trading coefficients. The maximum baseline value for the bilateral trading coefficients is defined by the parameter χ. Using $\Gamma^{(b,\text{rel})}$ and $\Gamma^{(s,\text{rel})}$, the final three-dimensional matrix of bilateral trading coefficients, Γ, is constructed.

Functionally, χ, acts as an upper bound that prevents bilateral coefficients from attaining excessively large magnitudes, which could otherwise lead to unrealistic P2P prices or destabilise exchange allocations. The value of χ is determined through an empirical calibration procedure to tune the strategy for the case study under analysis. This process seeks a practical trade-off between matching efficiency and economic stability.

When $y_{i,j,t} = 0$, households i and j are considered highly unlikely to engage in trading at time step t.

5 Blockchain Implementation Architecture and Technological Infrastructure

To validate the proposed strategy, a highly decoupled, multi-tier blockchain architecture was implemented. The environment was constructed using Hyperledger Fabric v2.5 and its permissioned network capabilities, ensuring privacy, immutability, and deterministic consensus.

5.1 Blockchain Network Topology

The core blockchain consortium, defined as the "SmartLEM Channel", consists of three distinct organisations representing the key stakeholders in a localised energy grid to meet the infrastructure requirements needed for setting the blockchain nodes:

- **Organisation 1 (Aggregator):** responsible for orchestrating the market, aggregating prosumers data, and initiating the settlement of energy transactions.
- **Organisation 2 (Auditor):** acts as an impartial regulatory observer, ensuring that community market guidelines are followed.
- **Organisation 3 (DSO – Distribution System Operator):** monitors the ledger to assess grid impact and physical power flows.

To ensure fault tolerance and high availability, each organisation operates two peer nodes (e.g., peer0 as the anchor peer and peer1 for redundancy), resulting in a 6-peer network. The ordering service utilises a Raft consensus mechanism (etcdraft) to provide crash fault tolerance and deterministic block creation. Figure 2 includes an overview illustration of the blockchain architecture, as well as the operations sequence for each payload requested by the experiment application.

The smart contract (chain-code), implemented in Node.js, acts as the gatekeeper to the ledger's LevelDB state database. It exposes critical market functions, primarily RegisterDeal, which standardises the asset data structure (Deal ID, Buyer, Seller, Amount, and Price). The channel enforces a majority endorsement policy, cryptographically mandating that at least two of the three organisations execute and agree on the transaction outcome before it can be committed to the ledger.

5.2 Experimental Setup and Methodology

To facilitate this experiment, the architecture was divided into two primary interacting components: a market experiment application and a blockchain integration gateway. The experiment application acts as the Aggregator's market-clearing algorithm. Once local energy supply and demand are matched, this engine packages the resulting trades and securely transmits them to the integration gateway. The gateway serves as middleware that abstracts the complexities of the underlying blockchain network. It automatically routes the proposed

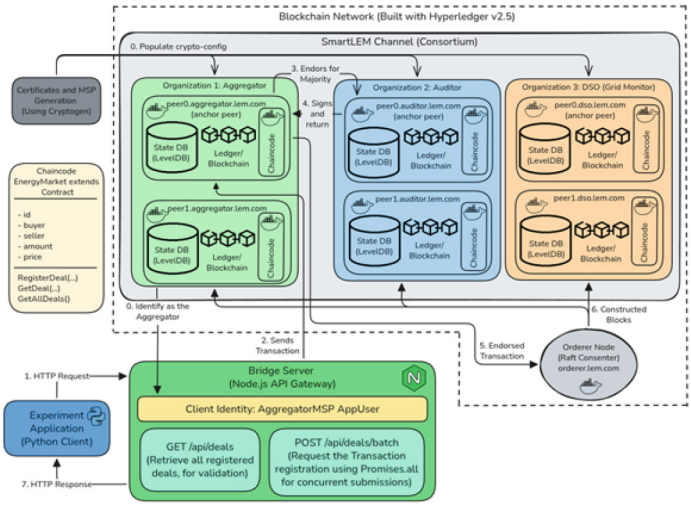

Fig. 2. Blockchain Architecture within the Experiment application and Bridge Interfaces.

energy transactions to the necessary stakeholder nodes, managing the communication required to achieve the majority consensus. This ensures that trades are only permanently registered on the distributed ledger once the required regulatory and operational agreements are met.

A core requirement of real-world local electricity markets is the ability to settle secure trades within rigorous time windows; for this experiment, a standard 15-minute market interval was utilised. The primary objective was to evaluate the blockchain system's throughput (processing capacity) and latency (processing delay) to confirm its operational feasibility for these temporal constraints. To simulate a realistic market-clearing event, the experiment aggregator application was configured to generate batches of electricity transactions. To efficiently manage this influx, the integration gateway was optimised for concurrent processing. The system enables the distributed network to validate, order, and commit the entire batch of transactions in parallel, rather than evaluating trades sequentially. This concurrent architecture maximises the network's operational speed while ensuring it can handle the dense transaction spikes typical of localised electricity market settlements.

This aggregated data was stored and is illustrated in Fig. 3. The primary metrics recorded during the experiment were:

1. Total Round-Trip Processing Time: The elapsed time (in seconds) from the moment the Python client dispatches the batch until the blockchain network fully commits the blocks and returns a success response.
2. Transactions Per Second (TPS): The network's throughput efficiency during the batch processing window.

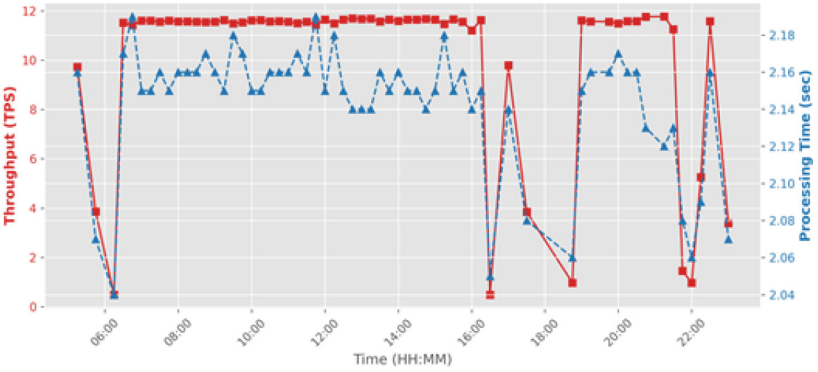

Fig. 3. Transactions per second and processing time benchmarks.

6 Results and Feasibility Analysis

The experimental simulation spanned a full 24-hour cycle, in order to capture the natural fluctuations of solar-based electricity generation. As shown in Table 1, the total amount of energy imported from the main grid, injected into it, and traded peer-to-peer (P2P) on the selected day reveals the balance between centralized supply, local surplus, and internal exchanges. Here, 'Grid import' sums all positive net withdrawals, 'Grid export' all net injections, and 'Total P2P traded energy' aggregates bilateral transfers within the community.

Table 1. Energy exchange metrics for different scenarios

Scenario	Grid Import (kWh)	Grid Export (kWh)	P2P Volume (kWh)
Baseline	56.85	27.32	–
Supply Demand Matching	47.50	17.95	9.37

As evidenced by Table 2, community self-consumption of locally generated renewables increases once P2P is used, i.e., the portion retained for local use ('Self-Consumed') grows substantially, underlining the efficiency of internal trading.

As shown in Table 3, the total procurement cost decreases from 9.25 euros in the baseline case to 7.91 euros in the supply-demand matching. This reduction is mainly explained by the traded energy volume in Supply–Demand Matching, which shifts demand from grid purchases to peer-to-peer exchanges at lower effective prices. Therefore, Supply–Demand Matching provides the best performance in terms of reduced grid-imports, enhanced self-consumption, and total cost savings, demonstrating the economic viability of the proposed decentralized market.

Table 2. Self-consumption metrics across scenarios

Scenario	Total Generation (kWh)	Self-Consumed (kWh)	Self-Consumption Rate (%)
Baseline	70.29	42.97	61.14
Supply Demand Matching	70.29	52.34	74.46

Table 3. Total cost comparison across scenarios

House	Supply–Demand Matching (euro)	Baseline (euro)
1	−0.05	0.11
2	−0.05	0.08
3	1.67	1.82
4	1.59	1.73
5	1.74	1.91
6	0.06	0.17
7	1.44	1.55
8	0.07	0.19
9	1.49	1.60
10	−0.05	0.09
Total	7.91	9.25

As shown in Fig. 4, the volume of traded electricity and total trade value (in euros) rose significantly during daylight hours (from 08:00 to 14:00), correlating with maximum photovoltaic generation. The average price remained highly stable at approximately 0.12 euros/kWh during this operational window.

The blockchain infrastructure had a robust performance when subjected to the batch transaction loads. During the peak trading periods, the network maintained a consistent throughput of nearly 12 TPS. The total processing time for these concurrent batches remained highly stable, ranging from 2.14 to 2.18 s. While throughput naturally dropped during off-peak night hours due to smaller batch sizes, the processing latency remained strictly bounded, never exceeding 2.2 s.

These results strongly validate the feasibility of the proposed architecture. In a real-world scenario, the market-clearing mechanism requires all local trades to be settled and registered within a 15-min (900-s) window. While this simulation was conducted in a localised Docker environment, meaning network propagation latency between geographically distributed nodes was minimised, the baseline processing time of $\sim$ 2.18 s leaves an exceptional operational margin. Even if physical deployment across distributed municipal and DSO servers introduces significant network latency, scaling the processing time by a factor of 10 or even 50 would still result in block commitments well under a single minute. Therefore,

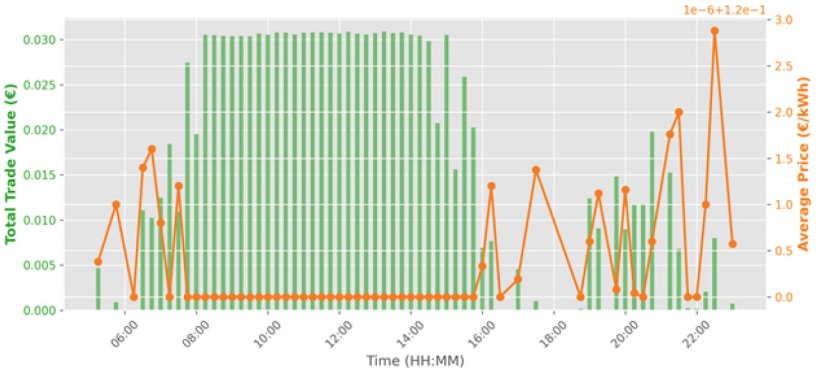

Fig. 4. Total Traded Value and Average Price during the day.

the Hyperledger Fabric infrastructure easily scales to meet the rigid temporal demands of a 15-min localised electricity market.

7 Conclusion and Future Work

This work presents a permissioned blockchain architecture for implementing a decentralized Supply-Demand Matching strategy in local peer-to-peer (P2P) electricity markets. The proposed framework combines a distributed market-clearing mechanism with a Hyperledger Fabric-based infrastructure designed to ensure privacy, immutability, and deterministic consensus. By separating the application, middleware, and ledger layers, the proposed architecture enables secure trade registration while preserving a clear boundary between sensitive household information and on-chain market records.

The results obtained for a single day indicate that the matching strategy is effective in aligning local surplus with local demand, thereby increasing the use of photovoltaic generation within the community, reducing reliance on the upstream grid, and improving self-consumption. The observed daytime trading patterns show that exchanges are concentrated during periods of high renewable production, which enhances both technical and economic performance. Moreover, the blockchain infrastructure proved capable of handling the transaction workload generated by the market-clearing process, maintaining stable processing times and operational feasibility within the timing requirements of local electricity markets.

Overall, the findings demonstrate that blockchain and distributed optimisation can be combined effectively to support local energy communities through secure, transparent, and operationally viable P2P trading. The proposed architecture therefore represents a practical step toward deployable decentralised electricity market platforms.

Future work should focus on extending the framework in both in terms of methodology and real-world deployment. On the market side, further work

will explore alternative matching strategies and adaptive pricing mechanisms to improve how trades are allocated under different demand and generation profiles. It is also important to test the approach over longer horizons and in more diverse operating scenarios, such as seasonal ups and downs and also larger communities.

From the blockchain perspective, scalability experiments involving more participants and heavier transaction loads are needed to define the limits of the proposed architecture under more demanding conditions. In addition, privacy-enhancing techniques such as selective disclosure, off-chain storage, and cryptographic access control should be explored to reduce exposure of sensitive data while preserving auditability.

Finally, it's worth examining how this architecture might work alongside distribution system operators and external market platforms. That kind of interoperability would help the system evolve from a local proof of concept into a broader, real-world solution for community electricity trading.

Acknowledgments. This work was supported by FCT - Fundação para a Ciência e Tecnologia, I.P. by projects: CeDRI, UID/05757/2025 (DOI: 10.54499/UID/05757/2025) and UID/PRR/05757/2025 (DOI: 10.54499/UID/PRR/05757/2025); SusTEC, LA/P/0007/2020 (DOI: 10.54499/LA/ P/0007/2020). Specifically, the financial assistance of the FCT grant CETP/0003/2022 (DOI 10.54499/CETP/0003/2022) towards this research is hereby acknowledged.

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Trustworthy AI for Energy-Efficient HPC Under Prediction Errors and Uncertainty

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Abstract. As High-Performance Computing (HPC) systems become faster and more complex, their energy consumption continues to increase, raising both economic and environmental concerns. Therefore, it is essential to manage energy usage efficiently, balancing energy consumption with application performance. In this work, we extend our prior research on predictive modeling for energy-efficient resource allocation in HPC systems, which uses the Energy-Delay Product (EDP) as a measure of energy efficiency. Furthermore, instead of focusing solely on predictive accuracy, we aim to provide a deeper understanding of model behavior and its impact on configuration decisions. While previous results demonstrated that an Extra Trees Regressor (ETR) can approximate Oracle configurations with high accuracy, little is known about when and why prediction errors occur. In this work, we present an analysis of prediction errors, an initial uncertainty-aware perspective, and model interpretability in EDP prediction. Our results show that although exact-match accuracy is 81.25%, over 90% of predictions fall within a small regret margin, indicating robust practical performance. Furthermore, uncertainty-aware filtering reduces high-error recommendations, improving reliability for real-world deployment. These findings position the proposed model as not only an accurate but also trustworthy tool for sustainable HPC resource allocation. This work contributes toward the development of explainable and reliable AI systems for energy-efficient computing, aligning with emerging goals in sustainable digital infrastructures.

Keywords: High-Performance Computing · Machine Learning · Resource Allocation · Model Interpretability · Uncertainty Quantification

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 260–276, 2026.
https://doi.org/10.1007/978-3-032-30524-4_17

1 Introduction

Energy consumption in High-Performance Computing (HPC) systems has become one of the main challenges in the field of parallel computing, driven by the increasing demand for computational capacity and the execution of large-scale scientific applications. In this context, it has become increasingly important to develop strategies that balance performance and energy efficiency in HPC environments [11]. This challenge is not only associated with low-level aspects, such as operating frequency and memory behavior, but also with high-level decisions made at application submission time, such as the choice of the number of computational nodes (#N) and the number of threads per node (#T).

The choice of these execution parameters can substantially affect both execution time and energy consumption, directly influencing the overall efficiency of the application in terms of both response time to obtain results and energy consumption during execution. A widely adopted way to capture this trade-off is through the Energy-Delay Product (EDP), a metric that combines time and energy into a single optimization criterion. From this perspective, the optimal configuration is not necessarily the one that minimizes execution time or energy consumption, but rather the one that achieves the best trade-off between these two metrics.

In recent years, Machine Learning (ML)-based techniques have gained prominence as an alternative for supporting efficient resource allocation in HPC, since they can capture complex relationships between input parameters, application characteristics, and performance metrics [4,5,14]. In particular, predictive models can be employed to estimate the EDP for different execution configurations and thus recommend promising allocations without the need for exhaustive searches across multiple executions. Despite this potential, many approaches still focus their evaluation only on predictive accuracy, or on a single performance dimension, such as execution time [15], while others depend on complex instrumentation or additional monitoring mechanisms [12].

In previous work, we proposed a methodology based on Extra Trees Regressor (ETR) to indicate the (#N,#T) configuration with the best EDP for the execution of parallel applications in HPC systems [5]. Using the RAxML [21] application as a case study, we showed that the model can approximate the Oracle configuration with good accuracy, defined as the configuration that yields the lowest real EDP for each input combination. However, although these results highlight the potential of the approach, they do not explain the model behavior in depth. In particular, a recommendation that differs from the optimal configuration does not necessarily constitute a severe failure from a practical standpoint, and the observed deviations may result from different trade-offs between execution time and energy consumption.

Motivated by this limitation, this work extends our previous analysis by shifting the focus from an evaluation centered only on accuracy to a more in-depth investigation of the predictability and interpretability of efficient resource allocation in HPC. Rather than introducing a new predictive method, our contribution lies in analyzing how an already validated ETR-based strategy behaves under

non-exact recommendations. More specifically, we analyze: *(i)* the structure of the experimental data from the RAxML application considering HPC system, Santos Dumont Supercomputer (SDumont)[1]; *(ii)* the variability across repeated executions; *(iii)* the impact of aggregating these executions on the definition of representative configurations, and, finally, (*iv*) the nature of prediction errors from complementary EDP, time, and energy perspectives. In this way, we seek to understand not only whether the model matches the Oracle configuration, but also how and why its deviations occur.

For this analysis, we again use the RAxML application [21], a representative bioinformatics application in the context of HPC, widely employed in large-scale phylogenetic inference. The application combines distributed-memory parallelism via the Message Passing Interface (MPI) with intra-node parallelism via *PThreads*, making it suitable for studying the impact of different resource allocation choices on execution time, energy consumption, and EDP.

In summary, the main contributions of this work are:

- an exploratory analysis of RAxML execution data, including aspects of variability, aggregation, and the interpretation of competitive configurations on the HPC system;
- a deeper analysis of prediction errors in EDP-oriented resource allocation, showing how deviations from the Oracle can be interpreted in terms of execution time and energy consumption.

The results show that, although the exact accuracy of the methodology remains high, at around 81.25% correct, the proposed ETR-based strategy remains consistently close to the Oracle across EDP, execution time, and energy consumption. Furthermore, the analyses reveal that the compared strategies, MaxRes and MinRes, never match the Oracle in the evaluated scenarios, and that their deviations correspond to distinct error profiles: excessive energy overhead in MaxRes and excessive runtime in MinRes. These findings indicate that the practical value of the proposed methodology lies not only in its exact-match accuracy but also in its ability to avoid the extreme inefficiencies observed in fixed-resource allocation strategies.

The remainder of this article is organized as follows. Section 2 reviews related work. Section 3 presents the theoretical background. Section 4 briefly describes the proposed methodology. Section 5 provides an exploratory study of the RAxML execution dataset. Section 6 reports and analyzes the prediction errors in our proposal. Section 7 concludes the paper and highlights future research directions.

2 Related Work

Several studies have investigated the use of ML techniques to support energy-aware decisions in HPC systems [1,12,14,19]. These studies differ in terms of

[1] http://sdumont.lncc.br.

optimization objective (e.g., execution time, energy, power, or EDP), required input information (e.g., application's inputs, number of nodes, and requested execution time), and the type of execution parameter being recommended (e.g., CPU or GPU frequencies, number of threads, or thread and data mappings). In this section, we focus on the works that are most closely related to our proposal, particularly those that employ predictive models to improve energy efficiency or to support resource allocation decisions.

Lorenzon et al. [14] employed a Random Forest model at runtime to select GPU frequency and execution node, achieving EDP improvements in the Frontier Supercomputer exascale system. Although effective, their approach is restricted to GPU-based environments and relies on Dynamic Voltage and Frequency Scaling (DVFS), whereas our work focuses on CPU-based systems and investigates resource allocation through the number of computational nodes and threads. Kunas et al. [12] proposed NeurOPar, a neural-network-based strategy that recommends the number of threads and CPU frequency to optimize EDP. Despite its favorable results, that approach depends on detailed profiling and standardized executions, increasing its deployment complexity.

Carastan-Santos et al. [4] also explored predictive support for energy-aware management in HPC environments. Their work focuses on lightweight prediction of power-related behavior to support scheduling decisions under power constraints. Similarly, Springborg et al. [2] investigate predictive support for energy-aware resource management at job submission time. In contrast, our approach is not designed as a scheduler-integrated mechanism but rather as an application-oriented predictive strategy that estimates EDP from historical execution data to recommend efficient resource configurations.

Scravaglier et al. [20] employ decision-tree models to identify efficient execution configurations involving NUMA placement and hardware prefetching. Their approach considers parameters such as thread count, thread and data affinity, number of NUMA nodes, and prefetcher configurations, while also accounting for different problem sizes. However, it relies on synthetic benchmarks and requires extensive profiling to gather detailed execution traces. In contrast, the approach proposed here is designed to be simpler and more practical: predictions are made early, using only information available at job submission time, without additional instrumentation. Furthermore, it is grounded in real execution data collected via RAPL and focuses on predicting EDP as the key metric for guiding configuration decisions.

The study by Imes et al. [9] applies classification models to identify efficient combinations of task sets and CPU frequencies, reporting an average energy reduction of 19.3% in bioinformatics workloads. These results demonstrate the effectiveness of machine learning in supporting energy-aware configuration. However, their approach does not employ a composite metric such as EDP as the primary optimization objective, nor does it rely on power measurements obtained via RAPL. In contrast, the present work leverages RAPL-based measurements and adopts EDP as the central metric to drive configuration selection.

Another relevant direction is the use of submission-time information to anticipate the energy behavior of HPC jobs. Patel et al. [18], for example, showed that a small set of submission attributes – user, number of nodes, and requested runtime – is sufficient to accurately predict per-node power consumption in academic clusters. This result reinforces the feasibility of early prediction based on job-level information, an idea that is also central to our work. However, their study focuses on power prediction rather than on recommending a resource allocation configuration that minimizes a composite metric such as EDP.

The work of Coelho et al. [5] (our previous work) introduced an ETR-based methodology to recommend (#N,#T) configurations that minimize EDP for parallel applications in HPC systems, without requiring application execution or code instrumentation during the recommendation phase. Using RAxML as a case study, the work showed that the methodology could accurately identify configurations close to the Oracle. The present work builds directly on that initi al proposal.

Our main contribution in this paper consists of, instead of introducing a new predictive methodology, we extend the evaluation beyond exact-match accuracy and investigate the behavior of the model from a broader perspective, including exploratory analysis of the execution data, variability across repeated runs, and the interpretation of prediction errors in terms of time and energy.

3 Theoretical Background

This section presents the main concepts that support the analyses developed in this work. In particular, we briefly discuss the ETR, the EDP, the coefficient of variation, and the Pareto frontier.

The ETR is an *ensemble* learning algorithm for regression that combines multiple decision trees built with a high degree of randomization [6]. Its main characteristic is that randomness is introduced both in the choice of candidate attributes and in the selection of split points during tree construction. This design increases diversity among the trees and helps reduce the variance of the final model. For regression tasks, the predictions of the individual trees are combined by averaging, producing a model with good generalization ability and reduced sensitivity to overfitting.

ETR is particularly suitable for tabular datasets, especially in scenarios where nonlinear relationships may exist between the input variables and the target metric [8]. In the present study, the execution data are organized exactly in this form, with each observation describing an application input and a resource configuration. For this reason, ETR is adopted as the predictive model used to estimate the EDP of candidate configurations and to support the recommendation of efficient resource allocations.

The EDP is a metric that expresses, in a single value, the trade-off between execution time and energy consumption [17]. It is defined as the product of these two variables, that is,

$$EDP(app) = Energy(app) \times Time(app), \tag{1}$$

where $Energy(app)$ and $Time(app)$ correspond to the energy consumption and execution time measured during the execution of application *app*. Because it jointly captures performance and energy cost, EDP is widely used in studies concerned with energy-efficient computing [7,14,17].

In this work, EDP plays a central role in two senses. First, it is the target variable predicted by the model. Second, it is the criterion used to define the Oracle configuration, that is, the configuration with the lowest real EDP for a given input. The analyses presented later in the paper are therefore organized around EDP, while also examining how deviations from the Oracle can be decomposed into time and energy components.

The Coefficient of Variation (CV) [3] is a normalized measure of dispersion, commonly defined as the ratio between the standard deviation and the mean of a set of observations. Unlike absolute measures of spread, the CV expresses variability relative to the scale of the data, which makes it useful for comparing dispersion across different groups or scenarios. Lower CV values indicate more stable observations, whereas higher values indicate greater relative variability.

In the context of this work, the CV is used to analyze the repeated executions of the same configuration. Since each configuration was executed multiple times, the CV helps quantify how much variability exists before aggregation. This is particularly important because the study relies on representative values derived from repeated runs, and the CV provides evidence about how much information may be lost when these repetitions are summarized into a single value, which could represent the whole poorly.

The Pareto frontier [13] is a fundamental concept in multi-objective optimization. A solution is said to be Pareto-optimal if there is no other solution that improves one objective without worsening at least one other objective. In other words, the Pareto frontier is formed by the set of non-dominated solutions, representing the best trade-offs available among the objectives under consideration.

In this study, the Pareto frontier is used to analyze the joint behavior of execution time and energy consumption. Although the Oracle is defined according to the minimum EDP, the Pareto frontier provides an additional perspective on the configuration space by identifying which solutions remain competitive in the time–energy trade-off. This perspective is useful for understanding not only the structure of the experimental data, but also the cases in which a predicted configuration differs from the Oracle while still remaining close to the set of competitive solutions.

4 Methodology

This work builds directly on the initial proposal presented in our previous work [5], and the methodological setup is as follows.

We used the RAxML application (version 8.2.12), which is widely used in bioinformatics for phylogenetic inference. The application is implemented in a hybrid manner, combining MPI for inter-node parallelism and *PThreads* for

intra-node parallelism. The input parameters considered in this study include the *bootstrap* value, which defines the number of statistical replicates performed to increase the reliability of the phylogenetic trees generated by the application, and the input file size. We consider two *bootstrap* values (100 and 1000) and eight input file sizes (182.6, 193.9, 225.7, 237.0, 266.2, 280.3, 368.2, and 473.2 Kilobytes) corresponding to multiple sequence alignments of Dengue virus genomes, obtained from Bacterial and Viral Bioinformatics Resource Center (BV-BRC) [16].

The experiments were conducted on the Santos Dumont supercomputer[2] (SDumont), operated by the National Laboratory for Scientific Computing (LNCC). The executions used up to 5 compute nodes, each equipped with two *Intel Xeon Cascade Lake Gold 6252* processors (24 physical cores per *socket*), totaling 48 physical cores per node, with *hyperthreading* disabled. Each node has 384 GB of RAM, runs the *Red Hat Enterprise* Linux 8.8 operating system with *kernel* version 4.18, and is interconnected via an *InfiniBand* network. Job management was performed using the *SLURM Workload Manager* (version 17.02).

The experiments consider the application of the proposed methodology over a subset of the possible resource allocations on SDumont, including #N equal to 1 or 5 and executions with #T equal to 2, 24, or 48. Based on these combinations, four resource allocation solutions in HPC were defined for comparison, as described below:

- **Oracle:** represents the best possible configuration of (#N, #T) for each combination of *bootstrap* values and input files, according to the possible values defined for each of these parameters;
- **MaxRes:** a strategy that prioritizes maximum performance, in which the user allocates #N = 5 compute nodes and #T = 48 *threads*;
- **MinRes:** a strategy focused on reducing computational costs, in which the user allocates #N = 1 compute node and #T = 2 *threads*, since the RAxML version used requires at least two *threads* for execution.
- **ComRes:** a strategy based on the most frequent configuration in the Oracle (observed in 60% of the cases), considering all *bootstrap* values and input files, in which #N = 5 compute nodes and #T = 2 *threads* are allocated.

The EDP values were computed according to Eq. (1), using execution time and energy consumption data collected as follows:

- **Execution Time.** Execution times were obtained using the `sacct`[3] command from the *Simple Linux Utility for Resource Management* (SLURM) [22], specifically the *ElapsedRaw* field, which provides the total duration of a *job* in seconds;
- **Energy Consumption.** Energy values were collected from counters provided by the *Running Average Power Limit* (RAPL) [10], with proper handling of possible *overflows* – energy readings were performed at intervals of up to 10 s.

[2] http://sdumont.lncc.br.
[3] https://slurm.schedmd.com/sacct.html.

For data collection, 5 executions of the RAxML application were performed for each of the 96 possible combinations of 2 *bootstraps* × 8 input files × 2 numbers of compute nodes × 3 numbers of *threads* per node, totaling 480 executions. Based on this data, we generated a dataset that enables us to move beyond exact-match accuracy and investigate model behavior from a broader perspective, including: *(i)* exploratory analysis of execution data and the variability across repeated runs, in Sect. 5; and *(ii)* the interpretation of prediction errors in terms of time and energy, in Sect. 6.

For error analysis *(ii)*, we compare all strategies with the Oracle using the normalized difference:

$$\text{Error} = (\text{Metric}_{\text{model}} - \text{Metric}_{\text{Oracle}}) / \text{Metric}_{\text{Oracle}},$$

where $\text{Metric}_{\text{model}}$ denotes the value of the evaluated metric for the suggested configuration and $\text{Metric}_{\text{Oracle}}$ denotes the corresponding value for the Oracle configuration.

5 Exploratory Data Analysis

In this section, we analyze the experimental data collected from RAxML executions. As described in the Sect. 2, the experimental dataset consists of repeated executions of RAxML collected under different combinations of input parameters and resource configurations, allowing us to observe the variability associated with execution time, energy consumption, and EDP. This analysis provides a broader understanding of how execution time, energy consumption, and EDP vary across different input sizes, bootstrap values, and resource configurations, while also supporting the preprocessing choices adopted later in the study.

5.1 Overview of the Raw Experimental Data

Figure 1 presents the raw execution data in the time (X-axis) and energy (Y-axis) space, organized by input size (columns) and bootstrap value (rows). Each point represents one observed execution configuration; marker style indicates the number of nodes, marker size indicates the number of threads, and color represents the corresponding EDP value: e.g., in the plot corresponding to Bootstrap=100 and RAxML input file size = 368.2 KB, the observation which stands out from the rest regards an execution with 5 nodes (for its marker style), 48 threads (for its marker size), and EDP $\simeq 10^7$ (for its "sea green" color) which corresponds to how much it spent regarding time $\simeq 10^2$ (for its position regarding the X-axis) and energy $\simeq 10^5$ (for its position regarding the Y-axis).

We can observe two patterns: *(i)* as the input size increases, the points tend to move toward regions of higher execution time and higher energy consumption; and *(ii)* for the same input size, the executions with bootstrap equal to 1000 generally appear in a more expensive region of the space than those with bootstrap equal to 100, reflecting the additional computational cost associated

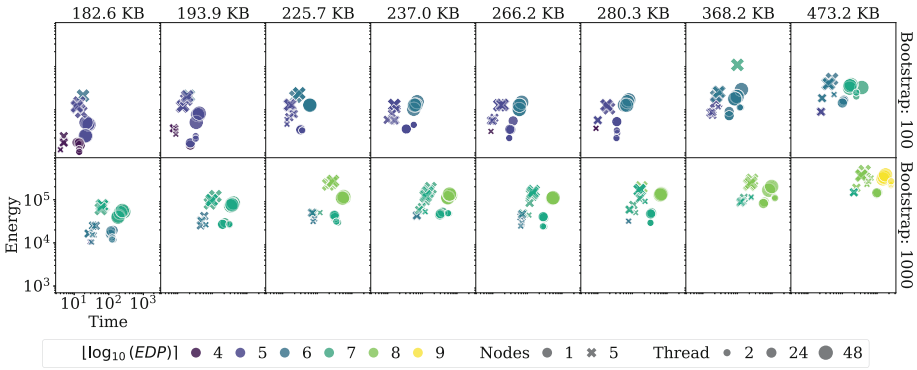

Fig. 1. Scatter plots of raw data. The size of the respective RAxML input files is indicated on top of each grid column.

with larger bootstrap values. The figure suggests that the relationship between runtime and energy consumption is not simple. In several panels, configurations that achieve shorter runtimes do not necessarily have lower energy consumption, and vice versa. This indicates the presence of a trade-off between the two objectives and justifies the use of EDP as a composite criterion.

5.2 Aggregated Configurations

Since each resource configuration was executed multiple times, the next step consists of summarizing repeated executions into a single representative point per configuration. In this work, we adopt the median of the observed values for each complete configuration. Figure 2 shows the resulting aggregated representation in the same time and energy space as Fig. 1, now enriched with the corresponding Pareto frontier (red line) and the Oracle solution (circle), defined as the configuration with minimum EDP, for each combination of bootstrap and input size. It can be observed that in each graph, each marker is unique, representing a singular combination of the number of nodes (1 or 5) and the number of threads (2, 24 or 48), so that there are $2 \times 3 = 6$ points in each graph.

Compared to the raw data, the aggregated view provides a clearer picture of the effective trade-offs between configurations. In each panel, only a small subset of the available configurations lies on the Pareto frontier (red line), indicating that only a few alternatives are truly competitive when execution time and energy are considered together. Figure 2 also helps connect the Pareto frontier and the Oracle construction. The Oracle generally lies on the Pareto frontier, which is expected since the EDP combines time and energy. At the same time, the frontier highlights that the Oracle is only one of the non-dominated solutions and that other configurations may remain attractive depending on the desired balance between runtime and energy consumption. This perspective is particularly useful for the later analysis of prediction errors, since a recommendation different from the Oracle may still be on or near the Pareto frontier.

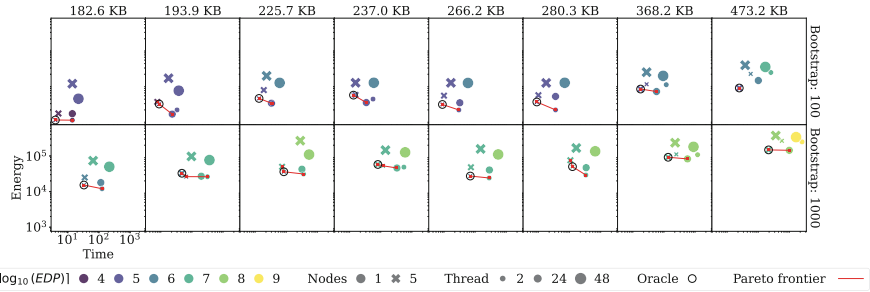

Fig. 2. Scatter plots of summarized data. The size of the respective RAxML input files is indicated on top of each grid column.

5.3 Execution Variability

Aggregating repeated executions inevitably discards part of the variability present in the raw data: the difference between Fig. 1 and Fig. 2 highlights this. To assess this loss, we analyze the coefficient of variation of EDP, denoted by cv(EDP), for repeated runs of the same complete configuration (i.e., a combination of a number of nodes, threads, bootstraps, and input size). Figure 3 presents histograms of these values for each combination of bootstrap and input size, so that each graph is based on the same 6 elements represented in each panel in Fig. 2, each of which in their turn is the aggregation of 5 executions of the same complete configuration, which were individually depicted in Fig. 1. In each panel of Fig. 1, the X-axis represents the observed cv(EDP) values and the Y-axis (Count) represents the number of configurations in each interval: the height of each bar regards the number of configurations whose repeated executions have a similar level of relative variability of EDP, and the sum of these heights is always 6.

In general, the distributions are similar across panels, with most values concentrated on the left side of the X-axis, indicating relatively low variability in the majority of cases. Only one clearly more extreme case appears in the dataset, corresponding to input size 368.2 KB and bootstrap 100, where the CV exceeds 1. Although this case remains isolated, it also suggests that the outlier filtering strategy could still be made more restrictive. Even so, the general pattern indicates that the variability among repeated executions is limited enough to support the use of a representative statistic per configuration.

Figure 4 shows the coincidence frequency between different summarization functions with respect to determining the optimal RAxML parameters. More specifically, for each pair of summarization functions, the value in the heatmap indicates how often they select the same resource configuration as optimal when repeated executions are summarized using median, mean, minimum, or maximum EDP values. Thus, a value of 1.00 means that two functions always lead to the same parameter choice, whereas smaller values indicate less agreement. The color scale reinforces this interpretation, with lighter tones corresponding

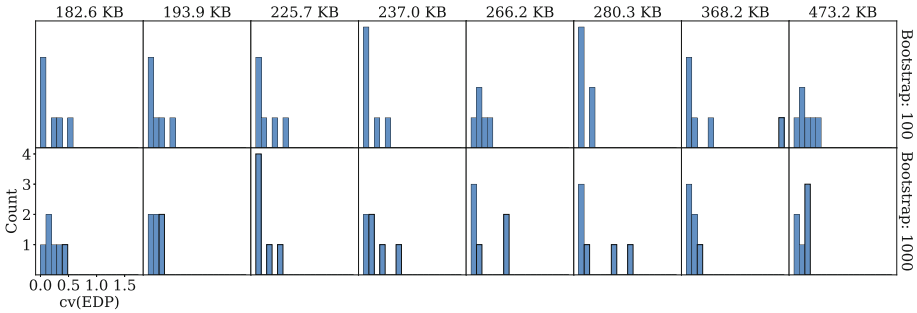

Fig. 3. Histograms of the coefficient of variation of EDP, grouped by input size and bootstrap value.

to higher coincidence frequencies and darker tones corresponding to lower ones. This comparison is relevant because each summarization function reflects a different view of configuration quality: the mean captures the average case, whereas the minimum and maximum represent more optimistic and more conservative perspectives, respectively.

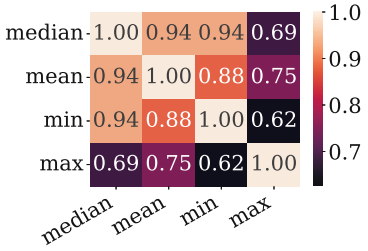

Fig. 4. Coincidence frequency of summarization functions with respect to determining optimal RAxML parameters.

The results indicate a high coincidence frequency between the median-based selection and those based on the mean and the minimum, with values of 0.94 in both cases. This suggests that, after outlier filtering, using the median or the mean rarely changes which configuration is selected as optimal. It also indicates that the configurations achieving the lowest observed EDP are often the same as those selected when more representative summaries are used. In contrast, the coincidence values involving the maximum are substantially lower, ranging from 0.62 to 0.75. This indicates that selecting configurations according to the worst observed EDP may lead to different parameter choices, since this criterion emphasizes unfavorable cases and therefore provides a more conservative view of configuration quality.

6 Prediction Errors Analysis

While our previous study [5] focused primarily on how often the proposed Extra Tree Regression (ETR) model matches the Oracle configuration and how close its recommendations are in terms of EDP, the results presented here allow a more detailed interpretation of prediction errors. Instead of evaluating the recommendations only through normalized EDP, we also examine normalized execution time and normalized energy consumption, always with respect to the Oracle configuration defined by the minimum real EDP.

This perspective is important because a recommendation that does not coincide with the Oracle may still fail in different ways. On the one hand, the model may suggest a more aggressive configuration, reducing runtime but increasing energy consumption excessively. On the other hand, it may recommend a more conservative configuration, saving energy but increasing runtime so much that the overall EDP becomes worse.

6.1 Normalized EDP

Figure 5 presents the normalized EDP (Y-axis) obtained by the evaluated strategies (represented by groups of bars in distinct colors) for each combination of bootstrap and input size. Values closer to 1 indicate closer agreement with the Oracle, whereas larger values indicate worse recommendations.

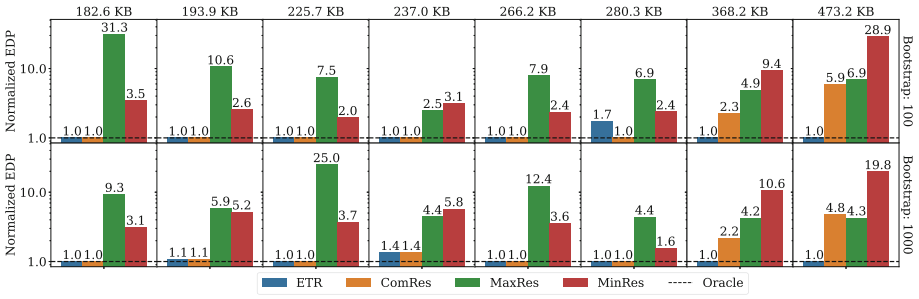

Fig. 5. EDP across all bootstrap samples for RAxML parameters.

The results show that MaxRes and MinRes do not match the Oracle in any of the evaluated cases. This result can be directly related to the exploratory analysis presented in Sect. 5.2. The Oracle solutions are consistently associated with configurations with 5 nodes, which explains why MinRes, fixed at 1 node and 2 threads, never becomes optimal. Furthermore, among the 5 node configurations, the Oracle is not associated with the 48 thread configuration, which explains why MaxRes, fixed at 5 nodes and 48 threads, also fails to match the Oracle in all cases.

On the other hand, ComRes is generally more competitive than these two extreme baselines, as it matches the most frequent Oracle configuration in the dataset. Even so, it still exhibits noticeable degradation in several cases, especially for larger inputs. These results reinforce the idea that fixed allocation policies are often inadequate for balancing execution time and energy consumption. Allocating the maximum amount of resources does not guarantee the best energy and performance, and minimizing resource use can be equally inefficient.

However, the strategy based on the ETR shows consistency. In both bootstrap configurations, its normalized EDP remains the same or very close to that of the Oracle in most cases, with only a few visible deviations. This confirms that the predictive approach is robust.

6.2 Normalized Execution Time

Figure 6 shows the same comparison from the perspective of normalized execution time. Again, the ETR recommendations remain close to the Oracle for most inputs, although some deviations become more visible.

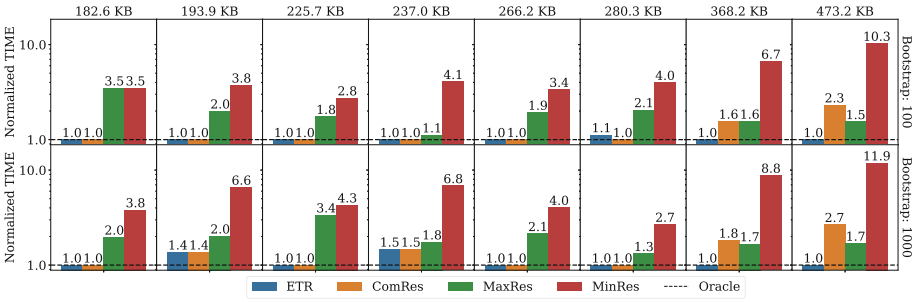

Fig. 6. Execution time across all bootstrap samples for RAxML parameters.

The results demonstrate that allocating more resources does not systematically lead to shorter execution times. Although an average user of HPC systems might expect MaxRes to dominate in terms of execution time, the figure shows that this is not always the case. For several inputs, its execution time remains above Oracle's, indicating that the additional resources do not translate into proportional performance gains. One hypothesis for why this happens is the overhead associated with coordination, synchronization, and parallel execution when more resources than necessary are employed. These results suggest that, under the workload and execution scales considered in this study, the benefits of additional resources may be partially offset by communication and coordination costs.

MinRes, in turn, performs poorly in this dimension, especially for larger inputs. Its normalized runtime grows sharply in several cases, showing that

reducing the resource allocation too aggressively may significantly increase execution time. This pattern characterizes a type of error in which the configuration is economical in terms of resource usage, but too slow to remain competitive. ComRes generally occupies an intermediate position. Although it performs better than MinRes from an execution time perspective, it still does not match the consistency of the recommendation based on ETR. Thus, this analysis indicates that both over-allocation and very conservative resource allocation strategies can fail in terms of execution time.

6.3 Normalized Energy Consumption

Figure 7 presents the results in terms of normalized energy consumption. Here, the contrast among the evaluated strategies becomes even clearer.

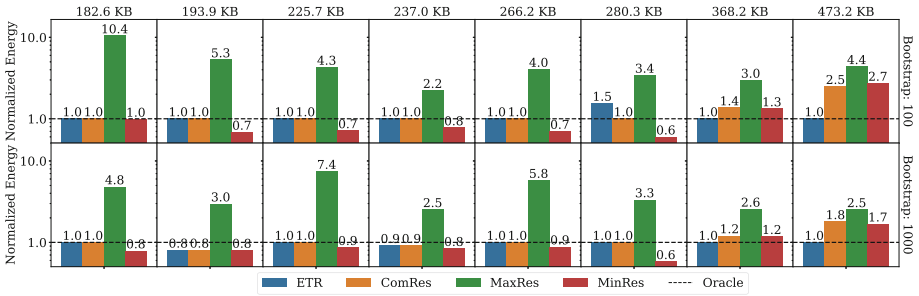

Fig. 7. Energy across all bootstrap samples for RAxML parameters.

MaxRes consistently exhibits the highest normalized energy consumption, often by a large margin, suggesting it is an energy-costly policy. Even in situations where additional resources can reduce execution time, the energy cost often outweighs this benefit. This confirms that systematically using the largest available resource configuration is not a suitable strategy for energy-efficient execution.

MinRes shows more varied behavior. For smaller input sizes, its normalized energy remains below or close to the Oracle, indicating that reducing resource usage can indeed help control energy consumption. However, this pattern does not hold in all cases; for larger input sizes, MinRes can also exceed Oracle's value in energy consumption. This is a particularly interesting result, as it shows that even a conservative configuration can become energy inefficient when the execution time penalty becomes too large (Fig. 6).

ETR recommendations also remain close to the Oracle, with only a few moderate deviations. These cases are informative because they show that when the model does not exactly reproduce the Oracle, the deviation is usually associated with a small change in the balance between execution time and energy, rather than a clearly inadequate recommendation.

7 Conclusion

This work extended our previous ETR-based approach for energy-efficient resource allocation in HPC by moving from an accuracy-only evaluation to a broader analysis of reliability and error behavior. Using RAxML as a case study, we investigated the structure of the execution data, the variability across repeated runs, and the practical meaning of prediction deviations with respect to the Oracle configuration.

The exploratory analysis showed that summarizing repeated executions with representative statistics is appropriate for this dataset, since most configurations present low relative variability. In addition, the time–energy space confirmed that only a subset of configurations is truly competitive, as indicated by the Pareto frontier, and that the Oracle is typically located among these non-dominated solutions. This Pareto-based perspective shows that non-dominated configurations other than the Oracle may also be relevant, depending on the desired trade-off between execution time and energy consumption.

From the prediction-error perspective, the results indicate that the ETR recommendations remain consistently close to the Oracle across EDP, execution time, and energy consumption. Although the exact-match accuracy is around 81.25%, most non-exact predictions still incur small practical regret. In contrast, fixed strategies based on extreme allocations (MaxRes and MinRes) systematically fail to reproduce Oracle decisions and exhibit distinct inefficiency profiles: MaxRes tends to incur high energy overhead, while MinRes frequently suffers from excessive runtime. These findings reinforce that trustworthy support for HPC resource allocation should be evaluated not only by exact matches but also by the quality and interpretability of non-exact recommendations.

Overall, the study provides additional evidence that the proposed predictive strategy is a robust and practical alternative for sustainable HPC operation. A limitation of this study is that it considers only one application and one HPC environment. Broader validation across other workloads and platforms remains future work. In addition, we intend to incorporate explicit uncertainty estimates into the recommendation process and investigate confidence-aware policies for low-confidence predictions.

Acknowledgments. The authors acknowledge the National Laboratory for Scientific Computing (LNCC/MCTI) for providing access to HPC resources on the SDumont supercomputer. This research was supported by the Brazilian National Council for Scientific and Technological Development (CNPq) under grant no.440360/2022-6, and by Portuguese national funds through FCT – Fundação para a Ciência e a Tecnologia, I.P., through project UIDB/05037/2025 with DOI 10.54499/UIDB/05037/2025 and BULL Ltda.

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

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Profiling Innovation Actors: Insights from Patentees Data for Intelligent Sustainable Development

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Abstract. Innovation actors play a pivotal role in sustainable development research. In spite of this, existing empirical studies often struggle to capture the full complexity of patentees' human attributes and motivational drivers. From prior work in organizational behavior and patenting dynamics, this paper introduces an integrated machine learning framework for patent-holder profiling that combines human resources (HR) data with survey-based measures of work motivation. We evaluate a diverse set of classification models, including logistic regression, random forests, gradient boosting, and support vector machines, across multiple behavioral prediction tasks. In addition, we assess how feature richness and principal component analysis (PCA)–based dimensionality reduction affect the trade-off between predictive accuracy and model interpretability. Results indicate that models augmented with motivational survey features consistently outperform HR-only benchmarks, while PCA offers an effective pathway to parsimonious representations with limited performance loss. In summary, the contributions of this work are a systematic comparison of machine learning techniques for profiling innovation actors, a demonstration of the added value of human-centered motivational data, and some practical insights for the deployment of explainable AI in Intelligent Sustainable Development (ISD).

Keywords: Sustainable Development · Machine Learning · Innovation · Model Interpretability

1 Introduction

Sustainable development heavily depends on understanding the human actors behind innovation, especially when patenting activity signals technological change with social and environmental consequences. Recently technical literature has highlighted the need for more insightful behavioral profiles of patentees

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 277–289, 2026.
https://doi.org/10.1007/978-3-032-30524-4_18

and the potential of data-driven methods to reveal the motivations and capabilities that lead to innovation [1–4,6–11,13–16]. In this context, innovation actors are way more than just inventors and patent filers, but also individuals whose organizational, demographic, and motivational attributes shape the design and adoption of novel technologies.

However, past studies often focused on either structural patent data or limited statistical summaries, leaving a gap in the integration of diverse machine learning approaches with human-centered survey evidence. Some of these studies suggested that work motivation, job characteristics, and HR-related (i.e., personal and institutional) information are relevant to innovation outcomes. However, the relative value of different classifiers and the impact of data analysis methods such as dimensionality reduction have remained underexamined. This gap is evident in the literature in the context of ISD, whose policies are relevant as much as the they exhibit properties such as explainability and model transparency.

This manuscript builds on prior research [7,8] by incorporating more machine-learning methods and techniques for profiling patentees and by explicitly comparing their performance on multiple classification tasks. Using an original dataset that integrates structured human-resources data with responses from a work-motivation survey, the study assesses how this multimodal approach enhances both predictive performance and interpretability. In addition, PCA-based dimensionality reduction is examined for preserving the most informative behavioral components while mitigating feature complexity.

Informed by the findings of the earlier studies and the requirements of explainable AI, this work aims to show that richer feature representations combined with deliberate model selection can generate more robust and actionable insights for ISD. The findings are intended to guide both practitioners and researchers in identifying modeling strategies that achieve an effective balance between predictive accuracy, transparency, and practical applicability.

The remainder of the paper is organized as follows. Section 2 reviews related work on innovation actors, sustainable development, and machine learning for behavioral profiling. Section 3 describes the dataset and motivations for combining HR and motivation data. Section 4 presents the methodology, including dataset construction, feature extraction, and model evaluation. Section 5 reports the experiments and results. Finally, Sect. 6 concludes with key findings and directions for future research.

2 Related Work

Research on patenting motivation and innovation actor profiling has advanced notably with Jesus et al. [7], who analyzed Brazilian university researchers' motivational factors for patenting, and Jesus et al. [8], who proposed a classification model for patenting motivation in Brazilian public universities. Jesus et al. [7] explores how intrinsic and extrinsic motivators interact with institutional incentives, while Jesus et al. [8] moves this research one step further by operationalizing motivation markers in a supervised learning framework. These foundational

studies establish the empirical and methodological baseline that this manuscript extends by adding a broader comparative evaluation of classifiers and richer human-centered and PCA-based feature sets. More than just improving predictive performance, this work also seeks to enhance the interpretability of models for ISD applications, where understanding the human and organizational drivers of innovation is crucial for policy design.

Broader studies of academic and university innovation confirm the importance of institutional incentives and actor-level characteristics. Baldini [1] examine university strategies for encouraging patenting through policy design and incentive mechanisms, while Dalmarco et al. [4] document how organizational ecosystems and managerial choices shape technology-transfer trajectories. Blind et al. [2] and Good et al. [5] highlight the tensions between academic publishing, technology transfer, and patent-driven innovation, pointing to the complex role of academic norms in shaping innovation behavior. Similarly, Lam [9], Moutinho et al. [11], Perkmann et al. [13] provide complementary evidence on individual-level drivers, such as career incentives, professional networks, and engagement with intellectual property.

The human and motivational dimensions of innovation are well represented in the literature. Jesus et al. [7] provides additional evidence on motivational constructs by comparing diverse survey measures, while Choi et al. [3], Issah et al. [6], Moletta and Pilatti [10], Ponta et al. [14], Rossoni et al. [16] examine motivational dimensions, barriers, and identification strategies that shape innovation activity across sectors. These studies collectively demonstrate that motivation is multifaceted, shaped by both personal aspirations and structural conditions, and that capturing it requires more than patent counts or bibliometric indicators.

At the intersection of data science and innovation studies, Choi et al. [3], Jesus et al. [8], Ponta et al. [14] show how classification models can identify innovation-related behavior from structured variables, while Issah et al. [6] emphasizes the need for systematic reviews and clearer interpretability in machine learning applications. Potekhina [15] and Blind [12] discuss the implications of technology use and organizational choices for innovation outcomes, and Torrisi et al. [17], Veer and Jell [18] examine contribution patterns in collaborative environments that are relevant to how innovation actors interact within research teams.

In summary, technical literature supports employing comprehensive machine learning modeling for innovation actors, but also suggests that this idea is yet to be fully explored. Existing work has documented the importance of motivation, institutional incentives, and actor-level characteristics, but it has rarely combined machine learning comparisons, HR information, and survey-derived motivation data in the same framework. The present study builds on these contributions by integrating HR variables, motivation survey data, and a comparative suite of predictive algorithms in the context of Intelligent Sustainable Development. This approach aims to deepen our understanding of how diverse data sources can improve both predictive performance and interpretability for profiling innovation actors.

3 Dataset

The dataset used in this manuscript is a subset of original sample employed in the prior works by Jesus et al. [7] and Jesus et al. [8]. It consists of Brazilian public university patentees and researchers whose administrative HR records were linked to a tailored survey on work motivation, organizational support, and innovation-related perceptions. The dataset includes demographic and employment attributes, patenting experience and outcomes, institutional affiliation, and psychometric measures for intrinsic/extrinsic motivation, perceived incentives, and barriers to innovation.

The original sample was collected through a combination of web-scraped data from publicly available resumés of patentees affiliated to major Brazilian universities as well as their answers to the aforementioned survey questionnaire. A total of 450 patentees were invited to participate, and 131 agreed to that, so that only 131 full records were considered for this study: such a relatively small and context-specific sample limits the generalizability of any analysis of it, but it plays an important role given the lack of comprehensive datasets in this context. Table 1 enumerates which HR-related input variables were ultimately used. Besides these, 27 additional input variables were derived from the survey responses, provided as 1-to-5 Likert-scale indicators.

With respect to the target variables, the study focuses on several key categorical attributes derived from the survey responses that capture the patentees' engagement in patenting activities, professional orientations, motivational drivers, and value alignments. These variables provide insights into the behavioral profiles of innovation actors. Table 2 summarizes the distribution of values according to their respective counts for each target variable analyzed in the dataset. The original classification of each patentee into these categories resulted from the application of conceptual rules on their survey responses [7,8]. Ultimately, assessing the ability to learn these rules from all available input variables or even the HR-related subset alone is one of the main objectives of this study.

4 Methodology

This study follows a supervised multi-class classification workflow to profile innovation actors from heterogeneous inputs that combine HR attributes and motivation-related survey indicators. Let $\mathbf{x}_i \in \mathbb{R}^d$ denote the feature vector of patentee i and y_i its categorical target label for one of the four behavioral outcomes introduced in Table 2. The objective is to learn a mapping $f : \mathbf{x} \mapsto y$ that generalizes across distinct target structures and class distributions while remaining informative for ISD-oriented decision support.

Table 1. Key input variables from the patentee dataset and their measurement types.

Input Variable	Type
Full articles published in journals	Numerical
Published book chapters	Numerical
Complete papers published in conference proceedings	Numerical
Abstracts published in conference proceedings	Numerical
Number of patents and registration requests	Numerical
Bachelor's degree location	Categorical
Master's degree location	Categorical
Doctorate's degree location	Categorical
Birth Interval	Categorical
Gender	Categorical
Birthplace	Categorical
Have you ever had a patent awarded?	Categorical
Have you ever had any patents licensed?	Categorical
Have you ever had a patent deposited abroad through Patent Cooperation Treaty (PCT)?	Categorical
Have any patent request been the result of interaction with the industry?	Categorical

Table 2. Summary of target variables values and their counts.

ID	Variable	Value	Count
1	Interaction in patenting process. Active or passive?	Active	59
		Passive	72
2	Classification regarding professional orientation	Hybrid	72
		Entrepreneurial	44
		Pragmatic traditional	11
		Pure Traditional	4
3	Nature of motivation	Extrinsic	44
		Mixed	44
		Intrinsic	43
4	Relationship between standards / personal values	Identification	55
		Introjection	34
		Integration	42

The methodological design is organized around four target variables: interaction in the patenting process, professional orientation, nature of motivation, and relationship between standards and personal values. For each target variable, we compare a diverse set of learning paradigms, including linear (Logistic

Regression), probabilistic (Gaussian Naive Bayes), kernel-based (Support Vector Machines), tree-based (Decision Trees), and ensemble models (Random Forests, Gradient Boosting, Voting Classifier combining Logistic Regression, Random Forest, and Gaussian Naive Bayes). Each of the considered classification models were subject to grid search for hyperparameter optimization, and were assessed through standard k-fold cross-validation on the same data splits.

To examine how predictive performance responds to feature availability, we define experimental scenarios along two binary dimensions: feature scope (full feature set versus an HR-only subset) and feature representation (original variables versus PCA-transformed features). PCA is employed as a linear projection technique to evaluate whether compact representations can retain discriminative capacity while alleviating variance inflation and reducing the risk of overfitting. The full feature configuration integrates both HR and survey-based information, while the HR-only setting restricts the input space to administrative and demographic attributes.

Model performance is evaluated using a complementary set of metrics, including Accuracy, Balanced Accuracy, Precision, Recall, and F1 score. This metric suite enables a nuanced assessment under class imbalance, which is particularly relevant for multi-class problems involving minority groups. Balanced Accuracy and macro-averaged measures are emphasized to prevent overly optimistic estimates driven by dominant classes.

Rather than focusing solely on pointwise metric outcomes, the analysis highlights performance distributions across targets, experimental scenarios, and model architectures. Results are therefore summarized using boxplot-based comparisons, which capture central tendencies, dispersion, and outlier behavior, offering insight into model stability and consistency. This approach supports three complementary analytical perspectives discussed in Sect. 5: sensitivity across targets, convergence across performance metrics, and robustness across architectures.

Finally, interpretability is addressed through feature-importance analyses conducted on representative models, enabling consistency checks between learned decision patterns and established conceptual assumptions. This component is particularly critical for ISD contexts, where transparency and traceability are essential for translating machine-learning outputs into actionable guidance for policy and institutional decision-makers.

5 Experiments

This section presents a structured empirical analysis of the proposed profiling pipeline under different feature-space constraints. First, we examine how predictive performance varies across the four target variables when toggling HR-only feature subsets and PCA-based dimensionality reduction (Sect. 5.1). Next, we assess the stability and convergence of evaluation metrics to verify whether performance changes are consistent across accuracy- and balance-oriented criteria (Sect. 5.2). Finally, we compare model architectures to identify which learning

paradigms are more robust under information-rich and information-constrained scenarios (Sect. 5.3). For the sake of reproducibility, the source code used in this study is available at a public repository[1] or upon request. It was implemented in Python using well-known data science libraries (e.g., scikit-learn, pandas, seaborn). Any details regarding the specific hyperparameter values and other similar aspects can be found in the codebase.

5.1 Analysis of Performance Across Target Variables

The boxplots presented in Fig. 1 delineate the aggregated empirical performance distributions of all considered classification models across four distinct target variables, specifically examining the sensitivity of these models to feature subsetting (HR-only) and linear dimensionality reduction (PCA).

In the control scenario (HR-only: False, PCA: False), the models utilize the full feature space. A significant finding is the near-perfect performance attained for target 1 (Interaction in the patenting process), with scores consistently converging at unity. This was to be expected because the conceptual rule used to define this target variable is very simple; it only depends on the question, "Have any patent requests been the result of interaction with the industry?" binary input variable. So, this could be seen as a way to check the dataset and the modelling pipeline for sanity. On the other hand, Targets 2, 3, and 4 show a lot of variation, which means they are more sensitive to certain model architectures and hyperparameter settings when given the full set of features.

Introducing PCA under the full-feature configuration (HR-only: False, PCA: True) projects the data into a reduced orthogonal space. Such a transformation reduced the interquartile range (IQR) for Targets 2 and 3, whereas the opposite effect happened for Targets 1 and 4. Besides Target 2, all targets exhibit an overall decline in performance. These findings indicate that although the principal components is sufficient to preserve baseline predictive capacity, certain idiosyncratic features, particularly those relevant to minority classes, are likely discarded.

The shift to the HR-only feature configuration without PCA (HR-only: True, PCA: False) constitutes a substantial reduction in domain-specific information. The performance distributions show a downward shift in Targets 2 and 4 median, and an even stronger degradation for Target 3: this is an evidence that "Nature of motivation" is harder to infer from common HR data, so that public policies aiming to foster intrinsic motivation for patenting may require more specific data collection and monitoring strategies. This decline supports the idea that non-HR features, especially those capturing technical or procedural aspects of patenting, contribute essential discriminative information absent from the restricted HR-only subset. Target 1 remains an exception, sustaining high performance levels, as its defining predictor resides entirely within the HR domain.

[1] https://github.com/rafaeluft/MLPatenteesProfiles.

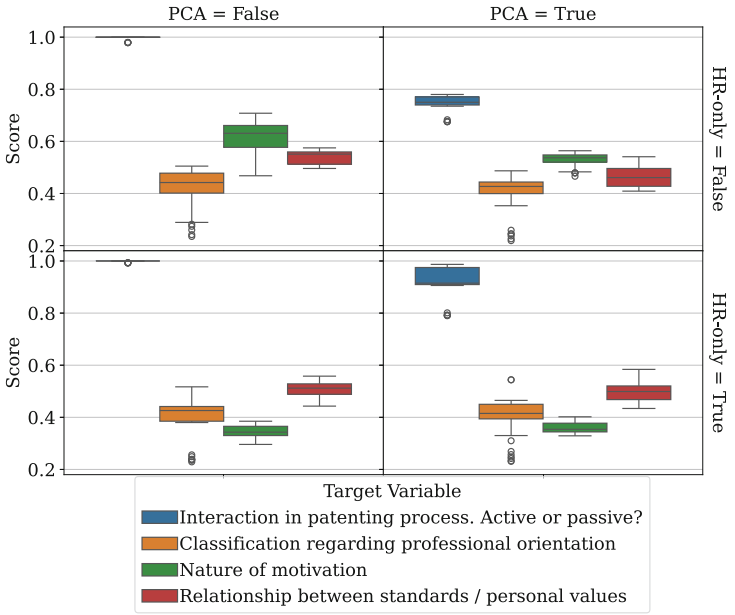

Fig. 1. Empirical Performances across Target Variables, aggregated over classifiers and evaluation metrics.

The most constrained experimental condition (HR-only: True, PCA: True) shows the compound information loss: the intersection of feature filtering and dimensionality reduction that could create a "bottleneck" effect, so that the reduced feature space could be insufficient to resolve the complexities of classification for subjective concepts represented by variables like 'Nature of motivation'. However, it can be observed the similarity of this scenario with its neighbors. The most evident difference regards target 1, since there is an increase in the performance compared to the other one with PCA = True, but a decrease compared to the other one with HR-only = True, suggesting that the effect of PCA on the larger feature space leads to a greater dillution of the discriminative power of the known predictor for this target variable.

5.2 Analysis of Evaluation Metric Stability

Figure 2 illustrates the stability and distribution of the considered performance metrics (Accuracy, F1-Score, Precision, Recall, and Balanced Accuracy) across the experimental pipeline. The analysis focuses on metric convergence and the impact of data transformations.

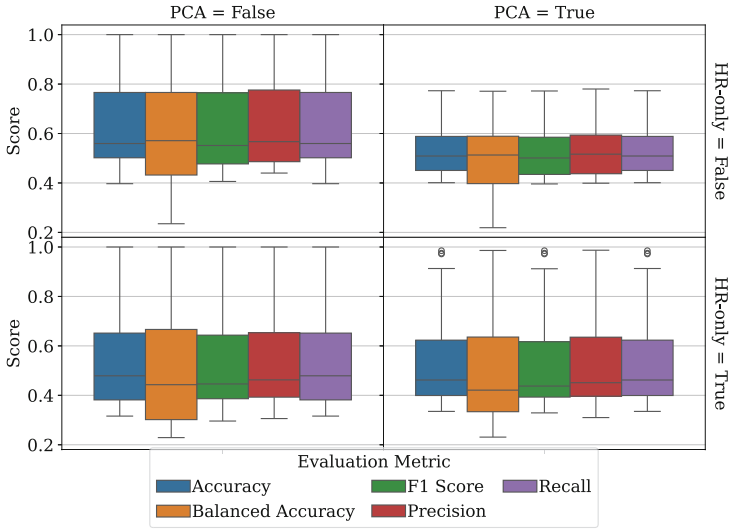

Fig. 2. Quantitative Assessment of Evaluation Metric Stability across Experimental Constraints

A key observation in the baseline configuration (HR-only: False, PCA: False) is the resemblance between evaluation metrics. The close alignment between Accuracy and Balanced Accuracy suggests that the target variables do not suffer from pronounced class imbalance that would otherwise inflate naive accuracy estimates. The substantial overlap in interquartile ranges (IQRs) for Precision, Recall, and F1-score indicates that the classifiers sustain a well-balanced trade-off between sensitivity and specificity.

When Principal Component Analysis is applied while retaining the full feature set (HR-only: False, PCA: True), a slight reduction in metric dispersion is observed, without a corresponding shift in median performance levels. The resulting metric stability suggests that the linear projection preserves the core decision boundaries, even as it suppresses minor feature-level variations that contribute primarily to extreme performance outliers in the unreduced feature space. The general pattern implies that the principal components adequately capture the effective dimensionality required for discrimination.

In contrast to dimensionality reduction, the restriction to HR-only feature subsets (HR-only: True, PCA: False) induces a systemic downward shift in the entire metric distribution. While the metrics remain tightly grouped, indicating that the models still function consistently within the limited information space, the overall predictive capacity is significantly curtailed. This performance decay suggests that the excluded technical and procedural metadata contain high-order discriminative signals that are non-redundant with the HR-only features.

The most constrained experimental condition (HR-only: True, PCA: True) illustrates the "information bottleneck" effect. Here, we observe the lowest median scores coupled with a higher degree of spreading over all metrics. This

convergence at a lower performance plateau implies that the combination of feature subsetting and linear transformation removes the necessary complexity required for high-fidelity classification. However, the existence of high-performing outliers in this quadrant suggests that for certain model architectures it is easier to overcome the explicit loss of feature diversity than the implicity loss of information through PCA, which may indicate that the latter is more detrimental to the preservation of critical discriminative signals than the former.

5.3 Comparative Evaluation of Model Architectures

Based on Fig. 3, the following analysis examines the performance variance and robustness of diverse classification algorithms (ranging from linear models to ensemble methods) across the experimental design space.

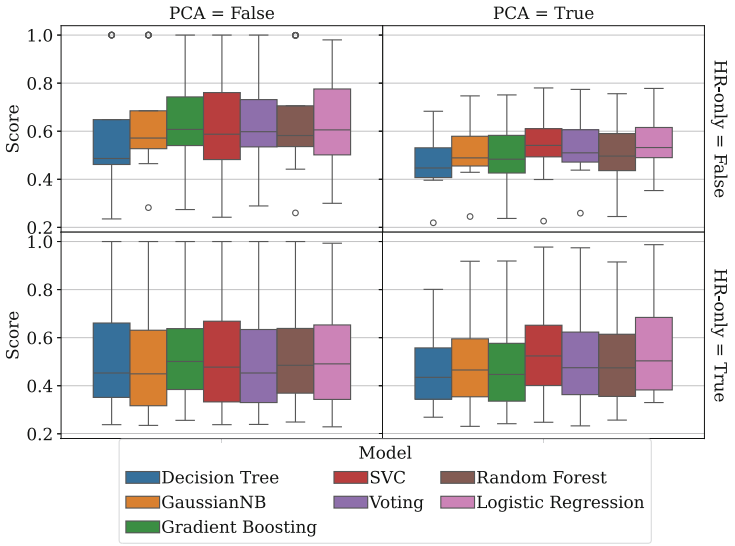

Fig. 3. Quantitative Assessment of Evaluation Metric Stability across Experimental Constraints

In the unconstrained configuration (HR-only: False, PCA: False), a pronounced divergence in model performance becomes evident. Ensemble approaches, most notably Random Forest and Gradient Boosting, achieve a substantially higher performance ceiling than linear baselines such as Logistic Regression. This pattern indicates that the full feature space encodes non-linear relationships and higher-order interactions that are more effectively leveraged by tree-based architectures than by purely linear models.

When PCA is applied while retaining the full feature set (HR-only: False, PCA: True), it functions as a regularization mechanism, particularly for models prone to high variance. Although peak performance levels remain largely

unchanged, the interquartile ranges for architectures such as Decision Trees tend to contract. This compression suggests that the projection onto a lower-dimensional orthogonal space attenuates noise that would otherwise encourage overfitting, yielding more stable performance across folds and targets.

Constraining the input space to HR-only features without dimensionality reduction (HR-only: True, PCA: False) produces a marked reordering of the model hierarchy. In this information-limited setting, the performance gap between complex ensemble methods and simpler models diminishes. This convergence implies that once key discriminative features are removed, the benefits of sophisticated inductive biases are reduced, and overall predictive capacity becomes bounded primarily by signal scarcity rather than architectural expressiveness.

In the most restrictive scenario (HR-only: True, PCA: True), Logistic Regression and Support Vector Classifiers often exhibit stability comparable to or exceeding that of ensemble methods. This outcome underscores that in low-dimensional, feature-constrained spaces, simpler models with strong regularization tend to be more resilient to information loss, whereas more complex architectures may struggle to identify meaningful decision boundaries in highly compressed representations.

6 Conclusion

This study introduced and empirically evaluated a machine-learning framework for profiling innovation actors through the integration of structured HR data and survey-based motivational information. The results demonstrate that model performance is strongly dependent on feature richness: settings with comprehensive information generally achieve higher and more discriminative predictive outcomes, whereas HR-only configurations introduce a clear performance bottleneck, particularly for targets reflecting more subjective behavioral constructs. Dimensionality reduction via PCA can enhance compactness and stability in selected scenarios; however, its effectiveness is contingent on target complexity, as it may also attenuate class-specific variability that supports discrimination.

Comparative analyses further reveal that ensemble and non-linear architectures consistently benefit from feature-rich representations, while simpler models become increasingly competitive as the feature space is constrained. This finding underscores an important methodological implication for ISD research: model architecture should not be selected independently of feature-space design. Moreover, the combined use of accuracy-based and balance-aware evaluation metrics proved essential for avoiding distorted interpretations in multi-class problems characterized by uneven class distributions.

The contributions of this work are threefold. First, it provides a structured benchmarking of diverse classifiers across multiple behavioral targets. Second, it offers empirical evidence for the predictive relevance of human-centered motivational variables in innovation profiling. Third, it presents an interpretable analytical pipeline that integrates performance distribution analysis with feature-importance reasoning. Collectively, these contributions offer actionable guidance

for researchers and practitioners seeking explainable approaches to profiling innovation actors.

Naturally, there are some limitations to be considered. The dataset is of moderate size and context-specific, and target labels are constructed from conceptual rules applied to survey responses, which may limit external validity. Future research should therefore seek to extend the analysis across institutions and time horizons, explore alternative representation-learning techniques beyond linear PCA, and incorporate calibration and uncertainty analyses to enhance the robustness and reliability of decision support in operational ISD settings.

Acknowledgments. This work has been funded by national funds through FCT–Fundação para a Ciência e a Tecnologia, I.P., through project UIDB/05037/2025 with DOI 10.54499/UIDB/05037/2025.

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

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Multidimensional Evolutionary Evaluations for Transformative Approaches (MEETA 2026)

Towards a More Than Human Assessment of Marginal Landscapes Through the Life Framework of Values

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Abstract. Anthropocentric approaches and utilitarian metrics have long dominated the assessment of marginal landscapes. Despite recent advances promoted by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) – which shift the focus from Ecosystem Services to Nature's Contributions to People (NCP) – such frameworks still struggle to recognise the full range of nature's values, particularly the relational, intrinsic, and shared dimensions that reflect the complexity of human–nonhuman relationships. In contrast, the disciplines of Environmental Humanities (EH) and Environmental Post-Humanities (EPH) have fundamentally redefined the role of humans within ecological systems, repositioning them not as dominant, autonomous agents but as nodes within a network of interconnected relationships and distributed agencies encompassing multiple human and non-human entities. This theoretical reorientation has in turn reshaped the conceptualisation of landscape – and of marginal landscape in particular – by foregrounding the ecological dimension as co-constitutive with, rather than subordinate to, the anthropogenic one. Within this framework, the Life Framework of Values offers a comprehensive basis for interpreting the instrumental, relational, and intrinsic values of Nature. This research adopts the Life Framework of Values as a critical, More Than Human lens for re-examining the spatial criteria employed in landscape evaluation frameworks. In doing so, it aims to identify and explicate the relational configurations among different territorial agencies, rendering visible the networks of coexistence between human and non-human entities that characterise marginal landscapes.

Keywords: Landscape assessment · Plural values · Nature's Contributions to People

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 293–310, 2026.
https://doi.org/10.1007/978-3-032-30524-4_19

1 Introduction

In Italy and across Europe, the concepts of rural areas – as defined within the Italian policy framework - and peripheral areas – as defined within the European one – refer to analogous territorial realities that can both be subsumed under the broader notion of marginality [1–3]. Despite the terminological divergence, both categories identify landscapes where ecological richness and territorial vulnerability converge. Their distance from productive and urban centres has allowed ecological processes to persist largely unaffected by intensive land use. However, this same distance has also resulted in population decline, limited access to essential services such as transport, education and healthcare, and structural disadvantage within dominant economic models [4].

These conditions undermine the economic, social, and cultural sustainability of such regions [5], and have consequently attracted growing attention from scholars and practitioners across planning, policy, and the social sciences, requiring great attention [6–8]. It is precisely this dual condition, ecologically significant yet territorially disadvantaged, that makes these areas a privileged vantage point through which to examine the relationship between ecosystems and society. Yet the very term "marginal" is not a neutral description, but a political-territorial construct that reflects a judgement made from the perspective of economic productivity and demographic density [9]. To call an area marginal is already an anthropocentric act, measuring landscape by its utility to human systems.

It is from this critical awareness that the present research departs, grounded in the specific assumption that margins are places where biodiversity and ecological relationships can flourish outside the logic of productivity and economic optimisation, as the British artist Nils Norman has long suggested through his practice [10].

Despite the remarkable ecological richness of these territories, the dominant frameworks used to define and assess them remain rooted in political-territorial constructs that privilege human presence as the primary measure of value. Largely based on demographic indicators, economic performance and proximity to services, such frameworks systematically render invisible the multiple forms of life and ecological relationships that persist and evolve within these landscapes [11, 12].

In response to this limitation, the conceptualisation of peripheral and rural areas has evolved in recent years, reflecting systemic and ecological changes. Spatial relationships, development models and evaluation policies from new perspectives are increasingly being approached from new theoretical perspectives, and these territories are no longer viewed solely as problem areas. Instead, they are being reconsidered as repositories of largely untapped natural and cultural capital [13], long sidelined by dominant models of valuation.

Considering this growing recognition, various assessment frameworks have been increasingly adopted, with a focus on the benefits that people derive from landscapes and the ecological processes that underpin them. While these represent genuine advances in making nature's contributions legible within economic and planning frameworks, they remain, as this section argues, structurally constrained by the same anthropocentric logic they seek to transcend.

The concept of Ecosystem Services (ES) [14–16] has been particularly influential in making Nature's contributions legible within economic and planning frameworks. More

recently, the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) introduced the term "Nature's Contributions to People" (NCP), as a broader alternative, explicitly designed to capture not only material and regulating functions but also the relational values associated with nature, those dimensions of human-nature interaction that resist quantification [17].

In the context of spatial planning and landscape assessment, however, both ES and NCP are generally operationalised through spatial indicators and mapping practices that quantify the distribution of benefits provided by ecosystems. This operationalisation has made these concepts powerful tools for policy, but it has also constrained them. The translation into measurable units tends to flatten the complexity of human-nature relationships. This logic reflects a deeper structural limitation. Both ES and NCP remain rooted in an anthropocentric view [18]: nature is assessed insofar as it contributes to human wellbeing, and its worth is measured accordingly. In doing so, these frameworks overlook nature's intrinsic value – the idea that ecosystems, species and processes hold significance independent of their utility to humans – as well as more holistic and relational understandings of the human-nature relationship [19].

This tension between ambition and practice is also visible at the level of international policy. The Kunming-Montreal Global Biodiversity Framework (GBF), adopted at COP15 (2023) [20] as the primary international policy reference on biodiversity, establishes four global objectives for 2050 and twenty-three targets for 2030 aimed at halting and reversing biodiversity loss. Two targets are of relevance here: Target 1, which shifts the focus from protected areas to the landscape as a whole; and Target 14, which aims to integrate biodiversity and its values into decision-making processes at all levels of governance. These targets signal a political openness to broader conceptions of value, yet in practice, as this paper argues, the identification and assessment of values continue to follow traditional anthropocentric logic, leaving non-human agents systematically unacknowledged.

Addressing this limitation requires not merely a refinement of existing indicators or metrics, but a more fundamental shift in the interpretative framework through which marginal areas are described and assessed. Anthropocentric frameworks, which place human beings at the centre of value, need to give way to what Pasqual et al. (2023) [21] describe as "pluricentric worldviews": orientations that do not have a single centre, but instead attend to the various intertwined relationships between humans, non-human beings and systemic processes, without privileging any single centre. This shift implies abandoning the idea of nature as something to be controlled or optimised and moving towards an ethic of coexistence grounded in the recognition of mutual interdependence across all life forms.

A major contribution to this reorientation comes from Environmental Humanities and post-humanist environmental thought. However, drawing clear disciplinary boundaries between these fields may be impossible [22]. What these approaches share is an investigation of the value of the non-human that moves beyond biocentrism's simple reversal of hierarchy, rejecting the notion of humans as the sole autonomous agent and situating them instead as one agent among others within a wider vitality of matter [23].

Within this intellectual landscape, relational approaches have gained significant momentum. Donna Haraway (1988; 1995) [24, 25] proposes a radical decentring of

the human subject, opening the way to recognising non-human entities as active participants in the making of landscapes; Karen Barad (2007) [26] develops the concept of agential realism, in which agency is not a property of individuals but emerges through material-discursive practices – a perspective that directly informs the relational understanding of territory; and Val Plumwood (2002) [27] argues that ecological humanities must resituate humans within, rather than above, the environment, providing the ethical foundation for a non-hierarchical reading of spatial relationships. Together, these perspectives have been instrumental in repositioning the sciences as cultural and political disciplines embedded within discourses on race, gender, and class rather than as objective or neutral vehicles of a "nature" separate from human beings [28]. It is within this intellectual current that David Abram introduced the term More Than Human (1996) [29], gesturing towards a world of perception and meaning shared between human and non-human bodies.

More Than Human geographies [30] have since developed this intuition in explicitly spatial terms: landscapes are actively co-constructed by bodies, processes and agencies that exceed the human [31]. This spatial dimension is central to the present paper. If landscapes are co-produced by human and non-human agencies, then the frameworks used to assess and plan them should be capable of registering and responding to that co-production. Addressing these challenges requires two complementary approaches (Fig. 1). The More Than Human approach provides the ontological lens, redefining who the agents of the landscape are, which relationships matter, and which temporalities are relevant. The Life Framework of Values approach serves as the analytical counterpart, providing a promising conceptual bridge between relational ontologies and the practical domain of environmental decision-making.

Building on O'Neill (2008) [32], O'Connor and Kenter (2019) [33] reframe intrinsic value not as an objective property of nature but as something that emerges through relationships. Organised around four positional orientations (living *with*, *from*, *in*, and *as* the world), the Life Framework of Values integrates the concepts of ES and NCP, combining instrumental, relational, and intrinsic values within a single framework and thereby overcoming the limitations of approaches grounded exclusively in human benefit.

It is against this backdrop that the paper develops its contribution, developing a critical reinterpretation of the spatial criteria typically employed in landscape assessment frameworks, reading them through the combined lens of a More Than Human perspective and the Life Framework of Values. The aim is to make visible the networks of coexistence between human and non-human entities, between slow ecological time and the accelerated temporalities of planning that constitute marginal landscapes and that current frameworks render illegible. This leads to the following research question: How can landscape assessment frameworks, and the values they articulate, be reinterpreted through a More Than Human perspective and the Life Framework of Values to reconsider the spatial criteria used in territorial decision-making? The paper is structured as follows: Sect. 2 outlines the theoretical foundations underpinning the proposed paradigm shift and identifies the key principles for reinterpreting spatial assessment criteria. Section 3 presents the methodological approach used to analyse and reinterpret existing landscape assessment frameworks. Section 4 presents the proposed reinterpretation of marginal

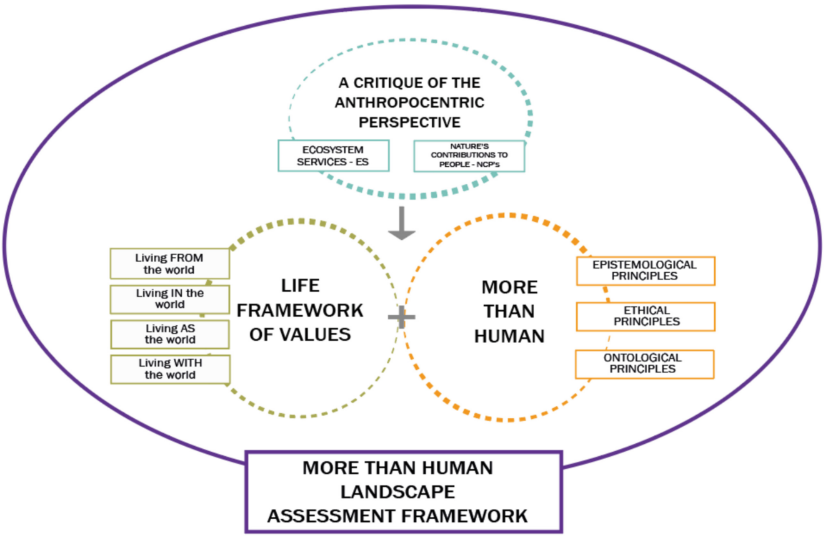

Fig. 1. An ontological lens and analytical perspective for marginal landscapes interpretation.

landscapes through a More Than Human lens. Section 5 discusses the implications of these findings for spatial planning and landscape assessment.

2 Theoretical Foundation

Understanding how landscapes are valued requires engaging with the deeper assumptions that shape their assessment. As Berbés-Blázquez et al. (2016) [34] argue, the values attributed to Nature are indicative of worldviews, systems of knowledge and power relations that underpin institutional structures in societies. The question of how landscapes are assessed is therefore never merely technical. It is always also a question of which worldview is doing the assessing, and which forms of life that worldview renders visible or invisible. Conceiving landscapes as co-produced systems, shaped by the interactions between human and non-human entities [35, 36], requires a theoretical foundation capable of articulating the agents of these systems, the obligations generated by their relationships, and the ways in which these relationships can be identified and represented.

A foundational contribution to this reconceptualisation comes from Actor-Network Theory [37–39], which holds that every entity, whether human or non-human, acquires its identity and significance through the relationships it establishes. The landscape, in this sense, stands as a relational field in which meaning and value emerge from networks of association. This perspective aligns with the notion of flat ontology [40] in which agency is distributed across a heterogeneous field of actors. Animals, plants, fungi, soils, waters, infrastructures and technologies are not passive elements of a backdrop but co-constitutive agents in the production of social and ecological realities [41]. Van Dooren and Rose (2015) [42] develop this further through the concept of the vivacity of

the world, proposing that the lives of other living beings are interwoven with meanings co-constructed through sets of shared relationships. Scott Gilbert's research in symbiotic biology [43] reinforces this point from a scientific angle, demonstrating that no organism exists in isolation: all beings are embedded in networks of mutual dependence and co-evolution. If agency is distributed and identities are constituted through relationships, then the question of how we relate to non-human entities is not merely descriptive but intrinsically ethical.

Donna Haraway (2015) [44] situates kinship at the core of her theoretical framework, positing it as a practice of fostering respect through the acknowledgement of the distinctiveness of other-than-human entities. In "Staying with the Trouble" (2016) [45], Haraway develops this through the concept of the Chthulucene: an era characterised by multispecies responsibility and the ecology of practices, in which remaining with uncertainty becomes a condition for generating unexpected forms of coexistence. Van Horn et al. (2021) [46] extend this notion, proposing that kinship with non-human entities is enacted through everyday actions guided by principles of reciprocity, respect, responsibility and care. María Puig de la Bellacasa (2017) [47] argues that care, understood as an ethical and political practice, is inseparable from the generation of non-exploitative forms of coexistence with other living beings and with the Earth.

Yet recognising ethical obligations towards non-human entities also raises an epistemological question: how such relationships can be known, perceived and represented. If the landscape is a relational field and care is a practice, then how we attend to that field is as important as the concepts we use to describe it.

Marzia Varrutti (2025) [48] proposes a rethinking of the human-non-human relationship through three interconnected perspectives: a conceptual one, engaging. Intellectual capacities to know the non-human; an affective one, perceiving the non-human through the senses and the body; and a practical one, acting upon thoughts and feelings. This tripartite structure is significant because it refuses to reduce the relationship with the non-human to a cognitive operation alone. Articulates, attention is inherently reactive, establishing relationships of correspondence between entities that coexist. The development of an ecological awareness, which commences with introspection concerning a relationship [49], engenders the capacity to respond to the world rather than merely act upon it.

From these theoretical foundations, a set of principles emerges that guide the reinterpretation of spatial assessment criteria proposed in this paper, organised across three levels: ontological, ethical and epistemological.

Ontological principles, concerning the nature of landscape agents and relationships:

- *Relationality*: the existence and meaning of any entity emerges exclusively through the networks of relationships in which it is embedded.
- *Distributed agency***:** non-human entities are not passive recipients or resources but active agents capable of influencing and being influenced by the systems they inhabit.
- *Co-habitation, co-construction and co-evolution*: landscapes are dynamic systems shaped by processes shared between species and materials over the long term.
- *Non-human temporality*: ecological time, slow time (tree growth, ecological succession) and deep time (evolution, pedogenesis), exceeds and precedes human-useful

time; standard metrics capture only a fraction of the temporal depth of landscape processes.

Ethical principles, concerning the obligations that relational ontology generates:

- *Care and kinship*: the relationship with the non-human is an ethical act that generates obligations of responsibility and reciprocity.
- *Responsibility*: Every spatial choice is a moral choice involving a community of living beings that extends beyond humans.

Epistemological principles, concerning how value is known and represented:

- *Embodiment*: the body as a site of relation with the More Than Human world.
- *Relational value*: the value of the landscape cannot be measured as the sum of individual services but emerges from the quality and density of the relationships that traverse it.
- *Intrinsic value*: non-human entities possess a value independent of their utility to humans, in line with the land ethic first articulated by Aldo Leopold [50].

These principles provide the conceptual scaffolding for the methodological work that follows. It is precisely in marginal landscapes, as relational milieus where human and non-human entities coexist and evolve in tandem, that the conditions for operationalising these principles are already present. To do so, this paper draws on the Life Framework of Values [33] as the analytical bridge between relational ontologies and territorial decision-making and is developed in full in Sect. 3.

3 Methodology

The Life Framework of Values [33] provides a methodological foundation for translating the theoretical principles outlined in Sect. 2 into an operational framework for landscape assessment. This framework has the potential to bridge the gap between theory and spatial representation, making values visible and reinterpreting them as relationships within territorial decision-making processes to promote an understanding of coexistence networks in marginal landscapes.

The framework is based on a structured critique of the operational logic underpinning both Ecosystem Services (ES) and the Nature's Contributions to People (NCP) framework developed by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES). ES classification systems, such as CICES [51], adopt a predominantly extractive and unidirectional logic in which nature is conceived as a provider of benefits for humans. The NCP represented an attempt at progress by recognising the importance of relational, intrinsic, and reciprocal values. However, the term itself betrays the limitations of the approach, as it implies a one-way flow of benefits from nature to people, thus maintaining a fundamentally anthropocentric dimension [52]. A further shortcoming lies in the limited consideration of abiotic ecosystem components.

Human–nature relationships are inherently nonlinear and multifaceted, encompassing elements such as a sense of place, cultural identity, and personal well-being that are difficult to reduce to scalar indicators [53]. In response to these limitations, the Life Framework of Values offers a means of operationalising a More Than Human perspective

within landscape assessment. It does so by reformulating intrinsic value as a subjective expression of objective intrinsic value – what O'Connor and Kenter term *articulated intrinsic values* – offering a more grounded alternative to the conventional triad of instrumental, relational, and intrinsic values, and one capable of registering the agencies and relationships that anthropocentric frameworks systematically overlook. The framework is structured around four relational dimensions, ranging from an instrumental orientation to increasingly symbiotic forms of recognition:

- *Living from the world* where the environment is seen as a source of sustenance, associated with predominantly instrumental and relational values.
- *Living in the world*, where the environment is understood as the setting for human experience, linked to relational and instrumental values.
- *Living with the world*, where importance is given to other living beings, situating humans as part of a biotic community, and activating intrinsic, relational and instrumental values.
- *Living as the world*, situates the More Than Human as both individuals and a collective self within deep ecology and relational perspectives, comprising predominantly relational and intrinsic values.

This relational gradient is particularly relevant in the context of marginal landscapes, which form the spatial focus of this research. Marginal landscapes are places where relationships with the More Than Human world are often already active and embedded in the territory, yet invisible to dominant evaluative frameworks.

The Life Framework of Values provides the conceptual tools to render non-humans legible and politically recognisable, viewing marginality not as an absence of value, but as a presence of relationship. Incorporating the framework into this research, therefore, means adopting an evaluative approach capable of capturing and reflecting the relational complexity that marginal landscapes inherently possess.

Building on this framework, the research undertakes a critical analysis to understand current models for assessing marginal landscapes, with particular reference to the NCP [17] model. The analysis aims to deconstruct the ontological assumptions underlying these frameworks and their implications for the spatialisation of value (Fig. 2). This critical work is based on the deconstruction of the logical-grammatical structure through which NCPs are defined [54]. The description follows a subject-verb-benefit structure, with the benefit being human-centred. While this structure recognises the complexity of relationships between humans and nature, in practice, the value of the landscape remains limited to its utility for human beings [55]. Moving away from the human perspective and challenging this assumption creates a conceptual and operational space in which a More Than Human perspective can be introduced, capable of recognising the multiple values that exist in the territory. This analysis focuses directly on the original IPBES documents rather than secondary adaptations to identify the underlying tensions on which the proposed reinterpretation acts.

The starting point is the selection of a subset of NCPs from the eighteen categories defined by IPBES, reduced based on their spatial applicability in rural and peripheral landscapes. The selected NCPs span regulatory, material, and non-material categories: NCP 1 – Habitat creation and maintenance, NCP 2 – Pollination and dispersal of seeds and other propagules, NCP 3 – Regulation of air quality, NCP 4 – Regulation of climate,

NCP 8 – Formation, protection and decontamination of soils and sediments, NCP 12 – Food and feed, NCP 15 – Learning and inspiration, NCP 16 – Physical and psychological experiences, NCP 17 – Supporting identities, NCP 18 – Maintenance of options.

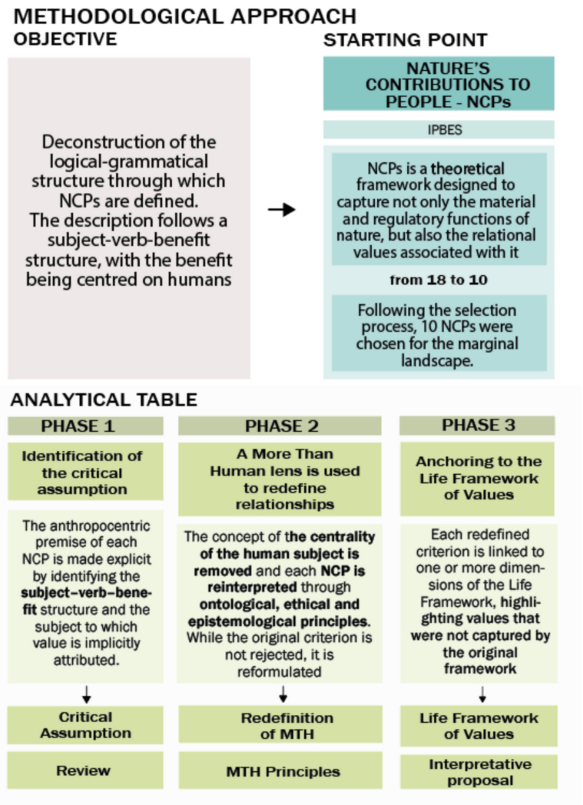

Fig. 2. A methodological process of deconstructing the subject-verb-benefit framework and reinterpreting it through the lens of More Than Human.

These NCPs are further specified through different aims and objectives [56–58] to spatialise the values of marginal landscapes. Figure 2 provides a schematic overview of the methodological process, organised across the following three phases:

– *Phase 1: Identification of the critical assumption.* For each NCP, the anthropocentric assumption is made explicit by identifying the subject-verb-benefit structure and the implicit assumption regarding what or who holds value.
– *Phase 2: Relational redefinition through a More Than Human lens.* The centrality of the human subject is removed in favour of a relational understanding of ecosystem value. Each NCP is reinterpreted through one or more of the ontological, ethical, and epistemological principles identified in Sect. 2. This redefinition does not reject the

original criterion but rather reformulates it. For example, what was previously categorised as a service is now considered a relationship; what was previously categorised as a beneficiary is now considered a co-participant.

– *Phase 3: Anchoring to the Life Framework of Values.* Each redefined criterion is associated with one or more dimensions of the Life Framework (O'Connor & Kenter, 2019). This phase reveals the values that emerge when the perspective changes, which the original framework failed to capture.

The outputs of these three phases are systematised in an analytical table (Table 1), which renders the full methodological process visible and comparable across the selected NCPs.

4 Results

This section presents the results of the critical reinterpretation process applied to the Nature's Contributions to People (NCP), operationalised through the analytical table described in Sect. 3 (Table 1). The proposed selection is based on scientific literature concerning landscape assessment in marginal areas characterised by demographic decline, distance from services, and low economic productivity [57]. Ten NCPs were selected and are distributed across the three defined categories.

Five regulatory NCPs were selected, as these represent the most frequently assessed contributions in marginal contexts, where ecosystem processes such as soil stability, carbon sequestration, pollination and habitat connectivity are commonly mapped and quantified using spatial indicators [59, 60]. In marginal Mediterranean landscapes in particular, soil formation and habitat maintenance are especially significant, supporting ecological dynamics that persist precisely because of their distance from intensive land use [61].

A single NCP was selected from the material services category: food and feed. In marginal landscapes, food production is not just an economic activity; it is also a practice embedded within a network of productive relationships involving soils, animals, plants, climate, and human knowledge. This is particularly evident in extensive pastoral systems [62]. Including this NCP in the assessment framework highlights its extractive logic: nature produces, humans benefit, and the relationships sustaining marginal landscapes are rendered invisible. Finally, four intangible NCPs were included to foreground the relational dimension that dominant frameworks struggle to operationalise. This is because analyses of marginal territories often focus on how human communities relate to their territory through concepts such as sense of place, cultural identity, ecological knowledge, and territorial awareness [63].

For this paper, the analytical procedure is illustrated through its application to NCP 1 – Creation and maintenance of habitats – as a representative example of the full reinterpretation process (Table 1).

Table 1 shows how the three-phase analytical procedure was applied to NCP 1 – creation and maintenance of habitats. The first column shows the original IPBES definition of habitat as the creation and maintenance of ecological conditions favourable to living organisms that are relevant to humans. The second column highlights the critical assumption embedded in this definition: that habitat has value only insofar as it supports

species or functions that are directly useful to humans. By attributing agency exclusively to ecosystems as service providers, the definition renders invisible all ecological relationships and processes whose significance extends beyond human benefit. The third column presents the More Than Human redefinition. Here, habitat is reinterpreted as a network of productive relationships among multiple agents – including plants, animals, fungi, soils, waters, microclimates and human practices – operating across different temporal scales, rather than as a service produced for humans.

Table 1. The table presents a critical and applied analysis of the selected NCPs

NCP Criteria	**IPBES Definition Critical Assumption**	**Critical Assumption Review**	**Redefinition of MTH**	**MTH Principles**	**Life Framework of Values**
NCP 1 - Habitat creation and maintenance	The creation and maintenance of ecological conditions favourable to living organisms relevant to humans by ecosystems	Habitat has value only insofar as it supports species or functions relevant to humans. Agency is attributed to ecosystems as service providers, rendering invisible all relationships that do not directly benefit humans A habitat has value only if it supports species or functions that are relevant to humans	Habitat is not a service produced by ecosystems for humans, but; rather, it is a network of productive relationships among multiple agents, operating between humans and non-humans. Emerging from the interactions of multiple agents operating across different timescales. Its value extends to the entire biotic community, not just human beneficiaries	Ontological principles: • Relationality • Distributed agency • Co-habitation and co-evolution • Non-human temporality Epistemological principles • Embodiment • Relational value • Intrinsic value	Living with the world: the habitat as a space of belonging to a biotic community Living in the world: the habitat as an experiential context

In this reformulation, agency is distributed rather than centralised, and the value of habitat extends to the entire biotic community, not just human beneficiaries. This redefinition is grounded in the ontological and epistemological principles identified in Sect. 2 – relationality, distributed agency, cohabitation and co-evolution, non-human temporality, embodiment, relational value and intrinsic value – which are listed in the fourth column. The fifth column anchors the redefined criterion within the Life Framework of Values. Two dimensions emerge that were absent from the original definition: "living with the world", recognising habitat as belonging to a biotic community; and "living in the world", framing it as an experiential context shaped by relationships between the human and non-human. Relational and intrinsic values thus enter the assessment, whereas previously only instrumental values were considered.

The relational redefinition of NCP 1 has direct implications for how it is implemented spatially. Standard GIS-based assessments of habitat creation and maintenance usually involve land cover classification, habitat quality indices and connectivity metrics. These are spatial units that measure the presence and extent of ecological elements, but not the relational configurations that constitute them. While recent efforts to develop collaborative spatial decision support systems centred on ecological proximity units have begun to reframe these spatial logics beyond conventional, indicator-based approaches [64] they still rely on human decision-making frameworks. A More Than Human reinterpretation would require a different set of spatial questions, such as where habitats are located, who co-inhabits them, which interspecies relationships sustain them and across what temporal rhythms they function. It would also require consideration of where the boundaries between human and non-human agency are most porous. Georeferencing these dimensions requires spatial units that are relational rather than categorical, organised around processes, interactions and temporal gradients rather than fixed land cover classes. While this does not render the criterion unmappable, it does require a redefinition of the spatial indicators through which it is operationalised. Rather than measuring the quantity of ecological elements present, relational indicators would need to capture the density and quality of interspecies relationships traversing a landscape, the temporal rhythms sustaining them, and the gradients of human and non-human agency shaping them. Therefore, the cartographic challenge is not the absence of measurable proxies, but rather the need to construct proxies that are adequate for a relational ontology.

The application of this procedure across the full set of selected NCPs has surfaced three interconnected issues that define the critical terrain on which this work operates. The first concerns the attribution of agency: although the anthropocentric frameworks recognise the importance of the ecological system, they attribute agency to it by defining ecosystems as service providers rather than relational fields co-produced by multiple entities. The second concerns the distribution of values: within the Life Framework of Values, the values articulated by current NCP descriptions are almost exclusively grouped within the dimension of "living from" the world, while, the relational interpretations of "living with" (recognising other living beings as cohabitants), "living in" (the embodied experience of the landscape) and "living as" (rejecting the separation between human beings and the ecosystem) remain systematically underrepresented. The third issue is methodological: current spatial indicators measure the quantity of landscape elements while ignoring the quality and density of the relationships that constitute them. These

three issues are not independent but mutually reinforcing, all grounded in the shared assumption that nature can be evaluated as a series of distinct, quantifiable services for human benefit. It is precisely this assumption that the proposed reinterpretation seeks to displace.

5 Discussions and Conclusion

The analytical application proposed in NCP 1 shows that reinterpreting the criterion from a non-human perspective involves a significant change in its underlying logic. Rather than producing a new indicator, the proposed approach alters the questions that landscape assessments are asked to answer. While standard metrics ask what a landscape offers, the reinterpretation asks who inhabits the landscape, what relationships constitute it, over what timescales it unfolds and for whom - both human and non-human – it holds value. This shift addresses not only a conceptual gap but also an empirically documented one. An exploratory search of the Scopus database (query: TITLE-ABS-KEY ("Nature's contributions to people" AND (rural OR peripheral OR marginal OR inner) AND (area OR areas)) AND PUBYEAR > 2019 AND PUBYEAR < 2027, conducted in early 2026, yielded approximately sixty articles. This limited body of literature suggests that the NCP framework is rarely applied in the territories where a relational approach would be most productive. This scarcity plausibly reflects the difficulty of operationalising intrinsic and relational values within evaluation frameworks designed to capture nature in terms of benefits to humans. Therefore, the gap is operational rather than theoretical, as the conceptual apparatus of the NCP is open to relational values in principle, but its application in marginal landscapes remains rare, and when present, it tends to rely on service-oriented metrics.

This operational gap becomes more apparent when considered alongside adjacent fields that address relational and More Than Human perspectives. Within ecological sciences, relational approaches have been developed through multispecies ecological networks [60], landscape-mediated coexistence models [65], and multispecies assemblage frameworks [66], approaches that operate with distributed agency, relational connectivity and non-human temporality. While these frameworks recognise non-human entities as agents that shape ecological relationships, they remain within the confines of ecology and conservation, extending little into spatial assessment frameworks for planning and territorial decision-making.

Within design, More Than Human methods have been explored through speculative techniques, material experimentation, and personification exercises that aim to make More Than Human connections visible [67–69]. While valuable for developing both theoretical and applied understanding, these contributions also reveal a persistent condition: the mediation through which non-human perspectives are articulated remains fundamentally anthropocentric. In these works, humans speak on behalf of the non-human, interpreting its needs and translating its agency into categories that human systems can process. This paper does not regard such mediation as a flaw to be corrected, but as an irreducible condition that demands reflexivity rather than resolution in any attempt to represent the non-human.

The Life Framework of Values occupies an intermediate position between two adjacent fields: ecology, which operates in a relational manner but does not extend to spatial

planning; and design, which extends to representation but remains anthropocentrically mediated. The Life Framework of Values has proven effective in integrating instrumental, relational, and intrinsic values within a single conceptual framework. However, existing studies do not address the spatial dimension of the framework, nor do they indicate where these relationships might manifest, persist, or generate conflicts within a territory. This contribution begins to address this spatial gap by anchoring the four dimensions of the framework to concrete evaluation criteria (the NCP) and the territorial reality of marginal landscapes. This triangulation is what makes this contribution original. To our knowledge, no other study has attempted to systematically deconstruct and reconstruct the ontological assumptions of the NCP criteria through relational and post-humanist principles.

The analysis developed here offers a concrete answer to the research question posed at the beginning of this article: how can landscape assessment frameworks and the values they express be reinterpreted through a More Than Human perspective and the Life Framework of Values to reconsider the spatial criteria used in territorial decision-making? This combined approach operates on two levels. Firstly, it ontologically dismantles the subject-verb-benefit grammar through which NCPs are currently formulated. It replaces a unidirectional flow of services from nature to humans with a relational field in which agency is distributed between human and non-human entities. Secondly, it extends the range of values that assessments can capture by highlighting relational and intrinsic dimensions that service-based metrics systematically overlook. By doing this, it creates a space within existing frameworks rather than replacing them, revealing what anthropocentric assessment has long made invisible: the relational density of marginal landscapes and their value as territories of coexistence.

The limitations of this contribution are both conceptual and methodological and point towards directions for future research. Although the analytical table demonstrates that a relational interpretation can expand the articulation of values within a territory, the redefined criteria and their associated values still need to be translated into practical spatial operations. The central remaining challenge is the mappability of relational values. Current GIS methodologies are largely calibrated to capture discrete, quantifiable phenomena, such as habitat extent, carbon stock and pollination density, and are not yet calibrated to represent configurations of coexistence, interspecies dependencies and non-human temporalities, which are foregrounded by the proposed reinterpretation. Bridging the gap between field measurements and planning assessments will require the kind of methodological work that this article begins but does not conclude.

This methodological work is also timely in the context of the Kunming-Montreal Global Biodiversity Framework, which calls for the integration of biodiversity values into decision-making at all levels of governance - a call that, as this paper argues, cannot be answered by expanding existing indicators alone, but requires the kind of interpretative reorientation proposed here.

Acknowledgments. The authors jointly conceived and developed the approach, defining the article's overall objective and structure: Conceptualisation: B.G., S.S., D.C. and M.C. Analysis and methodological approach: B.G. Validation: B.G., S.S., D.C. and M.C. Data management: B.G. Preparation of the original draft: B.G. Revision and editing: B.G., S.S., D.C. and M.C.

Visualisation: B.G. Supervision: S.S., D.C. and M.C. All authors have read and approved the published version of the manuscript.

Disclosure of Interests. The authors have no competing interests to declare relevant to this article's content.

Declaration on the Use of AI Tools. During the preparation of this manuscript, the authors used an AI program for language editing and proofreading purposes only, to improve grammar, readability and style. The tool was not used to generate scientific content or analyses. The authors reviewed and edited all output and take full responsibility for the content of the publication.

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Tourism, Assessment and Participation in the Tourist Destinations' Transition: A Literature Overview

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Abstract. Contemporary reflection on urban transformation highlights how tourism dynamics profoundly alter 'mature' destinations. The impacts of overtourism are multifaceted: whilst, on the one hand, they lead to the commodification and gentrification of cities, on the other, they generate social injustices that manifest as forms of tourismophobia. There are numerous initiatives aimed at the sustainable transformation of destinations, ranging from ETIS to local containment measures. There is growing interest in innovative theoretical paradigms and new governance tools. However, translating these approaches into concrete transition initiatives is a complex challenge. In this context, evaluation is crucial for incorporating diverse perspectives and promoting fairer decision-making processes. At the same time, the co-evaluation of tourism dynamics requires further study. This paper explores the intersection between tourism, evaluation and community participation to understand the role of local communities in the analysis and governance of urban transformations in destinations affected by overtourism. Through bibliometric analysis, the study maps the scientific landscape. The results confirm a fragmentation in the use of co-evaluation in tourism, highlighting the scarcity of research applying an integrated and pluralistic evaluation to promote transition processes and participatory governance of destinations. Furthermore, the study highlights the partiality of engagement approaches, both in stakeholder mapping and in the adoption of effective tools, concluding that it is necessary to develop methodological frameworks that integrate evaluation with the empowerment of residents, shifting the focus from the mere measurement of overtourism to its democratic and inclusive management.

Keywords: Evaluation methods · Destination co-governance · Local communities

1 Introduction

1.1 Commodification from an Economic to a Multi-value Perspective

In the contemporary debate on urban context dynamics, tourism plays a central role, acting as a catalyst for significant changes in the cities. These changes are geared toward promoting the interests of the hospitality sector, leading in the long term to the erosion

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 311–327, 2026.
https://doi.org/10.1007/978-3-032-30524-4_20

of residents' ability to exercise the right to the city [1]. In contexts under pressure, these changes exacerbate existing social conflicts and injustices and generate new ones, causing multidimensional impacts on local communities, transforming the city from a privileged place of life (both private and collective) into a strategic economic asset or a resource to be allocated for rapid tourist consumption [2]. Although the pandemic had interrupted research on the impacts of tourism, there is now renewed interest in this topic, partly because of the rise of revenge travel [3] and the explosion of remote work, which are driving greater mobility and temporary living precisely in response to the Covid crisis itself. This latter phenomenon is described through neologisms such as workation or digital nomadism [4]. These new forms of temporary living can generate geographical asymmetries and social injustices and increase the risks of tourism development in local areas. These two new tourism models join other forms of tourism already established and layered across various destinations, ranging from the well-known cruise tourism (a sub-segment of broader mass tourism) to the luxury segment, including educational, second-home, work, health, sex, beach, religious, and sports tourism, to which are added - among other niches - dark tourism, geotourism, and film tourism (also known as cinema-induced tourism). An ongoing democratization of travel has significantly contributed to the diversification of these demand segments, driven by the expansion of the low-cost carrier (LCC) sector and large cruise ships. For this reason, Canestrini argues that today anyone can be defined as *homo turisticus* [5]. In this sense, the term overtourism does not describe a new phenomenon, but rather serves as an indicator used in the literature to represent an increasingly prominent theme in the debate on different models of tourism development [6].

Examining the impacts of overtourism means recognising how tourism is causing significant alterations to urban contexts under pressure, which must be analysed in a holistic and multidimensional way. Focusing exclusively on spatial aspects, considering changes affecting the real estate market, it is recognized that tourism monoculture contributes to the real estate market crisis [7], the erosion of private residential space, and the gentrification [8] of high-demand neighbourhoods. These phenomena manifest through a reduction in housing supply for residents [9] and an increase in housing costs. This is linked, on the one hand, to the explosion of the sharing economy [10] and the resulting increase in short-term rental listings on market platforms. However, on the other hand, other forms of anomalies also coexist, developing particularly in coastal or ski destinations. One of these concerns the rise in accommodation facilities intended to house the community of seasonal workers in the sector. This community, whose residence is temporary, populates these destinations on a seasonal basis and is concentrated around the entry into the local market of large hotel chains, operating in the high-end and luxury sectors. These international entities alter market dynamics by converting a portion of the housing stock into accommodation for their own staff, while simultaneously offering rental prices below market rates for existing properties [11]. Furthermore, by raising the quality standards of the accommodation supply, in the medium term, they force local entrepreneurs to sell those family-run accommodations that cannot compete with the new standards, triggering a chain reaction that facilitates the entry into the market of other hotel chains. Another segment is linked to the increase in second homes. In this case, temporary communities linked to return tourism purchase a portion of the real

estate stock to use during vacations, making it unavailable on the rental market [12]. Added to this is the growth of timeshares, which are also linked to return tourism.

A further aspect of overtourism is the progressive erosion of public spaces in contexts under pressure. The emergence of numerous commercial activities catering to tourists' needs (particularly in the HORECA sector, the ultra-luxury fashion sector, and the souvenir industry) strongly influences the appearance and character of squares and streets, whose image adapts to visitors' expectations, in favour of which the complex identity values - which originally contributed to their charm - are subjected to significant simplification, falsification, or folklorization [13]. Neighbourhood services are giving way to restaurants, clothing stores, and souvenir shops. The increase in tourists is driving the expansion of the market segment linked to food services, leading to the transformation of entire neighbourhoods into dining districts: this phenomenon has been observed in numerous Italian cultural cities and is described as *foodification* [14], affecting both public space (due to the increase in outdoor dining areas) and private space (due to the change in use of building ground floors, replacing neighborhood shops and public services). In the most exclusive tourist neighbourhoods, local services are being replaced by luxury clothing boutiques, while in neighbourhoods affected by mass tourism, there is a proliferation of shops selling souvenirs of fake local handicrafts. These and many other phenomena collectively contribute to the growing commodification of areas with strong tourist appeal, which are progressively losing those complex and intangible values that helped shape their tourist image [15]. This image has also been strongly influenced by social media, which shapes the way tourists perceive, temporarily inhabit, and commodify places, to the point of leading to the emergence of so-called "selfie parks" [16].

While research in the 1980s had already identified the six stages of the life cycle of destinations [17], hypothesising that the saturation of places (the "maturity" stage) foreshadowed their subsequent decline, today there is a recognised urgency to consider solutions to mitigate and achieve the sustainable transformation of tourism. In this regard, the concept of sustainable tourism transition is gaining traction in academic circles; it is particularly compelling when linked to issues of spatial and social justice, as it emphasizes how strategies for the sustainable transformation of the tourism sector must take into account the impacts of such strategies on the communities - including non-human ones - that inhabit the areas affected by these strategies [18, 19]. This is linked to a growing interest in the concept of degrowth as it applies to tourism [20, 21], which defines a framework for a just and sustainable transition in tourism, aimed at respecting the environmental and social limits of destinations [22].

1.2 "Tourismophobia" and Local Communities' Role

Tourism monoculture leads local communities to engage in informal forms of resistance, voicing their needs through public protests. These movements [23], termed turismophobia [24], highlight the erosion of residents' rights. The concept of "tourismophobia" was coined in the media to describe the spontaneous (and often aggressive) reactions of dissent by residents in contexts of high tourist pressure, assigning a negative connotation to such reactions. *Tourismophobia* can be seen as residents' expression of a sense

of unease regarding an exclusionary system. Such energy could be valuable in identifying mitigation solutions if residents are actively involved in decision-making processes. In this sense, local communities can play a central role in defining innovative policies within urban contexts subject to high tourist pressure.

The principle of community involvement is now recognised by European policies as a pillar of the just transition [25], aimed at shared development and the legitimisation of plans and projects for the transformation of their living environments. In fact, the inclusion of multiple perspectives in decision-making processes is not only an ethical principle but is fundamental to the sustainable development of urban contexts, and communities' informal knowledge is a key resource for co-designing shared solutions.

Starting from Ostrom's reflections [26], we recognise the need to counter the top-down/bottom-up dichotomy with a collaborative urban governance approach [27], which interprets the city as a common good and as a horizontal decision-making platform, capable of managing conflicts and ensuring the sustainability of interventions through the construction of adaptive multi-helix models [28]. Within this framework of growing participatory urban democracy, the role of communities in the dynamics of sustainable transformation and destination governance can be crucial and operates on multiple levels: (1) bringing conflicts to light and ensuring that relevant issues are raised; (2) contributing to the development of shared solutions; (3) supporting the regeneration of cities' intrinsic values. Based on these premises, the role currently played by local communities and their contribution to the management and planning of destinations must be further explored.

1.3 Assessment Applied to Tourism Trends: What are the Key Issues?

The issue of tourism dynamics is inherently complex and multidimensional, as it involves a wide range of economic, social, environmental, and territorial factors. This complexity is reflected in the absence of a single, universally accepted evaluation approach: over time, in fact, research has developed and applied a wide range of tools, techniques, and methodologies - often quite different from one another - each designed to analyse specific aspects of tourism's impact on destinations. This results in a complex methodological landscape, in which even very different - and not always compatible - approaches can be interpreted as complementary, as they can provide a partial yet meaningful view of the phenomenon. This heterogeneity requires a systematic overview of the main methodologies adopted to understand their scope of application, potential, and limitations.

At the European level, tourism sustainability is assessed using the ETIS, which, despite the limitations acknowledged in recent literature, serves as a reference framework designed to guide destinations in measuring and managing their performance regarding sustainability [29]. Among the widely used approaches in the field of tourism assessment are the hedonic evaluation method [30] and the calculation of willingness to pay [31]. Other approaches make extensive use of techniques such as regression analysis [32] and contingency analysis. In recent years, research has explored new frameworks and indicators for tourism sustainability. For example, tourism carrying capacity is calculated to define threshold limits for destinations [33]. Evaluation objectives range from assessing tourism impacts to evaluating destination performance and real estate valuation.

In this fragmented context of evaluation use, local communities can play a central role when involved in the predictive evaluation of urban transformations in stressed contexts, where such evaluation is not interpreted as an approach to monitoring policy effects, but rather guides projects ex ante through the adoption of an evolutionary approach [34], in which the various stages of the decision-making process take into account the synergy among stakeholders. In this sense, the shift from a classical evaluation approach to a participatory evaluation (PE) approach is decisive [35, 36]. In the tourism sector, the need for co-evaluation is accentuated by the requirement to balance economic growth with social and environmental impacts, incorporating both qualitative and quantitative data and framing decision-making processes within a multidimensional perspective.

In recent years, evaluation research has expanded its scope, developing methodologies capable of capturing this complexity to inform sustainable urban transformation policies. A contribution is offered by families of multi-criteria methods, such as SMCE [37]. Other innovative approaches include spatial or spatial-temporal evaluation methods, which make use of geographic information systems (GIS). The validation of these approaches applied to tourism, the integration of different tools, and how diverse perspectives are incorporated into the context of sustainable destination transformation remain largely unexplored, with particular reference to how (and to what extent) communities are included in decision-making processes, how the social fabric of territories is shaped, which engagement tools are employed, and at what stage of the decision-making process people are involved. A review of the literature on participatory evaluation applied to tourism is therefore necessary to identify new trends.

In synthesis, this article explores the link between urban transformations driven by tourism dynamics and the role played by communities in evaluating these dynamics. The paper presents a comparative review of recent literature and defines the following research objectives: O1) to explore current research trends in the adoption of participatory evaluation approaches in the assessment of tourism dynamics; O2) to understand which research areas are under-explored or saturated. The following sections are structured as follows: Sect. 2 presents the methodological approach; Sect. 3 presents the main results; Sect. 4 describes the conclusions.

2 Methodology Workflow

The steps followed in constructing and analysing the relevant scientific landscape are outlined below: a. selection of the database and identification of themes; b. bibliometric analysis of the scientific landscape and selection of the most relevant contributions; c. summary of the results (Fig. 1).

Phase A.: Selection of the Database and Identification of Themes. The phase involves database selection and the identification of themes, considering a review of both academic and non-academic literature, with reference to international authors, policy documents and international organisations working on tourism from the perspective of urban studies, sustainable territorial development and spatial planning. At the same time, some fieldwork and reports on operational research experiences enabled the definition of situated and real-world research questions, stemming from the desire to interweave the study of urban dynamics linked to tourism, the need to redefine the leading role of local

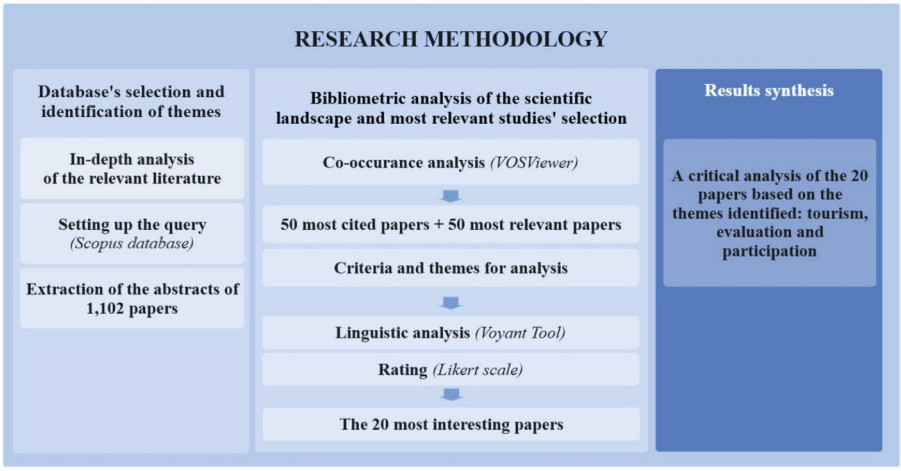

Fig. 1. Methodological framework adopted for the literature review

communities, and the role of evaluation as a tool for legitimising and guiding public policies. The subsequent phases focus on the research and analysis of recent scientific literature concerning the use of evaluation for the analysis and design of urban transformations in contexts under tourism pressure, and the various roles played by communities in sustainable tourism conversion processes. The results of this initial thematic survey enabled the main topics of the review to emerge, in relation to which it was possible to identify the relevant thematic area and the most appropriate database of scientific contributions. In particular, the Elsevier SCOPUS database was selected as the primary source. This allowed for the selection of a compendium of articles that intersected the fields of tourism, assessment and community participation in various forms. Starting from the identification of the main thematic fields (*tourism*, *assessment*, and *community participation*), a search string was progressively defined, and the three main labels of the research were identified as: tourism, assessment, and community participation. Each label was associated with its relevant recurring synonyms, identified following the initial explorations of the database: The topic "tourism" was associated with *destination; overtourism; touristification; foodification; hyper-tourism; mass tourism*. The second topic, 'assessment', was associated with *impact*; assess; assessing; *appraisal; evaluation; value; valuating; evaluating*. The topic 'community participation' was subdivided into two more specific labels: *community; communities; inhabitant; citizen; locals; resident; third sector; association; civil society*; *bottom-up; grassroots; participatory; participation; engagement; involvement; inclusion; participating; involving; engaging; including*. Furthermore, the results emerging from the initial searches highlighted a multitude of articles relating to the COVID-19 pandemic, with clear thematic polarisation due to the historical moment in which the review was conducted. To mitigate this effect, an additional filter was added to narrow the scope, excluding the terms: *covid; pandemic; health*. Subsequently, the search was restricted to the period 2020–2026, and subject areas relating to Health Sciences were excluded to reduce the prominence of

biomedical and biochemical approaches linked to the assessment of territorial dynamics and to ensure consistency and comparability among contributions from disciplinary fields more closely aligned with the research perspective. The scope is limited to the following document types: *article; conference paper; review; book chapter,* and contributions in English. Papers in *all open access, gold, green* were considered. Following this screening, the number of articles stands at 1102 (extracted on 14 October 2025).

Phase B.: Bibliometric Analysis of the Scientific Landscape and Selection of the Most Relevant Contributions. This phase, involving bibliometric analysis of the scientific landscape and selection of the most relevant contributions, was carried out using VOSViewer (VV) software to identify emerging research clusters and the main thematic nodes in recent literature. To this end, the database was extracted and then imported into VV.

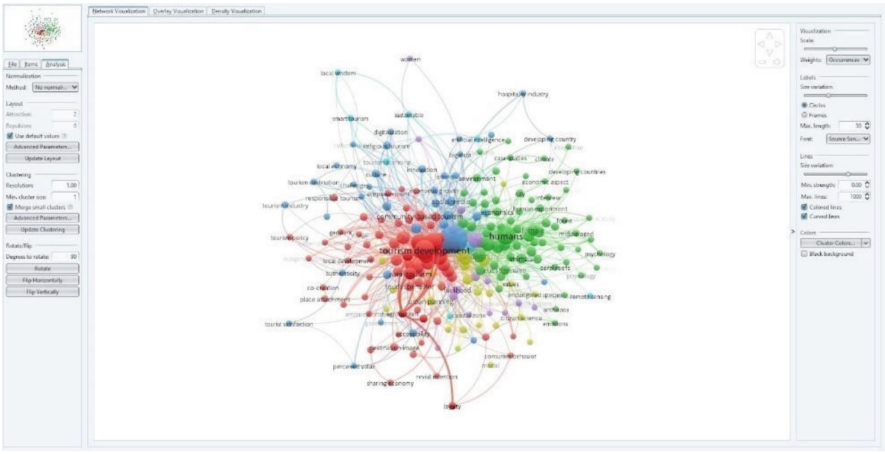

Fig. 2. Terms Co-occurrence Network

The analysis involved constructing a co-occurrence network between terms extracted from titles, abstracts and keywords. Furthermore, inclusion/exclusion thresholds were set for the most frequent and relevant terms. At the same time, a thesaurus was constructed to standardise the overall vocabulary and aggregate terms, followed by database cleaning, which involved the exclusion of words relating to the origin of the articles (China, Indonesia, etc.). Furthermore, those lemmas which, despite appearing as different words, convey the same underlying meaning (e.g. *community's engagement* and *community's involvement*) were merged into a single term. Lemmas referring to sector-specific terminology (e.g. literature review, research, conclusion, open access, etc.) were excluded from the count. In conclusion, it was possible to visualise the Terms Co-occurrence Network, which includes a mapping of 222 terms (Fig. 2). Following an exploration of the scientific landscape, the research continued with an in-depth analysis of several articles, particularly relevant to the research topic. This analysis began with the selection of two groups of papers, on which an initial systematic review was carried out based on the content of the abstracts and developed methodology.

Phase C.: Summary of the Results. From the corpus of 1,102 papers, two subgroups, each comprising 50 scientific contributions, were examined in depth. The 50 articles defined by Scopus as 'most relevant' (based on the match between the query and the document metadata) were analysed, followed by an in-depth examination of the 50 most cited articles. Certain contributions were excluded from the two groups according to the following rules: a) a document is excluded from the second collection if it already appears in the first (redundancy); b) a document is excluded if it lacks an abstract or a link to access the full text (methodological error); c) a document is excluded if it is entirely irrelevant to the research (substantive error). A criteria system was developed (Fig. 3), grouped into three dimensions: scope of the research, evaluative aspects, and participatory aspects. The first dimension included: type of contribution (review, case study, basic research article), scale of the research (XS = local, S = regional/territorial, M = national, L = international), geographical context (continent). The second dimension included: methodological approach adopted (qualitative, quantitative, mixed), evaluation objective, and evaluation method(s) adopted in the research. The third dimension included: definition of stakeholders, objective of participation, phase of involvement, participation tools.

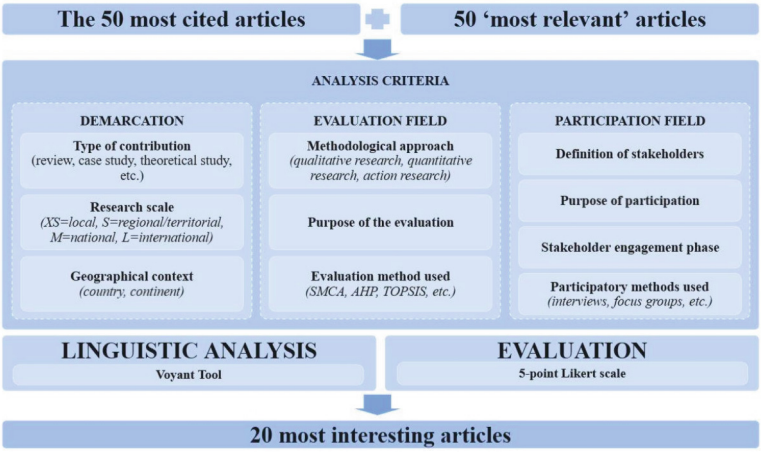

Fig. 3. Criteria for selecting scientific papers

The Voyant Tool (VT) is used to analyse the frequency of terms used within the papers, providing a further *overview* to help verify the selection of documents to be examined in greater depth. Specifically, the text of each paper was imported into the VT (Fig. 4), excluding the following content from the analysis: *title, abstract, keywords, affiliations, acknowledgements, and thanks*. The creation of a word cloud allows the salient aspects of the analysed documents to emerge, basing the analysis not only on the content of the abstract but also on the content of the entire document.

Therefore, the five most frequent words are selected to construct a thematic classification of the documents. Each paper was assessed for its relevance to the research topic using a five-point Likert scale, according to the following scoring system: 1 =

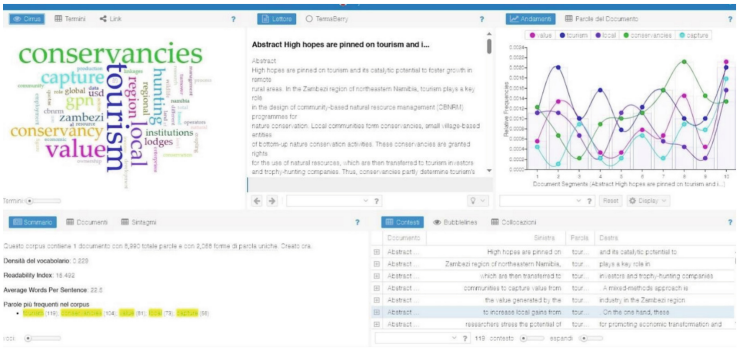

Fig. 4. An example of structured textual analysis using the *VT*

very irrelevant, 2 = irrelevant, 3 = somewhat relevant, 4 = very relevant, 5 = highly relevant. This enabled us to construct a relevance ranking for each contribution, based on which the papers with the highest scores were examined in greater depth. The summary of results is presented in the following paragraph.

3 Results of the Literature Review

The results are divided into two parts. The first (3.1) provides a summary of the main issues that emerged from the bibliometric analysis carried out using VV and supports the definition of criteria for a more in-depth examination of the sub-segment of papers analysed subsequently. This thematic analysis (3.2) focuses on issues more closely related to evaluation, tourism models and participation in decision-making processes, and examines the contributions in greater depth by carrying out a critical analysis of the identified publications.

3.1 Results of the Bibliometric Analysis

An analysis of the selected publications reveals that output is concentrated in the year 2024 (267 articles). The country with the highest output is Indonesia (123). Among the top ten countries by number of scientific publications, four European countries feature: the UK (103), Spain (93), Italy (67) and Portugal (53). The theme of sustainable tourism development takes centre stage, with a rich cluster of labels related to the theme (e.g. *sustainable development, sustainability, sustainable tourism, environmental sustainability, climate change*). It can be argued that all other thematic groups revolve around this theme, which is central to recent debate. The role of cultural heritage emerges, with numerous *labels* associated with it: *cultural heritage, heritage, cultural tourism, heritage conservation*, etc. Linked to this group of words is also the theme of rural development (e.g. *rural development, rural areas, rural economy, village*, etc.).

Furthermore, there is a growing interest in the theme of gender identity and the role played by various intersectional communities in the management and enjoyment of destinations. This is supported by the presence of many labels associated with this theme

(e.g. *woman, young-adult, female, male*, etc.). Furthermore, a progressive broadening of the definition of *stakeholder* is hypothesised, which also includes non-human agents, placing the risks that tourism dynamics pose to ecosystems at the centre. This is evident from the presence of a very dense cluster that includes terms such as: *non-humans, humans, animals, biodiversity, nature conservation, national parks*, etc. It is suggested that these aspects will represent a research trend in the coming years, as the cluster includes terms that are relevant in terms of frequency of use and citation period (from 2023 onwards). Associated with this group is also a sub-segment of *labels* relating to the theme of the sea, featuring terms such as *seaside, seashore, coral reefs, water quality, coastal waters, marine ecosystem*, etc. This suggests that interest in the participatory assessment of tourism dynamics in coastal areas is growing.

Among the models of sustainable tourism, the following emerge as predominant: *agrotourism*, *community-based tourism* (CBT), *ecotourism*, *smart tourism*, *regenerative tourism*, *geo-tourism*, *religious tourism.* As regards participatory tools, only the use of social media, interviews and questionnaires is highlighted. This could suggest that, although participation is a key element of the research, recent literature does not explore the use of innovative tools (typical of the social sciences and planning) for the inclusion of communities in evaluation processes (e.g. *living labs*, *deliberative processes*, *e-participation*).

Artificial intelligence is given only marginal attention, being associated solely with the theme of tourism marketing; however, it is suggested that this may be a bias resulting from the absence of papers currently in the process of being published in the compendium. Furthermore, there is a low frequency of certain potentially interesting topics: *degrowth*, *foodification*, *touristification.* One theme that appears is that of impacts. This term is linked to various *labels*, the most interesting and recently introduced in the literature being "*spatial analysis*". In relation to this, several *labels* appear: e.g. *spatial-temporal analysis, geographical information system, urban planning*. These *labels* are linked to the theme of spatial assessment, where an exploration of the scientific landscape does not reveal any specific assessment methods.

Nevertheless, the following terms appear: *assessment method, risk assessment, qualitative analysis, empirical analysis, and quantitative analysis.* No multi-criteria methods (AHP, MCDA, ANP, etc.) emerge in the scientific landscape. Among other *labels* linked to the theme of impacts, the following appear: *overtourism, quality of life, SDGs and tourism village.* The theme of values also appears infrequently and, when present, is linked to the theme of their protection and conservation, their perception or co-creation, as well as to the connection associated with the theme of destination image.

3.2 Results of the Critical Analysis

Based on the shortlist (100 papers), here is an overview of the most frequently addressed topics. About the scope of the papers, the topic of coastal areas features in 10 studies, with a focus on island areas appearing in 3 studies. Some studies (8), on the other hand, deal with the topic of destination image and *destination branding*, which is particularly interesting. Several contributions mention certain models of tourism governance (Destination Management Organisation = 9; Smart Tourism Destination = 2). There are 3 studies on the role of gender identity. About the overarching theme of digitalisation, there

are a wide variety of studies that include reflections on big data, artificial intelligence, the use of social media and *sharing economy apps*. There are 7 such studies. Of particular interest is the role played by CBT, which is explored in various forms across 5 studies. About the theme of evaluation, among the evaluation methods appearing within the hundred studies analysed, several studies (19) explore the Partial Least Squares Regression (PLS-SEM) method by analysing the results of questionnaires administered to various stakeholders.

Some studies adopt multi-criteria approaches, but only one study uses the AHP method [38], whilst a single study [39] mentions spatial evaluation approaches, with a focus on Public Participation Geographic Information System (PPGIS) methods. It can be surmised that only a marginal space is allocated to multi-criteria or spatial evaluation methods.

Regarding the theme of participation, the stakeholders can be classified into eight categories: local authorities, communities, the third sector, the business sector, destination governance bodies (e.g. DMOs), tourists, universities, and non-human agents. The role of local communities is recognised in 74 studies, whilst local authorities are included in 61 studies. The tourism business sector is considered in 53 studies. Only 9 studies consider the role of universities [40], whilst an even more marginal role is reserved for natural systems, included in 3 studies [41]. Tourists are considered in 34 studies, whilst destination management organisations are cited in 27 contributions. The third sector constitutes a marginal group and is cited in 16 studies.

Moving on to a critical analysis of the most relevant studies, and looking at both evaluative and participatory aspects, many studies focus on assessing the impacts of tourism on 'mature' destinations or, in other cases, on comparing perceptions of tourism among residents in tourist and non-tourist locations [42–46]. Salam et al. [47], for example, use a strictly qualitative evaluation model based on interviews and *focus groups* to measure the impacts perceived by authorities and the third sector on the resort of Bali. This study acknowledges the adoption of a partial perspective, based on gathering the opinions of only certain types of stakeholders and adopting a qualitative approach to evaluation. Another study [48] also adopts a qualitative approach to analyse how residents understand and address the socio-spatial impacts of urban transformations caused by tourism in Málaga. The article explores how the community interprets changes regarding housing, public spaces, services and opportunities for participation. The primary method used is semi-structured interviews, exploring the concept of *restorative justice* in the tourism context. This study considered only the perspective of residents who had lived in Málaga for at least five years, excluding other perspectives. Other studies [38, 49, 50] focus on assessing the effects of implementing community-based organisational models (CBT). For example, Ngo & Creutz [38] propose an approach aimed at assessing the multidimensional sustainability of CBT in a Vietnamese context. The assessment is carried out through interviews with residents, the use of the fuzzy AHP approach and the adoption of the Sustainability Barometer. Natalia et al. [50], on the other hand, use a methodology based on *Design Thinking* to identify key constructs relating to organisational design and its impact on strengthening CBT in San Pablo. In this case, questionnaires and interviews were conducted with a limited number of participants. Other studies focus on evaluating the performance of destinations against specific sets of criteria. Nguyen [51] assesses

the compliance of the Ba Na tourist area with the 'Set of criteria for the evaluation of destinations' issued by the Vietnamese Ministry of Culture, Sport and Tourism.

Regarding spatial approaches, one study [39] analyses the adoption of Public Participation Geographic Information Systems (PPGIS), highlighting the opportunities associated with the use of these tools in participatory destination management processes. Other studies explore evaluation in the participatory design of tourism services. Grammalidis & Grammatikopoulou [52] propose an ICT-based methodology adopting a bottom-up approach whereby the tourism offering is co-designed by the community. The study focuses on the promotion of tourism in rural or marginal areas, without addressing the issue of participation applied to the de-touristification of contexts under pressure. Whilst some studies aim to measure residents' perceptions regarding their involvement in destination governance [53], others seek to assess the extent to which community participation in tourism governance improves residents' perceptions of tourism in the destination [54–56]. Riyanto et al. [55] examine the influence of community involvement on residents' perceptions of tourism impacts, as well as the consequent effects of these perceived impacts on the well-being of residents, by analysing data from 175 interviews in the coastal context of Malang. The data were analysed using the PLS-SEM technique. The study concludes that community involvement improves people's perception of the impacts of tourism. One study [56], based on data from 415 residents of Orlando, examines the effects of resident involvement and the economic benefits of tourism on their psychological, social and political empowerment, quality of life and sense of place. Here too, the PLS-SEM approach is adopted.

Some studies assess the role of destination image (and, more generally, of imagery) in the development and management of destinations, highlighting how the destination image influences visitors' travel choices and how *place branding* contributes to sustainable tourism development [57–59]. Aidoo et al. [57] use the PLS-SEM approach to analyse data collected from participants during a cultural festival in Ghana. The results reveal that *place branding* has a significant impact on the sustainable development of destinations.

4 Conclusion

The analysis highlights several areas of research that could be explored further. Regarding evaluation objectives, although the use of evaluation in the context of tourism dynamics is now well established, further studies are needed to assess the impact of co-design and participatory co-governance processes, particularly in so-called "mature" tourism contexts. In this sense, evaluation must become a planning tool and must incorporate diverse perspectives [60] through truly inclusive forms of participatory evaluation. This may include the integrated application of SMCE evaluation approaches [37], capable of incorporating both qualitative and quantitative data and multiple perspectives. This entails paying greater attention to how community engagement can support de-touristification and the sustainable conversion of destinations *under pressure, using* engagement techniques aimed at creating an environment conducive to the equitable participation of all stakeholders. This may represent a particularly relevant area of research, aimed at verifying the crucial role of communities in generating counter-projects [61] and in promoting resilience in contexts of *overtourism.*

Furthermore, it is necessary to adopt specific multi-stakeholder models for interpreting social contexts, to include crucial segments of the community, such as young people and children, whose perspective is fundamental for equitable and future-oriented tourism planning. On the other hand, it is necessary to integrate tools from the social sciences and planning. In this regard, the Territorial Living Lab [62] is cited as a possible tool. Finally, regarding issues more closely related to tourism models, although there are many approaches to sustainable tourism development cited in the various in-depth studies examined in this essay (e.g., CBT, slow tourism, ecotourism, etc.), it is necessary to fully integrate the principles of degrowth [20]. In this sense, among the various models, the theoretical model of the Doughnut Economy [22] offers an interesting perspective that deserves further exploration to understand its application in the tourism sector. Adopting the DE would entail the obligation to link tourism development primarily to respect for carrying capacity and the quality of life of residents, steering development toward new popular ecologies.

Finally, several thematic clusters are emerging that scientific literature could focus on soon. On the one hand, there is growing interest in the role of destination image (and, more generally, tourism imaginaries), and on the other, the theme of coastal and island tourism contexts, with particular attention to those in the Mediterranean. Although the role of imaginaries in influencing the success of destinations is recognised, there is a lack of studies on how the destination's image and, more generally, tourist imaginaries influence the regeneration of destinations. Furthermore, it would be desirable to explore how these imaginaries can be co-produced or co-transformed by local communities within a degrowth framework [63–65]. In this regard, some interesting examples could form the basis for further research in the future [66].

A second theme, which according to the analyses is attracting growing research interest, concerns coastal and island contexts. These contexts, particularly island ones, are recognised as places where tourist overcrowding accelerates profound urban and social transformations. Coastal areas and islands, along with their communities, are currently facing dramatic challenges in resisting touristification. Therefore, reflecting on coastal and island contexts offers an opportunity to test new methodological and operational approaches in particularly complex settings, as well as providing a chance for redemption for fragile communities in need of useful and immediate responses. This study has several limitations, which the authors take care to highlight. In particular, the review cannot be considered a "systematic review." The selection of articles included in the study adopted a rigorous approach but does not follow a codified methodology (e.g., PRISMA); consequently, it may involve a certain degree of subjectivity or selection bias in the analysed documents. Second, the search was limited to a single academic database (Scopus), excluding contributions found in other databases. Furthermore, the search considered only bibliometric literature written in English, excluding non-bibliometric and regional perspectives. The review considered only scientific publications from 2020 onward, excluding earlier contributions. Finally, the classification of documents was carried out using a qualitative scale; therefore, the assigned rating may include a certain degree of bias. The analysis and interpretation of the results and the identification of gaps were conducted by the authors using a critical approach and are therefore subject to an additional degree of uncertainty.

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A Narrative Overview Towards More-Than-Human Principles for Embracing the Relational Dimension in Decision-Making Processes

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Abstract. The contemporary debate on territorial transformation highlights the limitations of anthropocentric paradigms in assessment and evaluation processes. Traditional frameworks primarily measure performance, efficiency, and functional outcomes, often neglecting the relational consequences that territorial projects generate between human and non-human entities. Against this backdrop, this research explores how More-Than-Human (MTH) principles can inform the reformulation of decision-making processes, with particular attention to the evaluation of the relational dimension between actors – human and non-human – and the distribution of agency. To address this question, a critical narrative overview method is adopted, suited to mapping heterogeneous and evolving theoretical fields where the goal is synthesis and interpretation rather than aggregation of quantitative evidence. A selected corpus of texts by key authors in the MTH and posthuman debates was analysed through an in-depth qualitative reading. The results show that these principles do not constitute predefined theoretical categories but emerge inductively from the comparative reading of the corpus. They establish relational orientations through which central categories of decision-making can be reconsidered from a More-Than-Human perspective, supporting the development of relational evaluation criteria capable of recognising non-human agency. The transition to operative relational principles represents a first step toward decision-making processes that are more adaptive, accountable, and ecologically responsive.

Keywords: More-Than-Human · Relationality · Spatial Justice

1 Introduction

In recent years, the limitations of anthropocentric approaches to territorial design and evaluation have become increasingly evident [1, 2]. Traditional models fail to capture the complexity that characterises current environmental, social, and economic crises and the limits of their underlying ethical assumptions [3]. The underlying theme of these models is primarily focused on human needs, performance indicators, and the

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 328–345, 2026.
https://doi.org/10.1007/978-3-032-30524-4_21

sustainability of choices aimed at responding to fundamentally human demands. Ethics tends to operate within major frameworks such as utilitarianism [4], according to which decisions are based on cost-benefit analysis and the maximisation of utility, with the necessity of confronting standardised value systems and, often, without managing to grasp the complexity of the relational systems that underpin life in places and the agents of change and resilience that remain invisible to mainstream paradigms.

An alternative tradition is represented by deontological theories [5], based on the centrality of rules, duties, and rights, which prove too rigid when applied to complex contexts. Both frameworks, however, share a fundamentally anthropo-centric orientation, and this ethical limitation is implicitly projected onto economic models. Within this framework, some main strands can be identified that attempt to reposition a multidimensional value system [6], such as neoclassical economics [7, 8], which ignores ecological relationships and material limits, and behavioural economics [9], which attempts to correct the classical model by demonstrating that human choices are often influenced by factors that are not purely economic [10]. Although the latter is more innovative, it remains centred on humans [11], considering nature and non-human entities merely as resources.

In turn, economic models shape decision-making processes that, despite having evolved beyond the synoptic-rational approach toward more adaptive frameworks such as bounded rationality [12, 13] and incrementalism [14], continue to operate within fundamentally anthropocentric boundaries. Among existing evaluative approaches, Multi-Criteria Decision Analysis (MCDA) [15, 16] represents one of the most inclusive frameworks, precisely because it attempts to compare values and criteria belonging to different domains – monetary and non-monetary, qualitative and quantitative – yet this very plurality too often subordinates the intangible dimension, favouring quantitative proxies that are more directly verifiable.

This anthropocentric boundary is not merely a technical limitation: it reflects a deeper ontological assumption – the implicit attribution of agency exclusively to human actors and the recognition of only human interests as legitimate grounds for evaluation and choice – whose systematic embedding in decision-making processes represents one of the most persistent structural constraints of contemporary evaluation frameworks.

This structural limitation extends across several disciplines, where a central challenge concerns the integration of ecological interdependencies and the agency of non-human entities [17, 18] within decision-making processes. The subordination of complex phenomena to human-centred theoretical frameworks contributes to ecological unsustainability, producing forms of economic growth that systematically disregard environmental relationships and limits. This reductive orientation is further reinforced by apparently neutral terminology: compound terms such as “natural resources”, “sustainable development”, “environmental management”, “wilderness areas”, and “natural disaster” [19] reproduce extractive and managerial assumptions, framing non-human entities primarily through their usefulness, controllability, or risk for human systems. Against this backdrop, rethinking the ontological and epistemological foundations of evaluation becomes necessary – not merely to broaden the range of actors considered, but to fundamentally reconceive the relational complexity of territories and the role of non-human beings within them.

Two distinct theoretical fields have progressively emerged in response to this need: post-humanism [20] and More-Than-Human theories [21]. While post-humanism primarily criticises the humanist conception of the autonomous and exceptional human subject [22], More-Than-Human approaches focus more directly on the relational entanglements between humans, nonhumans, technologies, and environments [23]. Despite their diverse disciplinary origins, both perspectives criticise anthropocentrism, reject classical dualisms, recognise non-human agency, and see reality as relational and interdependent [24]. For this reason, this research considers these perspectives as interconnected theoretical contributions. This conceptual shift has been embraced across many disciplines, and numerous authors have developed related theories, including Donna Haraway, Bruno Latour, Karen Barad, Jane Bennett, and Sarah Whatmore.

Yet translating these frameworks into evaluative and design practices remains particularly challenging. Despite their growing theoretical influence, More-Than-Human perspectives have so far struggled to achieve operational traction: existing evaluation processes continue to fall short in accounting for non-human agency, in tracing the reciprocal effects generated by multispecies interactions, and in developing criteria and tools capable of making these dynamics legible within structured decision-making procedures. Adopting More-Than-Human theories as a fundamental perspective implies a radical transformation of decision-making processes: from linear, optimisation-oriented procedures, they become relational practices that include both human and non-human entities as actors, grounding every evaluative choice in ecological interdependence and distributed agency rather than in predefined human goals.

This research aims to explore how More-Than-Human principles can inform the reformulation of decision-making and evaluation processes, with particular attention to the relational dimension between human and non-human actors, the distribution of agency, and the role of the evaluator as an embedded part of the local relational system rather than an external observer. The research question guiding this study is: how can More-Than-Human principles be translated into operational criteria and approaches for decision-making processes that incorporate non-human agency? To address this question, a narrative overview method is adopted, suited to mapping heterogeneous and still evolving theoretical fields where the goal is synthesis and interpretation rather than aggregation of quantitative evidence [25].

The paper is structured as follows: Sect. 2 defines the research field and the main topics that delimit the scope of the narrative overview, identifying the theoretical coordinates within which the review is conducted. Section 3 presents the methodological approach, describing the phases, tools, and strategies adopted for the construction and analysis of the corpus. Section 4 reports the results, articulating four conceptual nuclei and ten operative relational principles for More-Than-Human decision-making. Section 5 discusses the implications of these findings for the operationalisation of relational evaluation processes and outlines directions for future research.

2 Research Field and Main Topics

2.1 Including Multi-Agency in Territorial Governance

When decision-making processes are understood through a More-Than-Human lens, the distribution of agency across human and non-human actors becomes a constitutive – rather than merely instrumental – dimension of territorial governance. This reframing has implications for three interconnected dimensions: (i) the epistemological foundations of participation; (ii) the quality of de-liberative encounters; and (iii) the representation of non-human actors.

Participatory decision-making processes are premised on the idea that legitimate outcomes emerge not from the aggregation of pre-formed preferences but from the quality of interactions among actors [26, 27]. Central to this view is the recognition that knowledge is always situated: produced from a specific position, by specific actors, in relation to specific places and conditions [28]. If participation is understood as a process of collective knowledge production rather than mere preference aggregation, then the quality of the encounters through which that knowledge is generated – their openness, their attentiveness to difference, their capacity to hold heterogeneous voices – becomes itself a central design and evaluative concern.

This understanding resonates with Ivan Illich's concept of conviviality [29], which proposes a relational model of social life grounded in reciprocity, autonomy, and mutual limitation. Transposed into the planning domain, conviviality implies designing processes that are genuinely open to the knowledge, values, and rhythms of those who inhabit a territory – resisting the tendency of professional and institutional frameworks to reduce participation to tokenism [30]. The convivial dimension of decision-making thus calls for modes of encounter that are temporally attentive – resistant to the acceleration that institutional frameworks tend to impose – embodied, and genuinely open to difference [31], foregrounding the quality of relations over the efficiency of outcomes. Crucially, conviviality should not be conflated with harmony. Relational processes must also be capable of holding conflict and sustaining productive disagreement, recognising that genuine plurality is not a condition to be resolved but a permanent feature of democratic life [32, 33]. From this perspective, conflict is not a failure of participation but its most honest expression – and the capacity to make it legible, rather than dissolving it through aggregation, is itself a mark of evaluative rigour.

When the category of relevant actors is extended beyond the human – as the MTH approach demands – both participation and conviviality are pushed toward their limits. Non-human entities such as rivers, soils, forests, animals, or microbial communities do not participate in conventional deliberative arenas. Nevertheless, they are deeply implicated in the outcomes of territorial decisions, and their responses – flooding, soil degradation, species migration, ecological disruption – can be read as forms of agency that exceed human intention and control [23, 34]. The challenge, then, is not simply to add non-humans as stakeholders in an otherwise unchanged process, but to reconfigure what counts as a relevant signal, a meaningful response, or a legitimate claim – and, consequently, to develop evaluation approaches capable of making these signals legible within structured decision-making procedures.

This reconfiguration makes representation structurally unavoidable: deciding which ecological signals are amplified, which temporal scales are considered relevant, and which thresholds of response are deemed significant are inherently political choices that embed assumptions about what and who matters in a territory [35, 36]. Acknowledging this political dimension is not a concession to relativism but a precondition for designing governance processes that are genuinely responsive to the plural, human and non-human actors that constitute a living territory.

2.2 Embracing the Relational Dimension for just Decision-Making Processes

The most widely adopted evaluation frameworks – whether applied to spatial processes, programmes, or projects at different scales – share a foundational epistemological assumption: values pre-exist the evaluative act and are typically conceptualised as a property belonging to the evaluand – the subject, place, or process under assessment – identifiable through criteria and indicators, and ac-accessible to the evaluator through sufficiently refined and scientifically grounded instruments, including approaches capable of capturing intrinsic values and complex social dimensions [37]. The evaluator's task, within this paradigm, is one of progressive approximation: accumulating evidence to produce a description that is as complete as possible, commensurate with the scale and stakes of the decision.

The More-Than-Human paradigm offers evaluation theory and practice something more fundamental than an expanded inventory of actors and multidimensional variables: an alternative epistemological orientation grounded in recognition [38, 39] as a principle of spatial justice [40]. Within this framework, diversity and plurality are not intrinsic properties of places or subjects but relational achievements – values that emerge from the system of relations established within a specific context, and that therefore cannot be identified before the process that generates them. This perspective draws on a broader confluence of ecological, feminist, critical, and decolonial traditions [40], which share with More-Than-Human theories a common emphasis on relationality as the foundation of collective meaning-making, shared goods, and democratic futures grounded in inclusion rather than exclusion. In this sense, the relational dimension is not a measurable, pre-existing output of territorial processes: it is a value whose very uncertainty is constitutive, generated and regenerated through the relations that subjects – human and non-human, individual and collective, material and symbolic – establish within places, territories, and environments characterised by multiple and heterogeneous levels of agency.

Within this research field, applying a More-Than-Human perspective to evaluation in complex, multi-actor and multi-agency decision-making contexts implies a fundamental repositioning of the evaluator's role. Evaluation is not a neutral instrument applied to a pre-existing reality: it is itself a situated practice that participates in the construction of that reality, capable of reproducing or, conversely, of challenging the power asymmetries and technocratic dynamics that structure decision-making processes [41]. The evaluative act carries, in this sense, a transformative agency of its own – what Mertens [42] has theorised as the capacity of evaluation to function not merely as an accountability mechanism but as an enabler of recognition: a process through which marginalised voices, conflicting knowledge systems, and invisible power relations are made legible

and brought into dialogue. This transformative potential, however, is not automatic: it requires a deliberate reconceptualisation of how evaluation is designed and practised, shifting from frameworks oriented toward prediction and control toward approaches capable of embracing uncertainty, holding conflict, and supporting epistemically just decision-making processes [40].

This repositioning implies a shift from evaluation as measurement to evaluation as relational practice. Drawing on Guba and Lincoln's fourth-generation framework [43], and on Latour's understanding of the social as inherently relational [18], this approach recognises the reality under evaluation not as a pre-existing datum awaiting measurement but as an intersubjective construction that is produced and transformed within the very process of interaction among the evaluator, the programme, and the plural assemblage of human and non-human actors involved. Adopting a More-Than-Human orientation in evaluation means, in this sense, embracing Geertz's thick description [44] as an epistemological commitment in the service of more just decision-making processes: not abandoning methodological rigour, but redefining it as interpretive and situated rigour – oriented toward restoring the quality and depth of relational experience in its specific territorial and social context, rather than extracting comparable and generalisable data, and toward making visible who and what is excluded from decisions, and who bears the costs and invisible disvalues that those decisions produce.

Addressing this gap requires returning to the theoretical foundations of More-Than-Human thought and identifying, from within that body of work, the principles capable of guiding the construction of evaluation criteria and deliberative architectures that are genuinely responsive to relational complexity. It is precisely this operation – the translation of MTH theoretical perspectives into operative orientations for evaluation and decision-making – that the following methodological section sets out to develop.

3 Methodology

This research adopts a narrative overview to investigate the More-Than-Human theoretical field, with the scope of translating its conceptual contributions into operational relational principles, which are oriented toward decision-making processes [45], (Fig. 1). More-Than-Human theories constitute an interdisciplinary and continuously evolving field, characterised by multiple languages and perspectives; for this reason, the research focuses on detecting a series of convergent concepts, rather than comparing isolated theoretical positions.

Building on the thematic and operational contexts outlined in the preceding section, the methodology is designed to identify recurrent conceptual structures across different theoretical contributions within the More-Than-Human debate, with the specific aim of deriving from that body of work a set of principles capable of orienting the evaluation of projects and processes toward a perspective that genuinely accounts for the relational dimension.

The first phase consists of selecting key authors within the More-Than-Human and posthuman debates for this research, including Donna Haraway, Bruno Latour, Karen Barad, Anna Tsing, and Rosi Braidotti, who are figures central to the contemporary debate and aligned with the topics addressed in this research. On this basis, a corpus

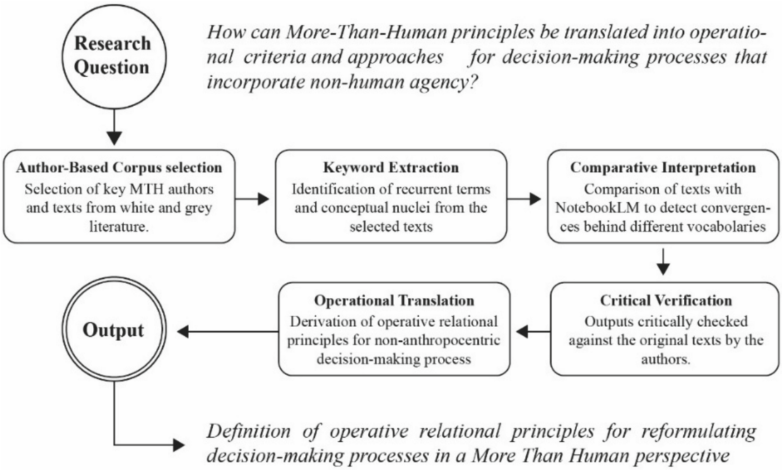

Fig. 1. The methodological steps for a narrative overview

of eight texts [17, 18, 20, 46–49] was established, selected to represent the variety of theoretical positions in the field.

The texts were analysed qualitatively through an in-depth reading, following a document-based and thematic interpretative approach [50], to locate keywords recurrent across More-Than-Human theories. Subsequently, the extracted terms were compared with the corpus using NotebookLM [51], a tool that supports the comparison of sources and facilitates the identification of recurring definitions and conceptual overlaps. Its outputs were critically verified against the original texts, with interpretive responsibility remaining with the authors. This cross-source comparison made it possible to recognise how different authors articulate, through varying terminology, a shared conceptual core. Through an interpretative analysis of recurrent concepts and their relations, a set of operative relational principles was identified and consolidated. These principles offer a basis for reinterpreting central categories of decision-making processes, such as actor, value, impact, benefit, and responsibility, from a More-Than-Human perspective.

4 Results

4.1 From Corpus Selection to the Emergence of More-Than-Human Semantic Field

The first result concerns the construction of the theoretical corpus. The selection was based on five authors, who occupy a central position in the More-Than-Human, posthuman and relational debates: Donna Haraway, Bruno Latour, Karen Barad, Anna Tsing, and Rosi Braidotti. The selection follows three explicit criteria. First, each author contributes a critical perspective on anthropocentric models that is directly relevant to the research question. Second, their interdisciplinary positioning, spanning science and technology studies, feminist theory, anthropology, political ecology, and posthuman philosophy, produces concepts that are transferable and applicable across different fields. Third,

despite adopting different vocabularies, their theories address shared challenges, and the concepts they develop carry operational potential for decision-making processes. The qualitative analysis of the corpus, comprising the most significant texts by the selected authors, identified recurrent keywords that made it possible to identify the conceptual convergences across their different theoretical languages.

4.2 Keyword Extraction and Identification of Recurrent Conceptual Nuclei

The keyword extraction phase enables a transition from isolated terms to broader conceptual nuclei, in which keywords function as indicators of underlying conceptual structures rather than as descriptive labels. The first result of this process is the construction of an initial conceptual vocabulary, which constitutes the semantic field from which the operative relational principles are subsequently derived. Terms belonging to different theoretical traditions, such as "actant", "distributed agency", and "intra-action", were interpreted as distinct formulations of a shared theoretical concern: the recognition of non-human agency. Through this interpretive process, four recurring conceptual nuclei emerged: Agency, Subjectivity, Mutual Response, and Response-Ability.

Table 1. Identification of recurrent conceptual nuclei.

Recurrent terms	Selected authors	Conceptual interpretation	Emerging conceptual nucleus
Agency, actant, material agency, distributed agency	Latour, Barad	Action is not limited to human intentionality	Agency
Subject, situated knowledge, becoming-with, posthuman subject	Haraway, Braidotti, Barad	Subjectivity emerges through situated relations	Subjectivity
Response, interaction, intra-action, reciprocity	Haraway, Barad, Tsing	Entities mutually affect, respond to, and transform one another	Mutual Response
Responsibility, response-ability, care, situated ethics	Haraway, Tsing	Ethical action depends on the situated capacity to respond within relations	Response-Ability

As Table 1 illustrates, each nucleus condenses a cluster of recurring terms drawn from multiple authors into a shared conceptual interpretation. Keyword extraction identifies recurrent conceptual nuclei that enable a transition from the plurality of More-Than-Human theoretical approaches toward the construction of operational principles.

4.3 Comparative Interpretation of Conceptual Nuclei

Following the identification of the four recurrent conceptual nuclei, the analysis examined how each selected author articulates those concepts through specific terms, definitions and theoretical orientations. The corpus of eight key texts was analysed through a comparative reading supported by NotebookLM, used as an analytical instrument to organise recurrent definitions and facilitate the identification of conceptual overlaps. The four conceptual nuclei are examined in turn below, tracing the theoretical convergences and tensions that emerge from the comparative reading of the selected corpus.

4.3.1 Agency

The comparative analysis reveals that all selected authors share a commitment to recognising non-human activity, but they diverge significantly in how they conceptualise the attribution of agency. A first tension concerns whether agency is understood as an enactment, a doing, a capacity or a power. Barad defines agency as a dynamic process rather than a property possessed by individual entities. Through intra-action, subjects and objects do not pre-exist relations but emerge through material-discursive processes. [47]. For Braidotti, by contrast, agency is grounded in potentia, the affirmative power to affect and be affected, which entities possess as a structural relational capacity [46]. A second tension concerns the "flatness" of agency within networks. Latour advocates a generalised symmetry between humans and non-humans, treating any entity that makes a difference as an actant [18]. Braidotti criticises this position, arguing that flattening all actors onto a single plane risk losing the subject function entirely, along with the political and ethical analyses of power relations that depend on it [46]. Haraway and Tsing both insist on the relational and multispecies dimension of agency. Haraway frames it through "becoming-with", emphasising the reciprocal capacity of entities to transform one another through encounter [17], while Tsing conceives agency as a world-making practice emerging from non-intentional assemblages [49]. These tensions do not weaken the conceptual nucleus; on the contrary, they clarify its operative importance. Agency can be understood as a distributed, relational, and transformative process through which human and non-human entities participate in the production of effects, meanings, and territorial transformations (Table 2).

Table 2. Theoretical formulations of the conceptual nucleus of Agency across the selected authors.

Selected authors	Quotations	References
K. Barad	"Agency is not an attribute but the ongoing reconfigurings of the world. The universe is agential intra-activity in its becoming"	Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning (2007, p. 141)

(*continued*)

Table 2. (*continued*)

Selected authors	Quotations	References
R. Braidotti	"Zoe embraces geologically and techno-logically bound egalitarianism, acknowledging that thinking and the capacity to produce knowledge are not the exclusive prerogative of humans alone, but are distributed across all living matter."	Posthuman Knowledge (2019, p. 58)
B. Latour	"Anything that does modify a state of affairs by making a difference is an actor—or, if it has no figuration yet, an actant."	Reassembling the Social: An Introduction to Actor-Network-Theory (2005, p. 71)
D. Haraway	"Pigeons are competent agents—in the double sense of both delegates and actors—who render each other and human beings capable of situated social, ecological, behavioural, and cognitive practices."	Staying with the Trouble: Making Kin in the Chthulucene (2016, p. 16)
A. Tsing	"Landscapes more generally are products of unintentional design, that is, the overlapping world-making activities of many agents, human and not human."	The Mushroom at the End of the World: On the Possibility of Life in Capitalist Ruins. (2015, p. 152)

4.3.2 Subjectivity

The comparative analysis reveals a shared rejection of subjectivity as an intrinsic individual property, but significant divergence in how constitutive relations are characterised. A first tension concerns the ontological status of the subject. For Barad, subject and object are co-constituted through agential cuts and do not pre-exist their intra-action [47], while for Braidotti, subjectivity is a structural relational capacity, defined as "potential", that extends transversally beyond the human to include biological "zoe" (non-human life) and technological networks, always remaining grounded and accountable [46]. A second tension concerns the scale of relationality. Latour distributes subjectivity across actor-networks, treating it as an "other-taken" effect of attachments and mediators [18], while Haraway and Tsing extend this understanding explicitly to multispecies encounters, through the "ontological choreography" of "becoming-with" [17] and historically shifting "ways of being" emerging from contamination and world-making practices [49] respectively. Subjectivity implies that decision-making processes cannot treat entities as equivalent and interchangeable actors: the situated positions from which human and non-human subjects enter relations and produce knowledge are not incidental but constitutive of the process itself (Table 3).

Table 3. Theoretical formulations of the conceptual nucleus of Subjectivity across the selected authors.

Selected authors	Quotations	References
K. Barad	"Subjects and objects do not preexist as such but are constituted through, within, and as part of particular practices"	Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning (2007, p. 208)
R. Braidotti	"I define the critical posthuman subject… as a relational subject constituted in and by multiplicity, that is to say a subject that works across differences and is also internally differentiated, but still grounded and accountable"	The Posthuman (2013, p. 49)
B. Latour	"Action is not done under the full control of consciousness; action should rather be felt as a node, a knot, and a conglomerate of many surprising sets of agencies that have to be slowly disentangled"	Reassembling the Social: An Introduction to Actor-Network-Theory (2005, p. 44)
D. Haraway	"The partners do not precede the meeting; species of all kinds, living and not, are consequent on a subject- and object-shaping dance of encounters"	When Species Meet (2008, p. 4)
A. Tsing	"Nonhuman ways of being, like human ones, shift historically… Ways of being are emergent effects of encounters"	The Mushroom at the End of the World: On the Possibility of Life in Capitalist Ruins. (2015, p. 23)

4.3.3 Mutual Response

The comparative analysis reveals a shared understanding of relations as transformative and co-constitutive processes, but significant divergence in how transformation and dependency are theorised across the selected authors. The first concerns the nature of transformation. For Barad, entities are ontologically reconfigured through intra-action and do not pre-exist their entangled relating, since "individuals do not preexist their interactions" [47]; for Latour, transformation occurs through translation, where mediators modify and redirect action rather than simply transmitting it [18]; for Haraway and Tsing, transformation is embodied and collaborative, through the "dance of encounters" [17] and multispecies contamination [49]. The second tension concerns dependency. For Braidotti, it is grounded in potentia and expressed as a "vital reliance on others" and a "shared sense of belonging to the common world", coupled with subjectivity as a

structural relational capacity to extend toward others [46]; for Latour, autonomy is redefined as attachment; for Haraway and Tsing, dependency implies vulnerability, precarity, and the obligations generated by encounter. Mutual Response implies that in decision-making processes, relations cannot be evaluated as unidirectional impacts but should be understood as reciprocal processes of transformation and co-constitution among human and non-human, material, and ecological entities (Table 4).

Table 4. Theoretical formulations of the conceptual nucleus of Mutual Response across the selected authors.

Selected authors	Quotations	References
K. Barad	"The neologism 'intra-action' signifies the mutual constitution of entangled agencies"	Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning (2007, p. 33)
R. Braidotti	"We are relational beings, defined by the capacity to affect and be affected"	Posthuman Knowledge (2019, p. 52)
B. Latour	"When a force manipulates another, it does not mean that it is a cause generating effects; it can also be an occasion for other things to start acting"	Reassembling the Social: An Introduction to Actor-Network-Theory (2005, p. 60)
D. Haraway	"Both, human and horse, are cause and effect of each other's movements. Both induce and are induced, affect and are affected. Both embody each other's mind"	When Species Meet (2008, p. 229)
A. Tsing	"We change through our collaborations both within and across species"	The Mushroom at the End of the World: On the Possibility of Life in Capitalist Ruins. (2015, p. 29)

4.3.4 Response-Ability

Across the selected authors, responsibility is reframed as relational and situated, emerging from encounters and world-making processes rather than from abstract universal principles, but they diverge significantly in how that responsibility is operationalised. Two main tensions emerge from the comparative analysis. The first concerns the ontological basis of responsibility. For Barad, it is inherent in entanglement itself, inseparable from knowing and being – "a matter of the ethical call that is embodied in the very worlding of the world" [47] – while for Latour it is constructed as traceability within actor-networks, requiring actors to account for every connection made and its material consequences [18]. The second tension concerns the scope and orientation of responsibility. Braidotti extends it transversally across species as an "embodied and embedded" accountability for planetary consequences, modelled on Spinoza's ethics of joy and oriented toward the generation of affirmative relations [20]; Tsing frames it as a commitment

to ongoingness within conditions of precarity, grounded in the recognition that survival depends on collaborative, multispecies encounter – "with or without intent" [48]. Haraway's notion of response-ability bridges both dimensions, defining it as the cultivated capacity to respond to the "unasked-for obligations of having met" [17], an ethics that is simultaneously ontological, embodied, and situated. These differences underline the importance of recognising response-ability as the primary ethical driver that orients a decision-making process toward a genuinely More-Than-Human perspective (Table 5).

Table 5. Theoretical formulations of the conceptual nucleus of Response-Ability across the selected authors.

Selected authors	Quotations	References
K. Barad	"Objectivity means being accountable for marks on bodies, that is, specific materializations in their differential mattering. We are responsible for the cuts that we help enact, not because we do the choosing… but because we are an agential part of the material becoming of the universe"	Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning (2007, p. 178)
R. Braidotti	"Accountability is both epistemic and ethical. Epistemologically, it is a matter of producing adequate knowledge in and for the world. Ethically, it involves generating affirmative relations"	Posthuman Knowledge (2019, p. 57)
B. Latour	"The full cost of every connection is now entirely payable. If a site wants to influence another site, it has to leverage the means. The tyranny of distance has been underlined again. Actors have become accountable"	Reassembling the Social: An Introduction to Actor-Network-Theory (2005, p. 174)
D. Haraway	"Human beings are not uniquely obligated to and gifted with responsibility; animals as workers in labs, animals in all their worlds, are response-able in the same sense as people are; that is, responsibility is a relationship crafted in intra-action"	When Species Meet (2008, p. 71)
A. Tsing	"Precarity is the condition of being vulnerable to others. Unpredictable encounters transform us; we are not in control, even of ourselves… Thinking through precarity makes it evident that indeterminacy also makes life possible"	The Mushroom at the End of the World: On the Possibility of Life in Capitalist Ruins. (2015, p. 29)

4.4 From Conceptual Nuclei to Operative Relational Principles

Starting from the four conceptual nuclei identified through the comparative analysis, ten operative relational principles were derived. These principles do not mechanically correspond to individual authors, nor do they emerge from a single theoretical tradition: they represent a synthetic translation of the recurrent tensions and convergences identified across the corpus into evaluative orientations applicable to decision-making processes. Each principle is formulated as a relational orientation, neither a procedural rule nor a normative prescription, that can guide the reconceptualisation of central categories of decision-making, such as actor, value, impact, benefit, and responsibility, from a More-Than-Human perspective. Table 6 summarises the ten operative relational principles, organising them by conceptual nucleus and providing a synthetic definition for each.

Table 6. Operative relational principles derived from the four conceptual nuclei, with corresponding definitions for their application in More-Than-Human decision-making processes.

Conceptual Nucleus	Principles	Definition
Agency	A.1 Distributed Agency	Every entity, human and non-human, participates in the production of material, territorial and relational reality
Agency	A.2 Relational Value	The effects produced by entities must be assessed not only based on their usefulness to man, but also in relation to the intrinsic and relational value they express
Agency	A.3 Non-human Representation	If non-human entities produce effects on reality, decision-making processes must include forms of representation capable of also considering their interests, needs, and responses
Subjectivity	S.1 Situated Subjectivity	Subjectivity is not an isolated property but emerges from the situated relationships that constitute each entity
Subjectivity	S.2 Relational Embeddedness	Every relationship must be considered within the broader network of material, ecological, and social connections, which is why every relationship takes on value
Subjectivity	S.3 Relational Quality	Decision-making processes must evaluate not only individual entities, but also the quality of the relationships that connect them

(*continued*)

Table 6. (*continued*)

Conceptual Nucleus	Principles	Definition
Mutual Response	M.R.1 Recognition of Response	Each entity manifests responses through effects, signals, transformations, or resistances that must be recognised as relevant elements of the decision-making process
Mutual Response	M.R.2 Mutual Transformation	Every interaction produces mutual transformations: the entities involved modify each other and redefine the conditions of the relationship
Response- Ability	R.A.1 Distributed Responsibility	Human beings, as actors capable of producing profound transformations, must assume concrete responsibility towards the entities and relationships they are involved in decision-making processes
Response- Ability	R.A.2 Asymmetry Acknowledgement	Recognising the asymmetric and often extractive position of humans with respect to ecological systems is the first step in building decision-making tools capable of reducing harm and generating more responsible relationships

5 Discussion and Conclusion

The ten operative relational principles identified in this research provide a first operational translation of More-Than-Human theories into orientations applicable to decision-making processes. Their relevance does not lie in adding non-human entities as new participants within otherwise unchanged deliberative arenas; they challenge the foundational categories through which decision-making defines actors, values, impacts, benefits, and responsibilities. From this perspective, decision-making is no longer understood as a linear process of optimisation but as a relational practice through which human and non-human entities participate in the co-production of territorial transformations.

The principles derived from Agency and Subjectivity expand the notion of actor beyond institutional, social, or economic stakeholders, recognising that non-human entities produce effects, occupy situated positions and participate in relational networks that cannot be reduced to human interest. The principles derived from Mutual Response reframe impact as a reciprocal and ongoing process, in which human actions and non-human responses continuously transform one another over time. The principles derived from Response-Ability redefine responsibility as a situated and distributed capacity to respond to the consequences generated by relations. This implies that decision-making processes should become more attentive to ecological feedback, uncertainty and the asymmetrical role of human actors in transforming territories.

The main contribution of this paper lies in bridging theoretical debates on More-Than-Human relationality with the operational needs of evaluation processes. The proposed narrative overview proved effective in mapping a heterogeneous theoretical field inductively, allowing conceptual convergences to emerge across diverse disciplinary traditions. Furthermore, the resulting principles provide a conceptual basis from which criteria, indicators, and participatory devices capable of recognising non-human agency and evaluating the relational consequences of territorial transformations could be developed in future work. Further research should therefore apply these principles to concrete territorial decision-making processes, assessing their capacity to support more adaptive, accountable, and ecologically responsive forms of evaluation.

Acknowledgments. The contribution is part of the research activity developed within the "GRINS – Growing Resilient, Inclusive and Sustainable" project, funded by the National Recovery and Resilience Plan (NRRP), Mission 4 (Infrastructure and Research), Component 2 (From Research to Enterprise), Investment 1.3 (Extended Partner-ships), Theme 9 (Economic and Financial Sustainability of Systems and Territories) (https://www.grins.it/progetto). The research findings further draw on the master's thesis in Architecture by A. Aprea, developed in collaboration with the other authors of this paper and under the supervision of M. Cerreta. The authors jointly conceived and developed the approach, defining the article's overall objective and structure: Conceptualisation: A.A., S.S., P.Z. and M.C. Analysis and methodological approach: A.A., S.S., P.Z. and M.C. Validation: A.A., S.S., P.Z. and M.C. Data management: A.GA. Preparation of the original draft: A.A. Revision and editing: A.A., S.S., P.Z. and M.C. Visualisation: A.A. Supervision: M.C., S.S., and P.Z. All authors have read and approved the published version of the manuscript.

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DECISIO: A Participatory Decision-Support Framework for Inclusive Energy Transition in Renewable Energy Communities

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Abstract. The transition toward renewable energy systems increasingly intersects with issues of social equity, governance, and territorial inclusion. Renewable Energy Communities (RECs), particularly Solidarity RECs (CERS), are expected to play a key role in this transition; however, their decision-making processes often lack structured methodologies that integrate economic efficiency, social impact, and participatory governance. This gap is significant for Third Sector organisations tasked with allocating financial resources among competing social-impact initiatives. This paper presents DECISIO, a participatory decision-support framework designed to enhance transparency, inclusiveness, and coherence in resource-allocation processes within renewable energy communities. The framework integrates multi-criteria evaluation methods with participatory co-design practices, translating stakeholders' qualitative preferences into structured and comparable project assessments. It also includes a set of indicators to evaluate redistributive governance, territorial vulnerability, and stakeholder engagement. The framework has been developed in collaboration with the Fondazione Energie di Comunità ETS, which coordinates multiple CACER configurations in the Turin metropolitan area. Although the project is still in its early stages and has not yet been empirically implemented, this paper outlines the framework's methodological design and its anticipated contributions, grounded in a Theory of Change perspective. By embedding evaluation practices directly within governance processes, DECISIO seeks to provide a structured decision-support system that promotes greater transparency, strengthens stakeholder participation, and fosters a more territorially responsive energy transition. These expected outcomes will be empirically tested in forthcoming phases of the project's implementation.

Keywords: Participatory Decision-Making · Social Impact Assessment · Renewable Energy Communities

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 346–357, 2026.
https://doi.org/10.1007/978-3-032-30524-4_22

1 Introduction

The transition toward renewable energy systems is no longer a technological challenge; it has increasingly become a matter of governance, social inclusion, and distributive justice [1]. Renewable Energy Communities (RECs) have emerged as key actors in this shift, promoting decentralised energy production while fostering collective ownership and local participation [2]. However, their ability to generate meaningful social impact depends greatly on the quality of their internal decision-making processes, particularly regarding the allocation of economic resources [3].

In Italy, the emergence of Solidarity Renewable Energy Communities (CERS) reflects an evolution of the REC model. While maintaining the existing regulatory framework, these initiatives place a stronger emphasis on addressing energy poverty [4–6], redistributing benefits to vulnerable groups [7], and strengthening social cohesion at the local level. Moreover, decisions about how funds are distributed within CERS often rely on implicit criteria or fragmented evaluation methods [8], limiting transparency and restricting genuine stakeholder participation [9]. This challenge is especially pronounced for CERS established as Third Sector organisations, which must balance economic sustainability with social objectives. As a result, there is a pressing need for structured methodologies that help decision-makers navigate complex trade-offs between efficiency, equity, and territorial relevance [10].

Responding to this need, the DECISIO project (DECISIO – "*DEcisioni Condivise per l'Inclusione Sociale e l'Innovazione Oltre i progetti energetici*/Shared Decision-Making for Social Inclusion and Innovation Beyond Energy Projects") introduces a participatory decision-support framework that reimagines decision-making as a collective, reflective, and inclusive process, rather than a purely technical one. DECISIO seeks to promote decision processes that are more transparent, legitimate, and context-sensitive by integrating multi-criteria evaluation methods with participatory practices [11, 12]. The effectiveness of such participatory evaluation processes depends on the continuity and representativeness of stakeholder engagement: in diverse REC contexts, variations in institutional capacity, technical literacy, and levels of social participation can critically shape both the quality and perceived fairness of deliberation.

Conceptually, this research stands at the intersection of decision-support systems, participatory governance, and energy justice [13]. These domains converge on the shared assumption that the quality of governance and decision-making within RECs directly affects their capacity to redistribute economic value and generate social impact, particularly in vulnerable territories [14]. Enhancing these decision processes is therefore not just an administrative improvement but a fundamental condition for achieving a socially just energy transition [9].

Despite growing scientific attention to RECs, there remains a notable gap in the availability of operational frameworks that effectively combine participatory approaches with structured evaluation models. Existing studies tend to address either social participation or economic assessment, without offering tools that bridge these dimensions within actionable decision-support systems. This gap is especially critical in contexts where organisations must distribute limited resources among competing projects with heterogeneous impacts.

The primary aim of this study is therefore to develop and test a methodological framework that enables the equitable and transparent allocation of funds within RECs. As the DECISIO project is still in its early stages and has not yet been fully implemented, this paper focuses on presenting the methodological design of the framework and its expected contributions, rather than empirical results. Specifically, it seeks to formalise a participatory evaluation model [11], apply it in a real-world context, and assess its potential to enhance governance outcomes. In doing so, the study also develops a set of indicators designed to measure the economic, social, and territorial impacts of decision-making processes, providing a foundation for continuous monitoring and adaptive improvement.

These indicators are structured in alignment with a Theory of Change approach, enabling the identification of causal linkages between inputs, activities, outputs, and expected outcomes. This framework supports a more comprehensive assessment of how specific decisions contribute to both short- and long-term impacts, while fostering learning, adaptation, and evidence-based refinement of governance practices.

The paper is organised as follows: Sect. 2 introduces the conceptual framework and research objectives, situating the study within the broader fields of energy justice, participatory governance, and decision-support systems. Section 3 details the methodological approach, describing the DECISIO framework, the multi-criteria evaluation model, and the system of social impact indicators. Section 4 presents the case study context and illustrates the framework's application in a real-world setting. Section 4 discusses preliminary methodological results and their implications, while Sect. 5 concludes by outlining the main contributions, limitations, and directions for future research.

2 Methodological Approach

This research adopts a transformative action-research approach, combining methodological development with empirical application in a real-world context. The DECISIO framework is structured around an iterative process, based on the "Theory of Change" [1–3], that integrates co-design, implementation, and evaluation, ensuring continuous interaction between researchers and stakeholders. In the medium to long term, DECISIO aims to foster a structural transformation in the governance of RECs and CERS and in the decision-making practices of the Third Sector, by translating principles of equity and transparency into operational metrics. The project contributes to consolidating enduring capacities in participatory evaluation and to establishing a stable framework for co-decision processes oriented towards the equitable allocation of resources and socially driven innovation.

The methodological structure comprises two main components: a decision-support model for evaluating social-impact projects [4–6] and an integrated set of indicators to measure socio-economic outcomes and impacts.

The decision-support model is grounded in a multi-criteria evaluation framework [4, 5], which enables the systematic comparison of alternative projects generated through a participatory process involving stakeholders. Within this process, stakeholders (namely, participants of RECs or CERS) are actively engaged in co-creating social-impact project ideas that reflect their needs, priorities, and aspirations.

The participatory activities are facilitated by trained experts who structure and guide the process to elicit and refine initial project proposals that respond to the community's specific socio-territorial context. This phase ensures that the set of alternatives under evaluation is both context-sensitive and collectively constructed.

Subsequently, evaluation criteria are co-defined with REC decision-makers to establish shared objectives and strategic orientations. During this phase, facilitators support the development of a structured evaluation framework that assigns relative importance to multiple dimensions, including economic efficiency, social impact, and territorial coherence. Stakeholders' qualitative preferences are thus translated into formalised evaluation metrics, enhancing the transparency, consistency, and traceability of the decision-making process (Fig. 1).

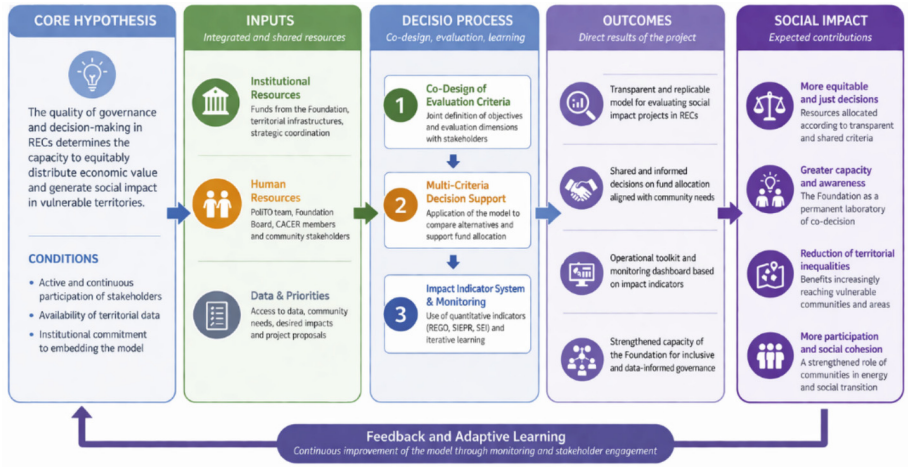

Fig. 1. Project workflow. (Authors' elaboration, generated with AI graphic support, OpenAI DALL·E).

Social-Impact Assessment. The impact assessment framework developed within DECISIO is based on an integrated system of quantitative and qualitative indicators, designed to systematically capture the economic, social, and territorial effects of applying a redistributive governance model. These indicators are developed using a combination of primary and secondary data, gathered through surveys, interviews, participant observation, open datasets, and administrative data sources:

– REGO (Redistributive Energy Governance Index): developed within the project, this index captures the quality of redistributive governance by combining two key dimensions: economic efficiency (the ratio between generated value and resources invested) and distributive equity (the proportion of benefits directed toward vulnerable groups or disadvantaged areas).
– SIEPR (Spatial Index for Energy Poverty Risk, [6]). This index measures territorial energy vulnerability by integrating energy-related and socio-economic variables,.

It is calculated through GIS-based spatial analysis using official national statistics, complemented by context-specific data on energy consumption and user profiles.

– SEI (Stakeholder Engagement Index, [7]). This index evaluates the quality and depth of stakeholder participation in collective decision-making, drawing on three dimensions: participation (attendance and continuity of engagement), representativeness (diversity of social groups involved), and perceived influence (the degree to which participants feel their input shapes decisions). Data collection relies on pre- and post-process questionnaires, direct observation of deliberative sessions, and analysis of workshop documentation.

Expected effects move across three interconnected levels, each explicitly linked to the proposed set of indicators. At the institutional level, improvements in the quality and coherence of economic decision-making are assessed through variations in the REGO (Redistributive Energy Governance Index). In particular, an increase in the average REGO value compared to the baseline is interpreted as evidence of enhanced alignment between efficiency and distributive equity within governance processes.

At the socio-economic level, the model captures changes in both the extent and the quality of participation. These effects are measured through the SEI (Stakeholder Engagement Index), which reflects participation intensity, representativeness, and perceived influence in decision-making processes.

At the territorial level, the framework assesses the model's capacity to address spatial inequalities. This dimension is operationalised through the SIEPR (Spatial Index for Energy Poverty Risk), with expected outcomes including a reduction in energy vulnerability and greater convergence of benefits towards marginal or disadvantaged areas. Such changes are assessed by comparing SIEPR values across pilot and control configurations over time.

To strengthen methodological robustness, DECISIO adopts a dynamic approach that enables the simulation of alternative investment scenarios and makes explicit the trade-offs between economic efficiency, social equity, and decision-making inclusiveness. Quantitative results are complemented by participatory evaluation moments, in which stakeholders and decision-makers collectively interpret observed divergences and iteratively redefine priorities. This integration of data analysis, numerical simulation, and social learning enhances the model's external validity and supports its scalability across diverse territorial contexts. Finally, the introduction of threshold-based alert mechanisms enables the early identification of unintended dynamics and supports timely adjustments in strategic decision-making.

3 Case Study Context and Application

Context. RECs are a relatively recent paradigm for the collective generation, sharing, and consumption of renewable energy, introduced at the European level by Directive (EU) 2018/2001 (RED II) [8]. In Italy, the current regulatory framework is mainly defined by ARERA's Integrated Text on Distributed Self-Consumption (TIAD, Annex A to Resolution 727/2022/R/eel, as subsequently updated) [9] and by the MASE Ministerial Decree No. 414/2023 (the so-called CACER Decree), together with the related GSE Operational Rules [10].

In this context, a REC is an autonomous legal entity whose main purpose is "to provide environmental, economic, or social benefits to its members or to the local area in which it operates, rather than to maximise financial profits" [8] (RED II). It may include citizens, associations, local authorities, and small and medium-sized enterprises (SMEs), which jointly manage renewable assets (e.g., photovoltaic panels) and to share the locally produced energy through the mechanism of "collective self-consumption". From a territorial perspective, REC members are connected through the public distribution network and, under the current Italian framework, must belong to the area underlying the same primary substation. This requirement usefully identifies the REC as a local energy configuration, even though energy sharing remains virtual rather than based on direct private lines.

REC members maintain their ordinary. At the same time, At the same time, producers may inject electricity into the grid according to relationships with the electricity supplier and the public grid: consumers continue to purchase electricity from their supplier. In contrast, producers may inject electricity into the grid under the applicable market arrangements. Within this scheme, the GSE calculates the "shared energy" as the minimum, in each hour, between the total electricity injected into the grid and the total electricity withdrawn by the members of the configuration. Such shared energy is compensated for by avoided high-voltage transmission losses and further supported by an incentive scheme designed to enhance the profitability of these investments. The resulting benefits can be redistributed among members, reinvested in the community, or allocated to social purposes, according to the governance rules defined by the REC itself.

Building upon the REC model, recent experiences in Italy have fostered the development of Solidarity Renewable Energy Communities (*Comunità Energetiche Rinnovabili Solidali*, CERS), which explicitly integrate energy objectives with social inclusion and welfare goals. While maintaining the technical and regulatory structure defined for RECs, CERS place a stronger emphasis on addressing energy poverty, redistributing benefits toward vulnerable users, and supporting local social services. In this sense, they represent an evolution of the community energy paradigm, in which the collective management of renewable resources is leveraged not only for environmental and economic purposes but also as a tool for territorial cohesion and social equity.

Case Study. The DECISIO framework is applied to the Fondazione *Energie di Comunità ETS*[11], which coordinates a network of CACER configurations (REC arrangements) in the Turin metropolitan area in Northern Italy. The Foundation operates within

a complex multi-level governance structure, ensuring coherence between locally generated initiatives and broader social and redistributive goals. Following the acquisition of new financial resources, the Foundation faced the challenge of allocating funds among multiple project proposals developed by local communities, each with heterogeneous economic, social, and territorial impacts.

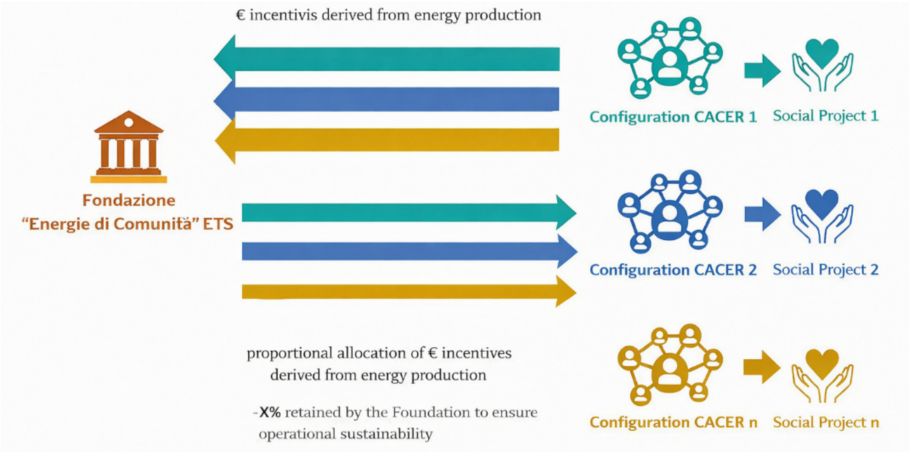

Fig. 2. Conceptual scheme of the governance and resource allocation mechanism adopted by the Fondazione Energie di Comunità ETS. (Authors' elaboration).

Within this context, the case study involves a set of interrelated stakeholders with distinct but complementary roles. The Foundation Energie di Comunità ETS acts as the primary institutional partner and direct beneficiary of the project, coordinating the CACER network and adopting the DECISIO framework as a decision-support tool for the socio-economic evaluation of funded initiatives. The CACER configurations themselves represent key territorial stakeholders, acting as intermediaries between local communities and the Foundation (Fig. 2). They actively participate in the co-design of project alternatives and in their co-evaluation to both construct the empirical dataset and validate the indicator system.

From a beneficiary perspective, the project generates both direct and indirect impacts. Direct beneficiaries include the Foundation and the participating CACER configurations, which benefit from the adoption of a structured, transparent, and redistributive governance model. Through the implementation of the evaluation framework and the associated monitoring indicators, the Foundation is expected to enhance the equity, consistency, and legitimacy of its resource allocation decisions. Indirect beneficiaries include socially and territorially vulnerable communities connected to the energy configurations, which are expected to benefit from more targeted, inclusive, and collectively defined investments. Beyond these immediate effects, the case study also highlights broader systemic implications. The DECISIO framework contributes to generating learning and capacity-building processes among a wider set of actors, including local administrators, Third Sector organisations, cooperatives, and other energy communities not directly involved

in the project. These actors may adopt or adapt the model within their own decision-making processes, thereby amplifying its impact. In the longer term, the application of DECISIO is expected to strengthen the collective capacity to address energy justice challenges, promoting more equitable, participatory, and territorially responsive governance practices.

4 Preliminary Results

At its current stage, the DECISIO project has not yet generated empirical results, as the pilot implementation is forthcoming. However, the project has already produced a set of methodological preliminary outcomes that define the conceptual architecture, analytical structure, and operational feasibility of the proposed framework.

First, DECISIO has established a formalised decision-support methodological approach to integrate multi-criteria evaluation methods with participatory governance processes. The model was designed to translate heterogeneous and qualitative stakeholder preferences into structured evaluation criteria and comparable project alternatives. While not yet applied, this formalisation provides a theoretically grounded and operationally explicit framework for addressing the allocation of resources in socially oriented RECs and CERS.

Second, the project has defined a co-design and co-evaluation approach that structures stakeholder involvement across different phases of the decision process. It uses specified methods, tools, and interaction formats (e.g., workshops, surveys, deliberative sessions) [5, 12, 13] to ensure inclusiveness, representativeness, and traceability of preferences. Although its empirical effectiveness remains to be tested, the co-evaluation approach [12, 13] constitutes a key methodological advancement by embedding participatory practices within a formal evaluation model, rather than treating them as external or ancillary components [14].

Third, the study has clarified the role of indicators as boundary objects between analytical and deliberative dimensions. Rather than being used solely as measurement tools, the proposed indicators are embedded within the decision process [2], supporting dialogue among actors, making trade-offs explicit, and enabling shared interpretation of outcomes. This shifts the function of evaluation from ex post assessment to an integral component of decision-making [4, 5].

At this stage, these indicators remain conceptual and operational constructs, whose robustness and sensitivity will be tested during the pilot phase. Nevertheless, their joint design already outlines a multidimensional evaluation framework that links governance processes to socio-spatial impacts [15].

The research outlines a scalable and transferable methodological framework, grounded in an adaptive logic. The combination of iterative evaluation, participatory feedback, and scenario simulation defines a flexible structure that can accommodate contextual variability while maintaining methodological coherence. This positions DECISIO as a candidate framework for broader application in contexts characterised by complex governance and competing socio-economic objectives.

Overall, these preliminary results should be interpreted as design-oriented contributions that establish the analytical and methodological foundations of DECISIO. The forthcoming implementation will be crucial for validating the model, testing its applicability, and assessing its scalability and replicability across different territorial contexts.

5 Conclusion

This paper has introduced DECISIO as a methodological framework designed to support inclusive and transparent decision-making in RECs and CERS, addressing a critical gap between normative principles (such as equity, participation, and energy justice [16]) and their operational implementation. Rather than focusing on empirical validation, the study provides a structured positioning contribution, outlining how decision-support systems can be integrated with participatory governance in complex socio-technical contexts. Although participatory MCDA approaches have been widely applied in environmental governance and energy planning, DECISIO stands out from existing frameworks in three key ways.

First, it embeds indicators of social redistribution and territorial vulnerability directly within the evaluation framework, rather than treating them as secondary or complementary dimensions. Lastly, it blends deliberative co-design practices with structured multi-criteria assessment, enabling collective priority-setting processes within Third Sector–led Renewable Energy Communities. Third, DECISIO adopts a Theory of Change [2] perspective, understanding evaluation not merely as a technical ranking exercise, but as a governance tool aimed at enhancing transparency, traceability, and stakeholder alignment in resource allocation processes.

At the output level, DECISIO establishes a comprehensive decision-support architecture that integrates participatory co-design, multi-criteria evaluation, and indicator-based monitoring. Together, these components produce a suite of operational tools, such as evaluation models, structured workflows, and composite indicators, that turn fragmented decision-making into transparent, traceable, and replicable procedures.

In the case of the Fondazione Energie di Comunità ETS, the framework is applied to a real allocation challenge involving the distribution of financial resources for social-impact initiatives across multiple CACER configurations. Here, the Foundation acts as a coordinating body, tasked with balancing local priorities against broader redistributive goals. DECISIO facilitates this role by structuring the collection, comparison, and assessment of project proposals emerging from local communities. This enables the Foundation to make explicit the trade-offs among economic efficiency, social equity, and territorial coherence, reinforcing its capacity to serve as a key node in redistributive governance. The case study demonstrates how the framework can be integrated into existing institutional routines, linking funding decisions to clearly defined outputs, expected outcomes, and long-term impacts.

From a methodological perspective, a major innovation lies in the active role assigned to indicators. Instead of being used solely for ex post evaluation, indicators are embedded within the decision-making process as instruments for interpretation, negotiation, and collective learning. This integration makes trade-offs explicit and supports adaptive decision-making, thereby improving the framework's scalability and transferability across diverse territorial settings.

Nonetheless, several limitations must be acknowledged. First, as the project remains in its early stages, the framework has not yet undergone full empirical validation, and its effectiveness in generating the expected outcomes remains to be tested. Second, implementing participatory decision-support processes may entail notable organisational and cognitive costs, raising questions about scalability and long-term sustainability. Third, the transferability of the indicator system may be limited by data availability and contextual variability, particularly in areas lacking robust informational infrastructures.

Although DECISIO was designed with adaptability in mind, its scalability across different REC configurations still requires empirical assessment. Variations in organisational structures, governance models, and local regulatory environments may all affect its transferability.

Future work will focus on the empirical application and validation of the framework within the case study, including the measurement of changes in governance quality, stakeholder participation, and territorial outcomes. Further research will refine the indicator system, test the model's robustness across different contexts, and explore its embeddedness in policy-making processes. Particular emphasis will be placed on assessing the approach's scalability and its potential to inform decision-making across varied institutional and territorial environments.

Acknowledgments. Ultimately, DECISIO reframes decision-making as a central mechanism of the energy transition, not simply a technical function, but a socio-political process through which equity, inclusion, and territorial justice can be actively built.

This research has been developed within the framework of the DECISIO – "*DEcisioni Condivise per l'Inclusione Sociale e l'Innovazione Oltre i progetti energetici*/Shared Decision-Making for Social Inclusion and Innovation Beyond Energy Projects" project. The project is funded under the Politecnico di Torino call for Social Impact Projects (PoliTO per il Sociale (POpS), Edition 2025), supported by Politecnico di Torino and Fondazione CRT. The project runs from 2025 to 2026 and is coordinated by Dr. Gianmarco Lorenti (PI) and Dr. Giorgia Malavasi.

Disclosure of Interests. The author has no competing interests to declare that are relevant to the content of this article.

Declaration of AI Usage. During the preparation of this manuscript, we used artificial intelligence-based tools to support language refinement, grammar and style improvement, and English editing. All outputs generated by these tools were critically reviewed, edited and approved by the author, who take full responsibility for the final content and language quality.

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Community Archives as Innovation Driver for a Network of Territorial Enterprises in Inner Areas

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Abstract. This contribution explores the role of community archives as enabling infrastructures for territorial regeneration and entrepreneurial innovation in inland areas. The research is developed within the framework of the "Archivio Atena" project, promoted by the Department of Architecture of the University of Naples Federico II in collaboration with the Municipality of Atena Lucana, a small town in Southern Italy involved in the National Recovery and Resilience Plan (PNRR) programme for the regeneration of historic villages. The study investigates how a community archive can evolve from a mere tool for preserving collective memory into a relational and operational innovation driver for local enterprises by fostering a new territorial business network. The contribution proposes and tests a methodological decision-making framework based on mutual learning and value-oriented territorial development, involving multiple actors and structured around four interconnected phases: identification of territorial values through the archive; co-design and reciprocal learning processes; experimentation between students and local enterprises; reintegration of results into the archive through a circular knowledge process. The experimentation, carried out between 2024 and 2026, highlights how community archives can support the emergence of collaborative networks, the strengthening of local skills and the transformation of cultural heritage into strategic resources for community-led development models.

Keywords: Community-based archive · Participatory mutual learning · Urban and cultural regeneration · Community enterprises · Collaborative decision-making

1 Introduction

1.1 The Research Context

Inner areas, which are considered peripheral in relation to urban and metropolitan centres, have served as a testing ground for new spatial planning and socio-cultural regeneration approaches for several years [1]. Since 2012, when the National Strategy for Inner Areas

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 358–372, 2026.
https://doi.org/10.1007/978-3-032-30524-4_23

(SNAI) [2] was introduced, the first public policy in fourteen years to address Italy's most peripheral territories, there has been a significant shift in planning, particularly due to the change in cohesion policy towards place-based approaches [3]. The strategy aimed to allocate the structural funds available during the 2014–2020 and 2020–2027 periods to regions based on their development potential and challenges [4]. This policy is primarily aimed at recognizing the social and physical vulnerabilities of remote areas and communities, while strengthening the delivery of essential public services to combat depopulation [5]. This place-based approach is grounded in the idea that areas experiencing marginalisation and underdevelopment possess the knowledge needed to overcome these issues. The place-based approach aims to restore territorial balance by reducing social exclusion and underutilization of local resources through long-term action involving multi-level governance. Intervention in the local area must be based on a thorough understanding of the place and be subject to monitoring and evaluation [6]. The SNAI was subsequently replaced by measures introduced by the National Recovery and Resilience Plan (PNRR).

The PNRR encourages public institutions and third-sector organizations to collaborate on initiatives aimed at inland areas. Its objectives include bridging regional disparities, as well as gender and generational gaps. On the other hand, the SNAI has encountered significant difficulties in collaborating and implementing the strategy due to its limited ability to function as a genuine inter-municipal system [7]. It has overlooked the importance of planning. A detailed analysis of the Strategy Documents for the 72 areas covered by the 2014–2020 programming period has revealed that a total of 14 areas are considering the possibility of drawing up a territorial plan as part of the implementation of their Strategy. The Vallo di Diano internal area includes, among the measures set out in the 'Strategy Document', a Strategic Tourism Plan aimed at enabling the territory to manage its tourism offering in a coordinated manner [8].

This research is therefore part of a wider framework of initiatives that promote the development of inland areas and encourage dialogue and co-design between different stakeholders through projects. Recent research highlights that regenerating these places requires integrating transformative local-level interventions with cultural and social innovation programmes that actively involve communities [9]. This multi-level approach, combining culture and public policy, is considered essential for ensuring a sustainable future for inland areas and reducing depopulation and abandonment.

1.2 From the Community Archive to Local Enterprises

According to the above perspective, this paper stems from an action-research initiative that brought together academics, researchers, local administrators and entrepreneurs to discuss cultural and territorial enterprise in inner areas. The aim was to reflect the full diversity of perspectives and activate a constructive dialogue and cooperation. The process serves as a methodological framework for interweaving research, teaching, and design experimentation to explore the role of enterprises in territorial transformation and regeneration processes. The initiative involves local businesses and university students. It is part of a wider educational project promoted by the Department of Architecture (DiARC) at the University of Naples Federico II, in collaboration with the Municipality of Atena Lucana, and implemented some territorial actions of the "Archivio Atena"

project, which won the public tender "Attrattività dei Borghi" (The Appeal of the Villages) under the National Recovery and Resilience Plan [10], funded by Next Generation EU.



Fig. 1. The Municipality of Atena Lucana

The Archivio Atena project aims to create a community archive in Atena Lucana (Fig. 1), a town of 2,400 inhabitants in the province of Salerno. Located in the inland areas of the Campania region (Fig. 2), in Italy, the project seeks to preserve and promote the town's historical and cultural heritage through innovative tools for collective participation. Community members have been involved in all stages of creating the archive, from defining the themes of the survey of tangible and intangible cultural heritage to identifying and describing the collected materials.



Fig. 2. The Municipality of Atena Lucana

The archive thus becomes a genuine "social space" [11]. Materials are collected through the digitisation of private photographs, the organisation of photography campaigns, the production of audiovisual material within the local area and the launch of

training courses. The community archive thus becomes an open cultural infrastructure [12] in which the collected memories and materials serve as tools for constructing a local community's narrative and initiating transformative processes Active involvement of the local population through mutual learning workshops, focus groups, surveys, residencies, art collectives, and participatory practices has enabled us to identify specific needs, strengthen social bonds, and highlight new heritage-related values [13].

The initiative took place within this decision context, involving students from the "Business networking" teaching course of the "Sustainable Development and Territorial Networks" degree programme at the Department of Architecture of the University of Naples Federico II, as well as businesses that won the "Imprese Borghi" ("Borghi Enterprises") call for proposals, which was promoted by Invitalia, the Italian National Agency for Development, [14] for municipalities that had won the previous competition. This educational experiment facilitates mutual learning [15] between students, entrepreneurs, and the archive. It develops ideas that can innovate the economic model, contributing to the identification of new synergies and multi-level collaborations based, in part, on cultural heritage [16]. Against this backdrop, there is a clear need for a methodological framework that can translate the values embodied in the community archive into practical resources for local regeneration and entrepreneurial innovation.

The proposed framework aims to achieve this by linking cultural heritage with local economic development through a circular, multi-stakeholder process, involving different local communities, universities, businesses, and institutions. The programme as a whole aims to enhance local professional resources and support projects of local interest, with a particular focus on collaborative networks. The mutual learning programme comprises lectures, explorations and discussions with experts, local stakeholders and students. These activities contribute to the creation of an open, dialogue-based learning environment.

1.3 Research Questions

This paper focuses on the following research question: how can a community archive trigger processes of cultural, social and economic regeneration? The research is set in inland areas characterised by territorial fragility and socio-economic fragmentation, as well as the underutilisation of cultural heritage and identity assets in local development processes. While the place-based policies introduced by the SNAI recognise the importance of territorial resources and multi-level governance, many initiatives have encountered challenges in establishing stable collaborative systems and translating cultural resources into shared projects and economic opportunities. Against this backdrop, there is a pressing need to identify operational tools that can effectively connect memory, community, innovation and territorial development.

The community archive is therefore not merely understood as a place for preserving memory, but also as a relational infrastructure that is accessible and reusable for project purposes. From this perspective, it can encourage new forms of cooperation between citizens, institutions, associations, and local economic actors, thereby triggering processes of territorial innovation. This paper proposes and tests a methodological framework for a collaborative decision-making process based on the mutual learning approach and the development of a value-based, multi-stakeholder local ecosystem.

The paper is structured as follows: Sect. 2 introduces the theoretical foundations on which the entire experiment is based. Section 3 presents the adopted methodological approach. Section 4 illustrates the main results emerging from the experiment. Section 5 presents the conclusions and possible implications for future research.

2 Theoretical Foundations: Values and Community

2.1 The Role of Values

Within this framework of action research [17], one of the central issues concerns the role of values in territorial processes. Certain types of values can serve not only as a starting point but also as a perspective through which transformations are dynamically guided. In this sense, value is not a static category but an incremental element that is constructed and redefined over time in relation to the territory [18]. Thinking in terms of values implies recognising a plurality of economies and approaches [19]. It is no longer a question of referring exclusively to a traditional economic model, but of considering a complex set of tools and practices that include economic, social, cultural and environmental dimensions. The territory thus emerges as a system of complex values [20] in which values help to define identity and opportunities for development.

From this perspective, cultural heritage, understood in both its tangible and intangible dimensions, plays a central role in regeneration processes [21]. However, harnessing its potential requires the ability to recognise the diversity of viewpoints and to address the conflicts that inevitably arise from them. The emergence of complex values, in turn, requires integrated assessment approaches.

Integration concerns both the dimensions of value and the tools used to analyse it. It therefore becomes necessary to bring together economic and non-economic values, recognising their interdependence in transformation processes [22]. It follows that decisions must be situated: rooted in local contexts, mindful of available resources and sensitive to specific needs. This implies that project proposals cannot be generic, but must emerge from a progressive and in-depth understanding of the Atena Lucana area.

Particularly relevant, in this context, is the issue of relationships. Alongside traditionally recognised values, importance is attached to those values which, in Anglo-Saxon literature, are defined as ‘glue values’ [23], or ‘binding’ values. These are values capable of fostering cohesion, strengthening bonds between people and sustaining relationships over time. When such values are put into practice, they set in motion self-generating processes, akin to autopoietic dynamics: systems that regenerate themselves and become vital to the community. In this sense, bonds prove to be more stable and generative than relationships, helping to build continuity and solidity in local processes. It therefore becomes essential to identify and build enabling contexts capable of fostering the emergence and consolidation of such bonds. The traditional dichotomies between public and private are insufficient to describe the complexity of the processes underway; it is necessary to adopt a broader perspective that brings together the public, private and social dimensions, recognising people as key actors.

Collaborating, cooperating and building alliances are distinct processes involving different levels of interaction. Understanding their specific characteristics is fundamental to building economic models capable of coexisting and integrating. Shared objectives

are not a prerequisite, but the result of a progressive process, built up over time through dialogue and negotiation. In this context, the workshop dimension takes on a central role. Co-design workshops provide a space in which the concepts learned are translated into practical action [24]. Participants are called upon to work on the creation of a values manifesto and the development of locally-rooted cultural enterprise ideas, defining models of sustainability and governance consistent with local resources. The outcomes cannot be predetermined, but are co-created through complex deliberative decision-making [25] and social learning processes.

2.2 Beyond the Concept of Community

Values thus act as unifying elements, contributing to the formation of communities that are not necessarily stable: on the contrary, they may be temporary, evolving, and continually redefined over time. The temporality and transformation of relationships, therefore, become structural components of the process. It is therefore necessary to explore the meaning of the word "community", not in the abstract, but starting from concrete experience and from certain theories that have shaped its evolution.

In the contemporary debate on urban and cultural regeneration, the word "community" is used with ever-increasing frequency; such persistent use risks weakening its meaning, especially when the term is used without being adequately rooted in a specific practice or context. The conception of this community experience draws inspiration from the legacy left by various authors, such as Elinor Ostrom [26]. The concept of community never coincides with an abstract or purely identity-based notion, but takes on a relational and institutional meaning [26]. For Ostrom, communities are groups of people involved in the use of a shared resource, which necessitates cooperation. What makes them significant is not merely proximity or territorial affiliation, but the presence of shared values and norms of behaviour. They share a common perception of collective problems and a diversity of preferences, elements which influence the spheres of action within which decisions are made. From this perspective, the community, viewed as a complex social structure, characterised simultaneously by mutual trust and local knowledge, as well as inequalities and conflicts, becomes a genuine institutional actor, capable of self-organisation, establishing rules, monitoring behaviour and applying sanctions, without relying exclusively on a state institution.

Ostrom demonstrates how communities can manage common-pool resources effectively and sustainably over time and generate robust organisations when there are shared mechanisms for participation, accountability and collective learning [26].

At the same time, for Bell Hooks, the concept of community is understood as an intentional and transformative practice, not as a given or spontaneous condition [27]. A community, for Hooks, does not arise from the simple sharing of identities and affiliations, but is built through a continuous and conscious commitment aimed at dismantling internalised and structural forms of domination, such as racism, sexism and classism, which prevent authentic relationships. It requires a willingness to navigate conflict and difference, overcoming the fear of the other, in order to cultivate bonds founded on reciprocity, responsibility and care [27]. According to this perspective, community is an ethical, political and pedagogical space: a place where we learn together how to live in non-oppressive relationships and how to transform ourselves and society. For

Hooks, "building community", therefore, means actively practising values of justice and inclusion, making the community not an abstract political ideal, but a daily process of collective learning.

Furthermore, Ivan Illich sees the community as a network of mutual learning; the community is conceived as a convivial network of direct relationships between people, founded on reciprocity, proximity and the shared use of tools and knowledge [28]. Unlike industrial and bureaucratic systems, which tend to monopolise skills and make individuals dependent, the community, according to Illich, is a space of collective autonomy, where individuals retain the capacity to act together, learn from one another and care for one another without delegating their lives to external organisations. It manifests itself in the possibility of self-production, the exchange of knowledge and informal learning, transforming every moment of life into an opportunity for active participation and solidarity. In this sense, the community is not a social or identity-based given, but a practical and relational process that promotes freedom, shared responsibility and conviviality among people.

Taken together, the contributions of Elinor Ostrom, Bell Hooks and Ivan Illich present a picture of the community as a multi-layered concept that cannot be reduced to a single dimension; in all three perspectives, it is a place of mutual learning. Whilst Ostrom's approach helps us understand how communities are structured and function over time through shared rules and institutions, Hooks' perspective shifts the focus to why and for whom the community is built, examining the conditions of justice, inclusion and the transformation of relationships. Finally, Illich prompts reflection on where and through which tools the community takes shape, placing conviviality and autonomy from external control systems at the centre. It is in the interplay of these levels, institutional, ethical-political and convivial, that the community emerges as a situated and dynamic practice, capable of serving as the appropriate setting for addressing the contemporary challenges of urban and cultural regeneration [29].

Looking back at the evolution of processes of territorial transformation, a link emerges between collective well-being, ethical progress and economic growth, which directs our thinking towards the many factors that contribute to a community's 'public happiness' [30].

3 Methodology

This paper proposes a methodological framework for a collaborative decision-making process designed to integrate community archives into territorial regeneration and entrepreneurial innovation [31, 32]. The framework is based on an approach in which the values embodied in local cultural heritage, as documented in the archive, are progressively transformed into operational resources for business innovation. The theoretical-methodological premise identifies the community archive as a dynamic mechanism, capable not only of preserving but also of articulating and activating the territory's identity values, thereby guiding decision-making processes [33]. These values, understood as knowledge, practices, memories and relationships, constitute elements of the community's tangible and intangible heritage and represent the starting point of the methodological process. They can be transformed into strategic resources and are dynamically

reinterpreted, acquiring new meanings and functions consistent with emerging needs. From this perspective, the framework is based on the identification of community shared values and their translation into project materials and collective actions, subsequently reworked by local businesses within their own innovation processes.

This methodological framework takes the form of a multi-stakeholder territorial ecosystem [34], based on mutualistic relationships between the various parties involved: the community archive, local businesses, the university, the inhabitants, non-profit associations and local administrators. Each stakeholder contributes to the process according to specific needs and skills: the archive articulates and organises the values; businesses translate them into products and services; the university plays a role in mediation, facilitation and knowledge transfer; the community of inhabitants and non-profit associations participates as both a source and recipient of the processes [35]; institutions support and guide development through governance tools. From an operational perspective, the framework of the collaborative decision-making process is structured into four interconnected phases (Fig. 3).

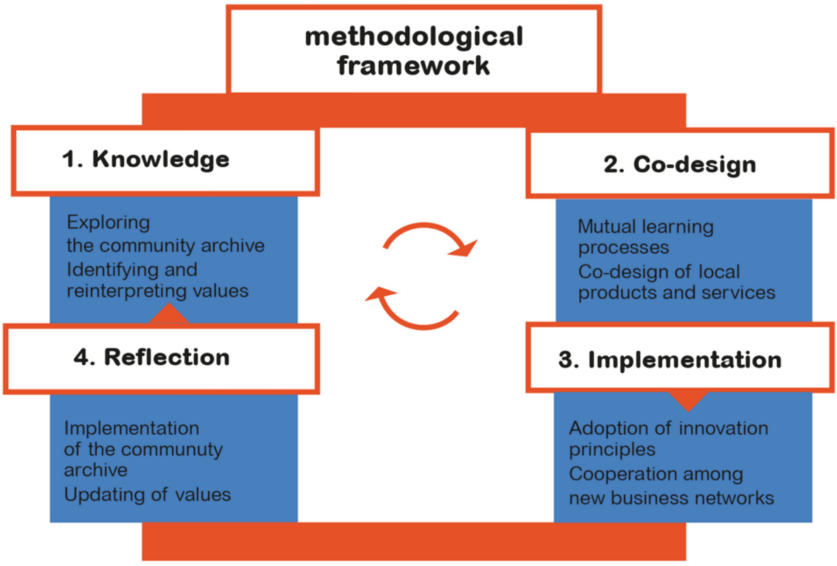

Fig. 3. Methodological framework: phases and steps

The first phase of the methodological process is one of knowledge and interpretation, aimed at identifying and systematising local values. This phase involves an exploratory process that encompasses both the values expressed by local businesses and those emerging from the community archive. Through analysis and cross-referencing of tangible and intangible sources, the values that emerge are subsequently shared amongst the various stakeholders involved and subjected to a process of collective reinterpretation in a contemporary context.

In the second phase, that of co-design, processes of mutual learning are developed amongst students, researchers, businesses and the community. It consists of training

programmes aimed at strengthening local skills and supporting the emergence of new entrepreneurial initiatives; this is also a design phase in which the values identified are transformed into resources that can be utilised in economic processes. Local businesses develop their economic models with the support of students, who apply the skills they have learned in a real-world context. Together, they initiate processes of product, service and organisational innovation.

The third phase concerns the implementation and sharing of innovation processes. Each business adopts the innovative principles that have emerged and shares them with the other organisations involved, triggering a process of continuous exchange. This interaction generates synergies that form the basis for building more structured alliances, such as a business network. Innovation is made possible by the recognition of the values expressed and acknowledged by the community and by the networking stimulated by the methodological framework. In this way, innovation develops simultaneously on two levels: on the one hand, it strengthens the individual enterprise through place-based processes; on the other, it consolidates systemic relationships between actors, contributing to the construction of a collaborative local ecosystem.

Finally, the fourth phase concerns the reflection and circularity of the process: the results of the experiments are reintegrated into the Atena Lucana archive and shared with the community, fuelling a continuous process of updating values and generating new knowledge. Institutional support and governance tools contribute to the consolidation and replicability of the model.

The methodological framework is characterised by a circular and incremental logic, in which the community archive plays a central role as a cognitive and relational infrastructure, capable of triggering innovation processes rooted in local values. In this way, social and cultural regeneration intertwine with entrepreneurial development, contributing to the construction of a culturally innovative ecosystem. The entire process is supported by a collaborative team comprising local administrators, cultural facilitators, entrepreneurs, community members and university researchers, which acts as a coordination and facilitation mechanism, contributing to building the enabling context for generative interactions.

4 Results

The testing of the methodological framework took place between 2024 and 2026 and involved entrepreneurs from Atena Lucana who had won the “Imprese Borghi” (“Borghi Enterprises”) call for proposals, which was promoted by Invitalia, the Italian National Agency for Development and students on the “Business networking” teaching course of the “Sustainable Development and Territorial Networks” degree programme at the Department of Architecture of the University of Naples Federico II. The experience highlighted how the establishment of ongoing relationships between universities, businesses, the local community and the administration can foster processes of territorial innovation in inland areas, transforming the cultural heritage and values emerging from the community archive into operational resources for local economic development. An initial outcome concerns the exploration of the community archive, which, combined with site visits and interactions with the cultural operators involved in the project, enabled the

recognition of tangible and intangible heritage as a strategic resource for the territory. Local memories, traditional practices and widespread knowledge were reinterpreted, contributing to the construction of new territorial narratives and the emergence of shared values.

During the co-design phase, the university teaching course fostered a dynamic of mutual learning between students and entrepreneurs. The students organised themselves into working groups, each linked to a participating business, to analyse its needs, challenges, potential and prospects for development. The interviews and focus groups coordinated by lecturers and researchers, using various analytical and decision-support tools, created opportunities for direct exchange between different areas of expertise, enabling businesses to acquire new interpretative frameworks and students to apply the knowledge they had learnt in a real-world context (Fig. 3).

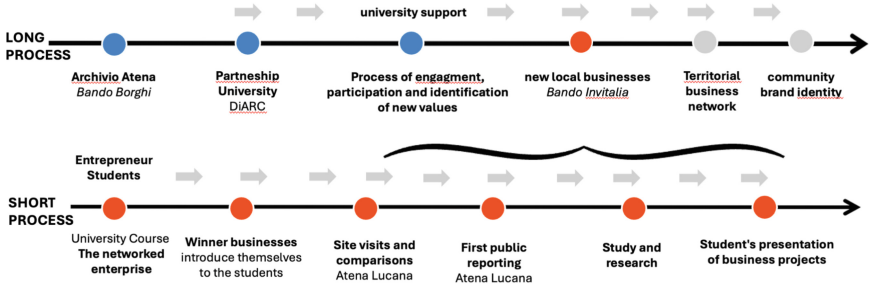

Fig. 4. Diagram of the dual mutual learning process

The diagram of the dual mutual learning process (Fig. 4) shows two interconnected pathways within a single mutual learning process, involving universities, students, entrepreneurs, the administration and the local community. The dual learning framework, structured around two parallel, interrelated processes, describes a long-term institutional pathway and a short-term educational pathway.

The first pathway outlines the overall process led by the university, which supports the creation of a community archive through stages such as engagement, participation, the identification of shared values and the development of an evaluation framework. This begins with the Archivio Atena call initiative, followed by a collaborative phase involving the Department of Architecture (DiARC) of the University Federico II. This is followed by a participatory process characterised by stakeholder engagement, community involvement and the identification of emerging local values.

These dynamics foster the development of new, locality-based enterprises which contribute to the formation of territorial business networks and the consolidation of a community-based brand identity. Throughout the entire process, continuous university support emphasises academia's role as a facilitator of long-term territorial development. The second pathway focuses on the experience developed between businesses and students and represents the short-term process, which is focused on educational and entrepreneurial learning activities. It originates within a university course and the

associated enterprise network. This involves interactions with selected and/or award-winning enterprises, followed by field visits and comparative analyses in Atena Lucana. These activities culminate in an initial phase of public reporting, which is then developed further through independent study and research. The pathway concludes with student-led presentations of business project proposals, reflecting the application of acquired knowledge in a practical context.

The two processes are visually connected, indicating the dynamic interplay between long-term territorial development and short-term educational practices. This interconnection highlights a reciprocal learning mechanism whereby academic research, local engagement and experiential learning reinforce each other mutually. This process of mutual learning helped to bridge the gap between academic education and local practices, fostering the development of relationships based on reciprocity, trust and cooperation.

The structuring of a training programme has fostered the exchange of skills and ideas and led to the development of projects capable of innovating the economic model initially proposed by the businesses and contributing to the identification of new synergies and multi-level collaborations, drawing on the values and suggestions from the community archive. The synergies and opportunities for collaboration between businesses have been made evident. Among the future actions, the establishment of a network of local businesses and the development of a community brand identity stand out in particular.



Fig. 5. Meeting with the winning enterprises and students, Department of Architecture at the University of Naples Federico II

In the next phase, the projects developed were shared both with the scientific community, through an academic seminar, and with the local community, via a public meeting aimed at the citizens and institutions of Atena Lucana. On both occasions, content, values and project perspectives emerged that will continue to enrich the community archive (Fig. 5).

In a context such as that of inland areas, where economic and demographic resources are limited, the creation of a local network is an achievement that ensures resilience and competitiveness. Tools such as Business Networks [36] and Local Business Networks [37] act as mechanisms for collaborative governance capable of fostering social, cultural and economic innovation, and promoting work-life balance.

This process has highlighted the specific nature of doing business in an inland area: where value lies not only in economic investment, but in the ability to build connections and transform territorial constraints into shared resources.

5 Conclusion

This paper explored the potential of the community archive as a mechanism capable of triggering processes of cultural, social and economic regeneration in inland areas, by linking heritage, values and local entrepreneurship. The results of the pilot project carried out in Atena Lucana demonstrate how the archive can evolve from a tool for preservation into a dynamic infrastructure, capable of generating knowledge, fostering relationships and guiding processes of place-based innovation. In particular, it emerges that the value dimension represents an enabling element in local processes: values act as operational resources which, if interpreted and shared, can guide the construction of new development trajectories. In this sense, the community archive acts as a mediator between memory and planning, making local knowledge and practices accessible and actionable within entrepreneurial processes. The proposed methodological framework has highlighted the effectiveness of a multi-stakeholder approach based on processes of mutual learning, negotiation and co-design. The role of relationships and so-called "glue values" proves to be a determining factor for the sustainability and continuity of processes over time.

In fragile contexts, such as inland areas, the ability to build stable and generative bonds is more strategic than the availability of economic resources. In this regard, the gradual development of a network of local businesses and support for the emergence of organisational forms as concrete outcomes of the process act as levers for endogenous and collaborative development. The community archive can therefore be interpreted as an enabling infrastructure for the construction of integrated local ecosystems, in which cultural, social and economic dimensions reinforce one another.

According to this perspective, the definition of a community brand identity represents a possible strategic evolution, capable of enhancing the recognisability of the territory and connecting heritage, local production and tourism dynamics, without reducing the complexity of local identities but rather enhancing them within a shared vision. The process analysed converges on the construction of a shared territorial agenda as the result of a continuous process of negotiation and collective learning among different actors, where the role of institutions is supporting these dynamics through tools of inclusive governance and policies, capable of ensuring continuity and consolidation over time.

The results of the implemented process open the way for further research opportunities; it seems relevant to investigate the conditions for replicating the framework in other territorial contexts. From this perspective, the focus on paradigms such as the economy of well-being and public happiness invites us to rethink development models for inland areas in a cooperative, inclusive and quality-of-life-oriented manner.

Acknowledgments. The contribution is part of the research activity developed in the "GRINS - Growing Resilient, Inclusive and Sustainable" project, financed by the National Recovery and Resilience Plan (NRP), Mission 4 (Infrastructure and Research), Component 2 (From Research to Enterprise), Investment 1.3 (Extended Partnerships), Theme 9 (Economic and Financial Sustainability of Systems and Territories) (https://www.grins.it/progetto).

Disclosure of Interests. It The authors jointly conceived and developed the approach and decided on the overall objective and structure of the paper: Conceptualization, C.L. B.G., L.LR. And M.C.; Methodology, C.L and L.LR.; Validation, M.C.; Formal Analysis, C.L., L.LR., and B.G; Investigation C.L., B.G. and M.C.; Data Curation, C.L., B.G. and L.LR.; Writing-Original Draft Preparation, C.L.; Writing-Review and Editing, C.L. L.LR and B.G.; Visualisation, C.L, L.LR; Supervision, M.C. All authors have read and agreed to the published version of the manuscript.

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Building Multi-dimensional Models for Assessing Complex Environmental Systems (MES 2026)

Interdisciplinary Spatial Documentation for the Revitalisation of Minor Historical Centres: A Systematic Literature Review

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Abstract. The Rural Alpine (RA) territories, especially in Italy, are facing a complex crisis of demographic decline, service reduction, and environmental vulnerability. While Minor Historical Centres (MHCs) possess significant cultural and architectural value, their revitalisation is often hindered by fragmented data and a lack of integrated planning tools. This paper presents a Systematic Literature Review (SLR) analysing 84 identified multidisciplinary sources across seven thematic pillars. The review serves as a foundational step to identify the requirements and variables for a future spatial multi-dimensional methodology. The methodology would be able to synthetise a list of indicators necessary for evidence-based decision-making. The review identifies a structural misalignment between "hazard-blind" architectural documentation, "heritage-blind" environmental risk assessments, and a pervasive detachment from the socio-economic realities that define a settlement's actual habitability. Findings reveal that only 7% of current literature achieves a high level of interdisciplinary integration, leaving a significant gap in operational tools for decision support.

Keywords: Minor Historical Centres (MHCs) · Rural Revitalisation · Systematic Literature Review · GIS Documentation · Environmental Risk · Socio-Economic Viability · Spatial Multi-Criteria Analysis (SMCA)

1 Introduction

Rural Alpine (RA) territories across Italy and the broader European context are experiencing long-term processes of demographic decline, service reduction, and infrastructural fragility. These dynamics have disproportionately affected small villages, hamlets, and historical centres, many of which have undergone partial or total abandonment over

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 375–394, 2026.
https://doi.org/10.1007/978-3-032-30524-4_24

the last decades [1–3]. In mountainous areas like the Alps, depopulation is further intensified by environmental restraints, including landslides, avalanches, and climate-related changes that increase exposure and maintenance costs [4, 5]. Minor Historical Centres (MHCs), small-scale settlements characterised by cultural, architectural, and landscape value, are particularly vulnerable within this context [6, 7]. Despite their recognised heritage significance and their renewed potential contribution to territorial regeneration, especially in the post–COVID-19 period, they often remain marginal within mainstream conservation and planning frameworks. Their limited demographic scale, fragmented ownership structures, and weak administrative capacity set back effective integration into standard policy instruments. While a range of regeneration initiatives have been implemented over recent decades, outcomes have frequently been uneven or modest, rarely producing long-term structural change [8–12]. As a result, many interventions remain episodic, project-based, or weakly embedded in long-term governance strategies. At the same time, national and European policy frameworks, including the Italian National Strategy for Inner Areas (SNAI), the Piano Nazionale di Ripresa e Resilienza (PNRR), and the EU Long-Term Vision for Rural Areas, clearly promote the revitalisation of marginal territories and historical settlements [11, 13–15]. However, there is often a clear disconnection between policy ambitions and their implementation in practice. Documentation initiatives, hazard assessments, demographic analyses, and funding programmes tend to be developed in parallel rather than in coordination, relying on heterogeneous datasets and incompatible spatial or semantic frameworks. This fragmentation makes it difficult for local administrations and planners to assess the potential for re-inhabitation in a systematic, risk-aware, and evidence-based way. Emerging geospatial datasets, such as Copernicus land monitoring [16], national and regional geoportals (such as Istituto Nazionale di Statistica (ISTAT), Agenzia Regionale per la Protezione Ambientale (ARPA), etc.), hazard inventories, and statistical archives, offer opportunities to understand RA territories with high spatial and thematic resolution. Yet these resources are rarely integrated into unified workflows that bridge environmental risk and physical building stock conditions with socio-economic indicators, such as accessibility to services, local market viability, and demographic resilience. This lack of a multiscale approach prevents the development of operational tools capable of supporting strategic decision-making for the re-inhabitation of MHCs in hazardous and fragile contexts. This means that while these areas hold cultural and architectural value, their survival depends on more than just physical preservation; it requires a strategy supported by strong, data-driven frameworks (both qualitative and quantitative). While the survival of MHCs is often linked to strategic repopulation, this research acknowledges that ‘repopulation’ must be defined through a broad, multidisciplinary lens. Scientific evidence suggests that viability in RA territories is increasingly driven by alternative strategies, such as seasonal reactivation, where temporary inhabitants provide essential economic surges, and adaptive reuse of heritage assets for decentralised services or hospitality. Consequently, the Spatial Multi-Criteria Analysis (SMCA) includes indicators for digital connectivity and service accessibility to evaluate the potential for service reorganisation and hybrid living models. This ensures the framework identifies opportunities for resilient development that transcend traditional permanent residency, aligning with the flexible territorial strategies proposed by SNAI.

1.1 Terminology and Territorial Semantics

The classification of RA territories involves a complex intersection of geographical and administrative semantics. Because the stakeholders involved in rural policy often employ divergent terminology, it is essential to clarify these concepts before the literature investigation. While the operational focus of this study is centred on the Italian landscape, a broader European Alpine perspective is fundamental to the research scope. The Italian Alps are part of a contiguous geographical, environmental, and cultural macro-region characterised by shared challenges, such as climate-related geotechnical instability and demographic fragility, which transcend national borders. Consequently, the European scale provides the necessary scientific and morphological context for understanding MHCs; moreover, the cross-border approach could give a comprehensive understanding of MHC phenomena. Within the broader European RA context, this study focuses on MHCs, a term that encompasses a diverse typology of small-scale settlements including hamlets and villages [17]. To ensure a high level of contextual accuracy for the Italian landscape, it is essential to incorporate localised terminology such as "borghi" and "centri storici minori", which carry specific cultural and morphological connotations often missed in broader international datasets [18]. While these terms are central to current policy instruments and funding initiatives, they are frequently associated with tourism-led initiatives that may overlook the structural socio-economic fragilities of the territory. In this study, 'borghi' is utilised as a key search descriptor to ensure alignment with existing academic databases and Italian national policy frameworks. However, the analysis prioritises 'functional habitability' and long-term re-inhabitation viability over episodic, project-based interventions. Furthermore, Alpine territories frequently overlap with the regulatory definition of Inner Areas (Aree Interne). As highlighted by SNAI, these regions are defined not only by their physical elevation but by their "peripherality", measured as the distance from essential service hubs. This classification implies that the mountainous nature of a settlement is often one of the primary drivers of its socio-economic isolation, requiring a nomenclature that integrates both topographic and policy-driven indicators [19].

1.2 Research Gaps and Objectives

The current scientific literature and institutional inventories provide extensive data on the physical aspects of settlements and environmental hazards. However, these domains are rarely intersected with each other or with the socio-economic realities that define a settlement's actual habitability. Traditional documentation practices remain largely hazard-blind, while environmental risk studies are often heritage-blind, treating abandoned villages as static geographic points rather than dynamic social systems. Most documentation frameworks fail to quantify the functional viability, such as accessibility to job markets, service proximity, and community resilience. This fragmentation leads to a fundamental paradox in current rural policy. Despite the proliferation of funded proposals and international initiatives, from "Case a un euro" [20] to SNAI [13], there is still no statistical evidence of a reversal in depopulation. Instead, demographic trends suggest the phenomenon is intensifying, with the UN World Urbanisation Prospects [21] projecting that 68% of the global population will reside in urban areas by 2050. This persistent

abandonment not only threatens cultural identity but accelerates ecological degradation, increasing downstream risks such as floods and landslides [22]. The failure of these initiatives often stems from a lack of continuity and a failure to integrate local development needs with technical safety, frequently relying on short-term cultural projects that lack the supporting infrastructure for long-term settlement. This is further compounded by the fragmentation or total absence of open data (spatial, statistical, and historical) in many MHCs. Consequently, the primary research gap is the lack of an integrated methodology that synthesises technical spatial layers with socio-economic indicators. This research is driven by the need to align documentation with current European and national policy frameworks, such as the PNRR, which advocate for territorial cohesion but lack operational tools to link risk governance to economic viability [14, 15]. Against this backdrop, the primary objective of this research is to identify the methodological requirements and variables for a future SMCA through a systematic review of the current state-of-the-art. The Systematic Literature Review (SLR), adapted from the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [23] approach, serves as a foundational step to bridge the gap between 'hazard-blind' and 'heritage-blind' studies by synthesising an interdisciplinary set of indicators. Consequently, this study seeks to answer: Which spatial, environmental, and socio-economic variables are necessary to assess the re-inhabitation potential of MHCs within a unified framework? To effectively document and understand MHCs, it is essential to adopt an interdisciplinary approach that captures their inherent complexity. Consequently, the fragmented state-of-the-art is synthesised by the authors across seven thematic pillars: (1) **GIS-based documentation,** (2) **hazard and climate exposure,** (3) **RA settlement morphology,** (4) **re-inhabitation strategies,** (5) **policy frameworks,** (6) **social dynamics,** and (7) **economic viability**. This taxonomy is methodologically aligned with the multidisciplinary principles of the Historic Urban Landscape (HUL) and the multidimensional indicator logic of the SNAI. These pillars constitute a "Revitalisation Lifecycle", a concept synthesised from the integrated management principles of the HUL approach [8] and the multi-scalar policy logic of the SNAI [19], that bridges the gap between static physical documentation and the dynamic factors necessary for re-inhabitation. The framework organises the SLR into three progressive phases: Baseline Pillars (1–3) establish the physical and environmental "shell"; Strategic Pillars (4–5) address the governance and planning context; and Viability Pillars (6–7) evaluate human and economic sustainability. This structure serves to identify the specific requirements and variables for the proposed SMCA.

The paper outlines the SLR methodology in Sect. 2, considering part of the PRISMA approach. Section 3 identifies structural gaps in current practices, providing the evidence base for Sect. 4, which proposes an interdisciplinary framework and future directions for managing and revitalising risk-prone territories through the identified SMCA variables.

2 Methodology: Systematic Literature Review

This study establishes a conceptual and methodological foundation for hazard-aware, multi-scale documentation through a SLR considering part of the PRISMA approach, selected to synthesise a fragmented body of research spanning geomatics, environmental engineering, heritage studies, socio-economic analysis, and spatial planning. Across

the globe, rural territories are increasingly affected by rapid urbanisation, demographic aging, and climate change, pressures that undermine their social, economic, and cultural resilience. In Italy, this challenge is particularly significant due to its alpine morphology and dense network of historic hamlets, which represent both a condition of vulnerability and a strategic opportunity to test resilient development models. The SLR identifies the methodological requirements for current GIS and spatial documentation methods, evaluates the availability of hazard and climate-risk datasets, and identifies a first group of possible variables necessary for data-driven strategies supporting re-inhabitation. By systematically integrating these domains, the review aims to identify critical gaps between existing documentation practices and the operational needs of rural regeneration policies, ultimately providing a replicable, interdisciplinary foundation for the proposed SMCA framework.

2.1 Strategy and Sources

The search process was designed to bridge the gap between academic theory, institutional data, and operational policy. Recognising that documentation of MHCs requires a layered understanding of the territory, the identification of relevant sources followed the four-tiered strategy detailed in Table 1. The process moved from high-level peer-reviewed research in Scopus to establish the state-of-the-art in Multi Criteria approach and heritage studies, followed by web searches and snowballing [24] to capture multi-scale methodologies and MHC semantics. Finally, gray literature and statistical data were integrated to align strategic policy objectives with quantitative indicators for demography and risk. This approach ensures the review is not merely a summary of papers, but a synthesis of the actual tools and regulations governing rural revitalisation in the RA context.

Table 1. Multidisciplinary Source Categorisation.

Source category		Specific repositories	Main research contribution
Academic databases		Scopus	State-of-the-art in GIS, MCA, & heritage studies
Web search		Google Scholar, General Web search, ResearchGate	Supplementary case studies, contemporary hospitality models
Snowballing		Backward/forward citation tracing	Multi-scale methodologies & MHC semantics & ontologies
Gray literature	Policy framework	EU Rural Vision, Alpine Convention, SNAI, PNRR	Strategic objectives for rural regeneration & policy drivers
	Statistical & environmental	ISTAT, ISPRA, Copernicus	Quantitative indicators for demography, & risk

To identify the requirements and variables for the proposed SMCA, the research identified seven thematic pillars representing the "Revitalisation Lifecycle" previously mentioned in Sect. 1.2. This categorisation ensures covering the lifecycle of a revitalisation project: from its physical/morphological baseline (Pillars 1, 2, 3) to the strategic and policy drivers (Pillars 4, 5) and the human and economic aspects (Pillars 6, 7). This decision is based on the multi-domain nature of re-inhabitation and because the process involves a wide array of stakeholders, from residents and private investors to regional policymakers and environmental engineers. Consequently, 4 primary domains of intersection from these pillars were selected: **(i) Technical-Spatial Documentation**, which focuses on multi-scale GIS workflows and the digital documentation of the architectural shell of MHCs; **(ii) Environmental-Risk Assessment**, addressing the geotechnical constraints and climate-related hazards that define the physical limits and safety of the Alpine territory; **(iii) Strategic-Planning & Revitalisation**, investigating data-driven policy frameworks and territorial strategies aimed at reversing rural depopulation; and **(iv) Socio-Economic & Decision Support**, which evaluates the human element through social and economic indicators while utilising a Multi-Criteria Approach to determine the long-term viability and repopulation potential of abandoned hamlets. The initial search phase revealed a high volume of unrelated results, particularly from global contexts outside of Europe that did not share the specific morphological or legislative constraints of the Italian RA regions. To address this and set geographical and thematic boundaries, the search strings in Table 2 were specifically calibrated to balance geographic depth with policy precision. For instance, the initial search for environmental hazards yielded over 7,000 records. Therefore, a macro-scale (European/Alpine) perspective was applied to strings (i) and (ii) to capture environmental hazards and climate-risk datasets, as RA territories share contiguous geomorphological vulnerabilities that transcend national borders. Keywords such as "alpine," and "mountain area," were integrated to isolate settlements with these specific geotechnical vulnerabilities. Conversely, a micro-scale (Italian) focus was prioritised in strings (iii) and (iv) by integrating localised qualifiers like "borghi" and "aree interne" to ensure compatibility with the specific regulatory and funding frameworks of the SNAI and PNRR. As a result of integrating specific settlement and geographical qualifiers, the corpus was narrowed to research specifically addressing the intersection of geotechnical risk and built heritage in RA areas.

The SLR was conducted within a defined temporal and linguistic scope to ensure contemporary relevance and historical depth. It covered the period from 2000 to the present, aligned with the evolution of modern GIS and the emergence of major European rural development policies. It included literature in English and Italian, reflecting the dual need for global methodological standards and specific national case studies. The primary focus is restricted to Europe, with a specific emphasis on the Italian RA regions.

2.2 Screening and PRISMA Workflow

Following the initial identification of records from databases (n = 44), policy literature (n = 22), snowballing (n = 20), and web searches (n = 28), a four-stage screening process was applied by adapting the PRISMA workflow specifically for the identification and selection of multidisciplinary sources. While this study does not follow the full PRISMA 2020 clinical protocol, such as formal protocol registration or independent

Table 2. Scopus search strings for the four domains.

Domains	Scopus strings	N
(i) GIS-based multi-scale documentation	TITLE-ABS (“rural village” OR “small village” OR “historic centre” OR “minor historical centre”) AND (GIS OR “multi-scale” OR “spatial documentation”) AND (“Alpine”)	23
(ii)Hazard & climate exposure	TITLE-ABS (“alpine” OR “mountain area” OR “inner area” OR “borghi”) AND (“hazard” OR “risk” OR “avalanche” OR “landslide” OR “debris flow” OR “flood”) AND (“GIS” OR “spatial modelling” OR “remote sensing”) AND (“historic settlement” OR “MHC” OR “small village”)	8
(iii) Re-inhabitation & rural revitalisation	TITLE-ABS (“re-inhabitation” OR “repopulation” OR “adaptive reuse”) AND (GIS OR “spatial planning” OR “data-driven”) AND (“borghi” OR “MHC” OR “abandoned village” OR “historic settlement”)	6
(iv) Socio-Economic & Decision Support	TITLE-ABS-KEY (“indicator”) AND (“decision support system”) AND (“village” OR “hamlet” OR “borghi”) AND (“spatial” OR “GIS”)	7

double-screening, the approach was utilised to ensure a transparent, replicable, and rigorous funnel for narrowing the initial corpus of 114 sources to the final 84 key references. As detailed in Fig. 1, first, duplicate records across the four strings of Scopus and four source categories were identified and removed. Second, titles were screened to exclude unrelated disciplines, and studies that focused on non-European geographical contexts. Third, abstracts were evaluated against strict eligibility criteria; records were excluded if they focused on large metropolitan areas rather than MHCs, or if they presented purely historical/archival narratives lacking explicit spatial or GIS data. Furthermore, records were removed if they lacked explicit spatial data. This thematic filter further excluded studies focused solely on macro-regional scales, tourism marketing, or industrial agriculture, as these do not address the structural challenges of re-inhabitation. Finally, full-text articles were accessed, with the exclusion of non-open-access reports declared as a limitation to prioritize data accessibility for territorial stakeholders. This process resulted in a final corpus of 84 references, achieving a strategic equilibrium between high-impact peer-reviewed research and institutional policy data (SNAI, PNRR, and Alpine Convention reports). The selection of databases and keywords was specifically calibrated to MHC vocabulary and existing hazard datasets (Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA), ARPA), ensuring the resulting methodology is interoperable with national and European data standards.

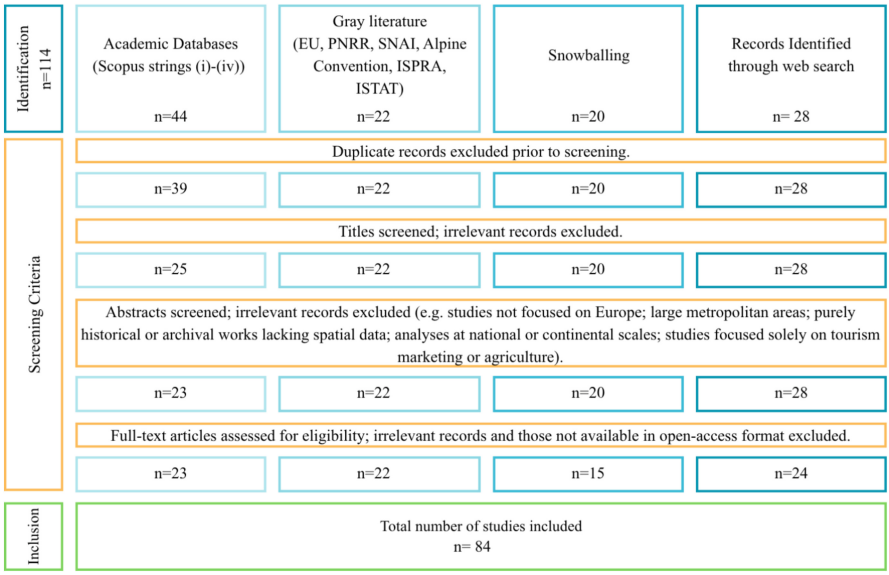

Fig. 1. Adapted PRISMA-style flow diagram with the results of the SLR.

2.3 Methodological Scope and Limitations

The SLR was designed to balance academic rigor with operational utility. To ensure that the derived indicators remain accessible to local administrations and territorial stakeholders, the search was primarily focused on open-access sources, thereby prioritizing 'data democracy' in rural revitalisation planning. While Scopus served as the primary academic database, the inclusion of gray literature, including reports from ISTAT, ISPRA, and the Alpine Convention, was essential to capture the local-scale policy data and localised socio-economic indicators that are often absent from global academic databases. Furthermore, the screening and scoring process was conducted by the authors through a collaborative internal review to ensure thematic consistency across the seven pillars, providing a multidisciplinary quality check on the final corpus.

3 First Results and Discussions

The SLR process initially identified 114 records across the four primary search domains. After applying the inclusion and exclusion criteria, specifically filtering for geographical relevance, spatial data availability, and thematic focus, the corpus was refined to 84 key references. A comprehensive summary of these identified sources is provided in the Annex. A significant observation during the screening phase was the high volume of research originating from outside Europe, particularly from China and Southeast Asia. Studies such as those by Chen et al. (2017) on village-level poverty and Zhang et al. (2025) on data driven heritage demonstrate that multidimensional spatial modelling for rural settlements is a prominent global interest. Despite their relevance, these studies were excluded to maintain the strictly European and Alpine legislative focus of this

research. The exclusion of these high-quality international models confirms a critical research gap: the primary challenge in the RA context is not a lack of models, but a lack of integrated spatial documentation that bridges global technical methods with local Alpine vulnerability and Italian national strategies.

3.1 Thematic Distribution and Pillar Weighting

The final 84 references were analysed using a thematic content analysis to evaluate their relevance to the seven pillars. Each source was rated on a qualitative scale from 0 to 4 to quantify the depth of integration within the SLR. To ensure consistency, the following scoring rubric was applied: 0 (Absent), where keywords related to the pillar do not appear in the text; 1 (Incidental), where the pillar is mentioned as context but its objectives are not integrated into the methodology; 2 (Conceptual), where the pillar is discussed as a relevant factor but lacks specific variables or data application; 3 (Partial), where the pillar is a significant component of the research methodology and findings; and 4 (Core Focus), where the pillar is the primary objective and driver of the study's analytical framework. The distribution of these ratings across the corpus is visualised in Fig. 2.

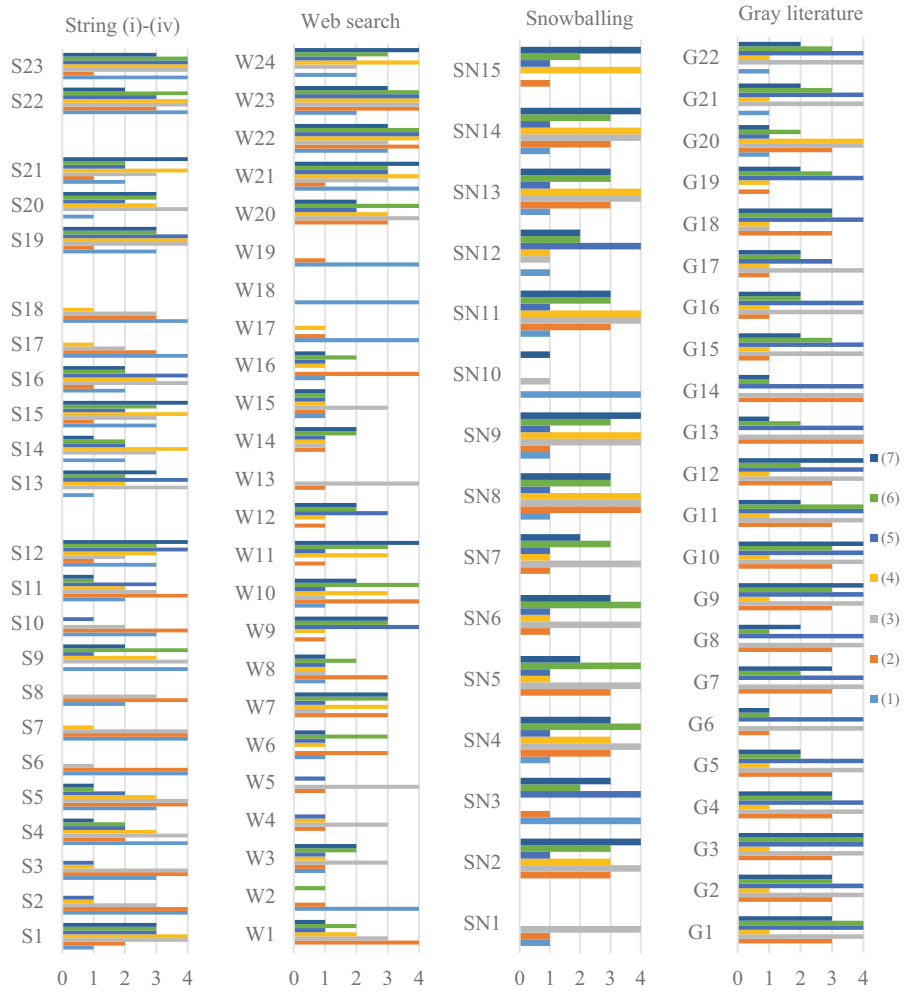

Fig. 2. Thematic rating based on search sources. Pillars: (1) GIS-Documentation; (2) Hazard-Exposure; (3) RA-Morphology; (4) Re-inhabitation Strategies; (5) Policy; (6) Social; (7) Economic. Scoring: 0 = Absent to 4 = Core Focus.

Table 3 synthesises the results of the thematic content analysis by identifying the specific references that achieved high-relevance scores (3 or 4) across the seven pillars. This matrix serves as a cross-reference tool, mapping the final corpus of 84 sources to the specific domains where they offer the most significant methodological or theoretical contributions. The "Count" row quantifies the frequency of high-relevance occurrences for each pillar, highlighting the relative density of research in areas like RA settlement morphology compared to the more limited focus on GIS-based documentation or policy frameworks. By isolating these core contributions, the table provides the evidentiary basis for the extraction of the interdisciplinary indicators and variables subsequently utilised in the SMCA framework.

Table 3. Thematic coding matrix (1)–(7) = thematic pillars as mentioned in Sect. 1.2.

Thematic pillars	GIS-Documentation(1)	Hazard-Exposure(2)	RA-Morphology(3)	Re-inhabitation Strategies(4)	Policy(5)	Social(6)	Economic(7)
References with 3 = Partial OR 4 = core Focus values in relation to (7) pillars	S2, S3, S4, S5, S6, S7, S9, S10, S12, S15, S17, S18, S19, S22, S23, W2, W17, W18, W19, W21, W22, SN3, SN10	S2, S3, S5, S6, S7, S8, S10, S11, S17, S18, S22, W1, W6, W7, W8, W10, W16, W20, W22, W23, SN2, SN4, SN5, SN8, SN11, SN13, SN14, G1, G2, G3, G4, G5, G7, G8, G9, G10, G11, G12, G13, G14, G18, G20	S1, S2, S3, S4, S5, S7, S8, S9, S11, S13, S14, S15, S16, S18, S19, S20, S21, S22, S23, W1, W3, W4, W5, W13, W14, W15, W20, W21, W22, W23, SN1, SN2, SN4, SN5, SN6, SN7, SN8, SN9, SN11, SN13, SN14, G1, G2, G3, G4, G5, G6, G7, G8, G9, G10, G11, G12, G13, G14, G15, G16, G17, G20, G21, G22	S1, S4, S5, S9, S12, S14, S15, S16, S19, S20, S21, S22, S23, W7, W10, W11, W20, W21, W22, W23, W24, SN2, SN4, SN8, SN9, SN11, SN13, SN14, SN15, G20	S1, S11, S12, S13, S16, S19, S22, S23, W9, W12, W21, W22, W23, SN3, SN12, G1, G2, G3, G4, G5, G6, G7, G8, G9, G10, G11, G12, G13, G14, G15, G16, G17, G18, G19, G21, G22	S1, S9, S12, S15, S19, S20, S22, S23, W6, W7, W9, W10, W11, W20, W21, W22, W23, W24, SN2, SN4, SN5, SN6, SN7, SN8, SN9, SN11, SN13, SN14, G1, G2, G3, G4, G9, G10, G11, G15, G18, G19, G21, G22	S1, S12, S13, S15, S19, S20, S21, S23, W7, W9, W11, W21, W22, W23, W24, SN2, SN3, SN4, SN6, SN8, SN9, SN11, SN13, SN14, SN15, G1, G2, G3, G4, G7, G9, G10, G12, G18
Count	23	42	61	30	36	40	34

The analysis of the 84 references reveals a structural misalignment between documentation, risk assessment, and policy. While the seven pillars are frequently discussed in isolation, their operational integration remains critically weak. Current literature on MHCs often focuses on architectural documentation that remains hazard-blind and socio-economically detached. This fragmentation highlights a significant decision-support gap. Although frameworks like the PNRR and SNAI emphasise the strategic value of MHCs for territorial cohesion, the literature primarily offers qualitative governance analyses rather than operational datasets. Consequently, a methodology to bridge policy objectives with technical spatial documentation, required for future project selection and long-term monitoring, remains underdeveloped. Figure 3 quantifies thematic integration by tracking how many of the seven pillars each reference addresses with high significance (scoring 3 or 4). While papers scoring in only one or two pillars represent specialized contributions, the data reveal a critical lack of interdisciplinary depth: only 7% of the corpus bridges 6 or 7 pillars. This finding confirms that current research fails to provide holistic variable sets needed to define a comprehensive SMCA.

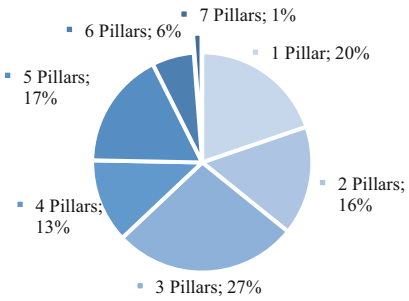

Fig. 3. Distribution of high-relevance scores across (7) thematic pillars.

4 Conclusion and Future Perspectives

The SLR of 84 multidisciplinary sources confirms a structural misalignment between documentation practices, risk assessment, and regional policy. While the RA context is characterised by high architectural value, it remains trapped in a cycle of demographic decline and environmental fragility [4]. Current research frequently treats these settlements as static shells, focusing on physical preservation while remaining hazard-blind to risks and socio-economically detached from the realities of modern habitability. To bridge these gaps, this research highlights the potential of an SMCA integrated into spatial analysis. Unlike a traditional Multi Criteria Analysis (MCA), which may treat variables as homogeneous across a territory, the proposed SMCA acknowledges that data varies significantly across space, requiring a site-specific, multidimensional lens. Furthermore, this approach intentionally moves beyond CBA (Cost-Benefit Analysis), as purely monetary transposition would drastically reduce the complexity of these inherently spatial and interdisciplinary challenges. The indicators detailed in Table 4 represent a synthesis of the requirements identified across the seven thematic pillars. The proposed framework holds the potential to serve as an operational tool to support strategic decision-making and guide targeted investments from national and European policy frameworks, such as the PNRR and SNAI. Moreover, a future Web-GIS platform could be a user-friendly tool in which the stakeholders involved in MHC actions can visualise and query the data. The WebGIS can provide a multi-level and multi-scale living tool that allows non-technical stakeholders and local administrations to monitor long-term regeneration progress and transition from territorial mapping to building-level documentation.

A critical next step for this framework is the transition from "top-down" institutional data to "bottom-up" community insights. Future perspectives include actor-based data collection, which involves organizing structured questionnaires and interviews with local stakeholders, such as residents, private investors, and planners, to refine the social resilience indicators used in the SMCA. Additionally, the research highlights the possibility for Digital Twin interoperability, evolving the Web-GIS into a dynamic environment capable of simulating climate-change impacts on building-level vulnerability in real-time. This transition could ensure that documentation remains a living tool for long-term rural regeneration. Ultimately, the survival of MHCs depends on a shift from episodic, project-based interventions to a data-driven, risk-aware governance model that ensures these territories are not only preserved but actively re-inhabited.

Table 4. Interdisciplinary Indicators for SMCA. Pillars: (1) GIS-Documentation; (2) Hazard-Exposure; (3) RA-Morphology; (4) Re-inhabitation Strategies; (5) Policy; (6) Social; (7) Economic.

Domain	Indicator Category	Specific Spatial/Quantitative Indicators	Pillar Ref
Baseline (Pillars 1–3)			
Technical-Spatial	Physical "Shell" Condition	Building decay levels, structural typology (URM), and architectural value/authenticity	(1), (3)
	Settlement Morphology	Volumetric consistency, urban grain, and presence of "borghi" specific connotations	(3)
Environmental-Risk	Geotechnical Hazards	Landslide susceptibility, avalanche zones, and debris flow history	(2)
	Climate Exposure	Flood risk (hydraulic), soil erosion, and climate-related maintenance costs	(2)
Strategic (Pillars 4–5)			
Strategic-Planning	Policy Alignment	Proximity to SNAI focus areas, PNRR funding eligibility, and EU Rural Vision goals	(4), (5)
	Adaptive Reuse	Potential for "Albergo Diffuso" models or public property availability	(4)
Viability (Pillars 6–7)			
Socio-Economic	Accessibility	Distance from essential service hubs (peripherality) and transport infrastructure	(6), (7)
	Functional Viability	Digital connectivity (broadband), proximity to job markets, and local market viability	(6), (7)
	Demographic Resilience	Population age index, migration trends, and community capacity for re-inhabitation	(6)

A Appendix: Detailed SLR Corpus

This annex provides the complete database for the 114 references selected through the SLR process detailed in Table 5. Each source is coded by its primary domain across the seven thematic pillars: (1) GIS-based documentation, (2) hazard and climate exposure, (3) RA settlement morphology, (4) re-inhabitation strategies, (5) policy frameworks, (6) social dynamics, and (7) economic viability.

Table 5. SLR by Search Strategy and Inclusion Criteria (S = String search, W = Web search, SN = Snowballing, G = Gray literature, E (prefix) = Excluded studies; In. = Include, EX. = Exclude. (1)–(7) = pillars.

Source	Code	Title	Status	Relevant pillars or ...
Academic database - String (i)	S1	Grecchi, M.; Colucci, A.; Malighetti, L.E.; Speciale, F..Reinventing Mountain and Rural Villages Strategies for Regeneration in the Perspective of a Circular Economy,2025	In.	(3), (4),
	SE1	Terrone, M.; Mandarino, A.; Piana, P.; Faccini, F..Identification, computation, and mapping of anthropogenic landforms in urban areas: Case studies in the historical centre of Genoa, Italy (UNESCO World Heritage),2024	Ex.	Genoa Large scale
	S2	Barrile, V.; Bibbò, L.; Bilotta, G.; Meduri, G.M.; Genovese, E..Geomatics Innovation and Simulation for Landslide Risk Management: The Use of Cellular Automata and Random Forest Automation,2024	In.	(1), (2),
	S3	Ardizzone, F.; Esposito, G.; Cavalli, M.; Crema, S.; Fiorucci, F..Sediment connectivity as a key to understand geomorphic effects of the Storm Alex in two mountain catchments of the Mediterranean Alps (Italy),2024	In.	(2), (3),
	SE2	Hussain, A.; Schmidt, S.; Nüsser, M..Dynamics of Mountain Urbanisation: Evidence from the Trans-Himalayan Town of Kargil, Ladakh, India,2023	Ex.	India outside Eu
	SE3	Zhuang, Q.; Hussein, M.K.; Mohd Ariffin, N.F.; Mohd. Yunos, M.Y.; Chen, S..Rural landscape characterization from the perspective of the tourist using online reviews: A case study of Yayou Gou Village in Shandong, China,2022	Ex.	China outside Eu
	SE4	Jiménez-Espada, M.; Cuartero, A.; Le Breton, M..Sustainability Assessment through Urban Accessibility Indicators and GIS in a Middle-Sized World Heritage City: The Case of Cáceres, Spain,2022	Ex.	Middle-Sized City.
	S4	Colucci, E.; Lingua, A.M.; Kokla, M.; Spanò, A..Minor historical centres ontology enrichment and population: An Hamlet case study,2022	In.	(1), (3),
	S5	Colucci, E..Mountain Hamlet Heritage Between Risk and Enhancement,2022	In.	(2), (3),
	S6	Nappo, N.; Peduto, D.; Polcari, M.; Stramondo, S.; Michetti, A.M..Subsidence in Como historic centre (northern Italy): Assessment of building vulnerability combining hydrogeological and stratigraphic features, Cosmo-SkyMed InSAR and damage data,2021	In.	(1), (2),
	SE5	Petrosino, P.; Claudia Angrisani, A.; Barra, D.; Jicha, B.R.; Calcaterra, D..Multiproxy approach to urban geology of the historical center of Naples, Italy,2021	Ex.	Naples large scale
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LCA and AHP-Based Sustainability Assessment for Heritage Building Renovation

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Abstract. Addressing the lack of high-precision Building Information Modeling (BIM) and structured archives for heritage buildings, this study proposes a decision-making framework integrating Life Cycle Assessment (LCA) and Analytic Hierarchy Process (AHP) derived from 2D CAD drawings. By extracting geometric features via a segmented section method and applying historical construction standards, unstructured information is transformed into standardized LCA material flows. Three restoration schemes—minimal intervention (A1), traditional (A2), and composite reinforcement (A3)—are evaluated using the Ecoinvent database. AHP is then employed to synthesize LCA results with qualitative criteria, including heritage protection, structural performance, and economic efficiency. Results indicate the framework effectively quantifies strategy benefits, providing a transparent basis for sustainable heritage protection despite data scarcity.

Keywords: LCA · AHP · Historical Buildings · Unavailable data · Sensitivity Analysis · Structural Restoration · HBIM-light

1 Introduction

The construction industry consumes massive resources and accounts for approximately 35% of EU carbon emissions throughout its life cycle. Addressing implicit carbon issues in the production and transport of building materials is increasingly critical for policymakers and academia [1]. In this context, protecting historical religious buildings faces a dual challenge: adhering to heritage authenticity while responding to entire life-cycle carbon reduction requirements [2]. Natural disasters, such as earthquakes, exacerbate this conflict, as post-disaster reinforcement often faces resource shortages and time urgency, leading to the use of high-impact carbon materials. While Building Information Modeling (BIM) and Life Cycle Assessment (LCA) have advanced environmental load quantification, existing HBIM-LCA paths remain highly dependent on high-precision parametric models and complete databases. In heritage-rich regions like Italy, many sites lack such data, relying instead on basic 2D CAD drawings that lack the parametric information required for BIM. This "digital gap" hinders the direct transfer of mainstream HBIM-LCA processes into practice.

This paper proposes a framework to overcome this "data bottleneck" by establishing a direct mapping mechanism from unstructured 2D CAD geometric data to material environmental properties. This approach enables accurate environmental load calculation

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 395–412, 2026.
https://doi.org/10.1007/978-3-032-30524-4_25

for complex historical components without high-precision BIM support. The framework integrates LCA with the Analytic Hierarchy Process (AHP) to evaluate restoration schemes—such as those for the Church of Beata Vergine della Cintura of San Giovanni in Persiceto, Italy—balancing structural safety, ecological sustainability, and cultural authenticity. This research provides a methodological basis for low-carbon restoration decisions within data-scarce environments.

2 Literature Review

The concept of LCA has grown into a fully developed mechanism in environmental performance analysis of the new buildings. In recent years, scholars have begun to adapt it into the field of historical building conservation. Karglou et al. [3] applied LCA to the conservation intervention assessment of traditional architectural heritage and found that material selection and repair techniques have a significant impact on environmental performance. Franzoni et al. [4] further extended the LCA method to the environmental impact assessment of historical building cleaning procedures, revealing the environmental load generated by the conservation operation itself. However, Akşar et al. [5] pointed out through bibliometric analysis that although research on historical building LCA is on the rise, compared with new buildings, historical buildings have complex structures and environmental data on traditional materials are often missing. This "non-standardized" characteristic poses significant challenges to the quantitative application of LCA in historical heritage.

In order to solve this data extraction problem, the mainstream trend in recent years has been to integrating BIM as a bridge to LCA. This "BIM-LCA" integration path theoretically provides data-driven decision support for conservation projects. For example, Al-Zrigat [6] achieved a parametric assessment of the energy performance of historic buildings by integrating the ISO 14040 principle with spatial ETL technology. Valipour et al. [7] quantified the carbon reduction potential (approximately 30%) of optimized material combinations in the restoration of historic buildings by integrating BIM, LCA, and multi-criteria decision-making models. However, this method, which relies on high-precision three-dimensional models, is facing a serious "information gap" in actual engineering. Shehata et al. [8] pointed out through SWOT analysis that the high modeling cost and the scarcity of historical data constitute a very high technical threshold. In particular, for a large number of historic buildings with only basic two-dimensional CAD drawings, it is not realistic to mandate a high-precision BIM modeling. This leads to a huge "digital divide" between "basic CAD drawings" and "structured LCA evaluation".

On the other hand, even if the problem of basic data extraction is solved, the renovation and regeneration of historical buildings still face complex value trade-offs. Heritage protection not only needs to consider environmental sustainability, but also must take into account cultural authenticity and economic feasibility. For this reason, the multi-criteria decision-making (MCDA) method has been widely introduced. For example, Ferretti [9] used the AHP to transform abstract cultural values into an operational evaluation system to explore the priority ranking of adaptive reuse of heritage sites. Furthermore, Abastante et al. [10] introduced the SRF-II method to compare different hypotheses for the adaptive reuse of iconic historical buildings, emphasizing the importance of ranking

criteria based on diverse stakeholder perspectives. However, existing AHP studies often overemphasize qualitative socio-cultural indicators, and environmental performance is usually only regarded as a rough secondary consideration, lacking a systematic combination with the precise quantitative data of LCA. Based on the above-mentioned real pain points, this paper aims to provide an alternative for the real engineering scenario of "data limitation". This paper proposes an integrated "CAD-LCA-AHP" evaluation framework that explores a lightweight path to extract data directly from basic two-dimensional CAD drawings to LCA, and then use the AHP decision model to deeply integrate the objective quantitative data produced by LCA with subjective qualitative principles such as cultural heritage protection. This framework aims to provide a multi-dimensional evaluation system for the renovation and regeneration of historical religious buildings that takes into account both feasibility and scientific transparency.

3 Methodology

This study constructs a progressive comprehensive evaluation workflow for the restoration of historical buildings concerning LCA evaluation. This methodology aims to overcome the limitations of single-dimensional evaluation and is divided into four core stages: the first stage is data acquisition, which involves extracting architectural geometry and material information from basic CAD drawings; the second stage is scheme generation, which involves developing different renovation strategies based on the extracted information; the third stage is objective quantification, which uses LCA to accurately calculate the environmental performance of each restoration scenario; and the fourth stage is comprehensive decision-making, which introduces AHP to construct a multi-criteria evaluation system. This framework focus on a decision-making view of four dimensions, including heritage conservation value (A), technical structural performance (B), environmental sustainability (C), and economic feasibility (D). By scientifically allocating weights, it ultimately identifies the overall optimal restoration scheme.

3.1 Material Flow Characterization: A Geometric Data Extraction Process Based on 2D Drawings

Given the general lack of high-precision Building Information Models (HBIMs) for historic heritage buildings, this study proposes a method for quantity extraction and data conversion based on 2D CAD drawings to address the challenge of converting unstructured drawings into LCI material flow data.

First, in the geometric information acquisition stage, for irregular walls and complex vault systems in historic masonry structures, this study employs a segmented section method to compile a Quantity Take-off (QTO): The characteristic cross-sectional area (Ai) of each component is extracted in the CAD environment, and its geometric volume is calculated by combining it with the measured height or thickness (Hi). Subsequently, by combining regional historical building construction codes and literature, corresponding physical parameters (such as brick density, mortar mix ratio, etc.) are matched to the above geometric volumes, thereby converting the geometric volumes of the components into the actual mass (kg) of the materials. Lastly, the standardized mass data

is transformed and converted and integrated with the LCI database. This whole procedure, including 2D geometric breaking out to material mass conversion to environmental influence correspondence, is essentially addresses the assessment challenge posed by the absence of 3D structure, which has supplied trusted groundwork knowledge concerning the next correct determination of the environmental load of historic buildings.

The logical progression from geometric reduction to LCA integration is summarized in Fig. 1.

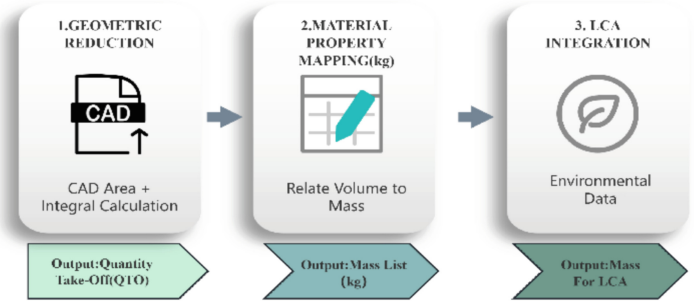

Fig. 1. Integration path of historical building quantity accounting and LCI

3.2 Repair Scenarios

To substantially contrast the overall benefits of the intervention strategies in a multidimensional assessment system, this work selected three representative scheme backgrounds of historical building restoration (A1-A3) as the objects of analysis to the decision-making criteria in the subsequent stages:

Option 1 (A1) - Minimal Intervention (Existing Baseline): This alternative promotes the principle of minimal intervention; only the routine preventative level of intervention (surface treatment and crack grouting) would be done. Option A1 preserves the building's material authenticity to the greatest extent possible, but essentially does not alter the existing structural stress state and cannot effectively improve seismic performance. It is mostly used in this paper as a reference point in making the comparison of the environmental and technical merits of the other structural reinforcement structures.

Option 2 (A2) - Traditional Retrofitting: This alternative is the typical engineering practice during the last several decades, this objective enhances safety primarily by increasing structural rigidity. Some of the specific measures involve the installation of reinforced concrete (RC) ring beam, steel bracing, or a massive tie rod. Although this alternative has great potential to boost the final bearing capacity of the building, it usually involves introducing large masses of new high-energy materials (high embodied carbon content) and involves much destruction of the historical texture. Reversibility of the intervention measures is also not good and the physical compatibility of materials is poor.

Option 3 (A3) - Novel Composite Material Reinforcement: Scheme presents an advanced composite materials-based repair technology, which is a low-intervention, high-toughness type named as FRCM [11]. Seismic ductility by laying high-performance

mesh onto the surface of the masonry may be attained without materially altering the initial stiffness distribution of the structure. Moreover, the lightweight and thinness properties of composite materials not only significantly reduce the implicit carbon emissions of substances, but also guarantee the extensive reversibility of the reinforcing actions, and consequently, it provides a greater ratio between the structural performance, environmental sustainability and the safeguarding of heritage.

3.3 Environmental Performance Quantitative Evaluation Framework

In this paper, the total mass (kg) of the different component materials (including mortar, reinforcing fibers, and steel) obtained in the last step was mapped to the internationally accepted Ecoinvent 3.10 database. Through connecting with the relevant background dataset and extracting. Environmental emission factors, the conversion process of the engineering physical quantities into the environmental load data was completed.

During the Life Cycle Impact Assessment (LCIA) stage, three primary quantitative indicators were selected to address global warming and resource depletion:

Global Warming Potential (GWP): Used to compute the greenhouse gas emissions (i.e., carbon footprint) of each restoration scheme over its life cycle.

Acidification Potential (AP): Evaluates the acidification burden on local soil and water conditions resulting from acid gas emissions (e.g., SO_2 and NO_x) during the manufacturing, transportation, and construction phases.

Resource Utilization (RU): Focuses on the concentration of primary resources within the materials and their recyclability at the end-of-life stage, thereby reflecting the circular economy benefits of each scheme.

The outputs of these three indicators serve as direct quantitative inputs for the subsequent AHP multi-criteria decision-making model. This ensures that the selection of the optimal solution is supported by objective data within the environmental sustainability dimension.

3.4 Construction of Decision Model: AHP Weight Allocation and Comprehensive Evaluation.

The preservation and renovation of historic buildings involve a complex interplay among structural safety, environmental conservation, and cultural heritage preservation. To balance these needs scientifically, this study employs an integrated AHP-Weighted Scoring model. While AHP is employed to determine the hierarchical weights of the criteria—Heritage Preservation Value (A), Technical Structural Performance (B), Environmental Sustainability (C), and Economic Feasibility (D)—a direct weighted-sum method aggregates the performance of alternatives. This hybrid approach allows for the seamless integration of quantitative LCA results and qualitative expert ratings.

During the weight allocation stage was done by the authors, addressing their experience in construction renovation projects, architectural heritage conservation, structural engineering, and sustainable design. The weight allocation was performed by pairwise comparisons for each appraisal standard using Saaty's 1–9 scale. Once the judgment matrices were constructed and consistency ratios (CR) were verified to be below 0.1,

the final weights were computed. At last, In the final evaluation step, the individual performance of each restoration scheme was measured. To ensure transparency and replicability, the scores for environmental indicators were obtained by linearly normalizing the absolute LCA results into a 1–10 scale (see Table 6), where the lowest environmental impact corresponds to a score of 10. Qualitative scores were based on standardized performance rubrics. This scientific integration of environmental load data and qualitative heritage protection assessments ensures a robust basis for selecting the optimal transformation strategy.

4 Case Study

4.1 Site Context

This study employs a case study of the Beata Vergine della Cintura Church of San Giovanni in Persiceto, Italy. The church is a common historical masonry religious construction, the backbone of which is made up of load-bearing brick walls and complicated interlocked vaults. The building needs structural reinforcement and performance improvement as a result of a long-term combination of natural weathering factors and possible risks of earthquakes.

The project, however, had a common problem of data constraints in the initial phases of the redesign procedure. The church does not have a high-precision HBIM, as most of the local heritage sites that have not been overly developed in terms of commercialization have not received such models. Current technical archives have rudimentary two-dimensional drawings in CAD and do not have systematic records of materials' physical properties. This huge discrepancy between the fact that spatial geometry is highly complex and the underlying data is low-structured is the very reality of numerous small and medium-sized historical building renovation projects today. Thus, this church was a perfect place where it was necessary to check how the offered "CAD-LCA-AHP" light-weight embedded assessment framework is feasible.

4.2 Geometric Representation and Material Quantification

In this research, the unit of analysis used in extracting the quantity of the longitudinal aspect is the U-shaped section of the part of the wall on the north side of the church which has a total length of approximately 12.95 m. Asymmetrical door and window openings have been added to this wall, and the top elevation reaches a maximum of 11.40 m (see Fig. 2). Despite these geometric complexities, this section is considered a representative structural unit of the entire church nave. It encompasses the standard masonry patterns, opening modules, and typical degradation characteristics found throughout the longitudinal walls. Since the material composition and load-bearing logic are consistent across the main body of the building, the findings derived from this typical section can be generalized to the entire structure. Due to the use of an irregular geometric form of the masonry walls of historical buildings, the use of complex openings on the facade, and the complex shape of the overall estimation processes lead to serious errors. Thus, to complete the calculation correctly, the segmented section method is used in this research:

the geometric features of the wall section are subdivided into many regular blocks and the net cross-sectional area of each block is calculated and multiplied by the average wall thickness, and the volume of openings is deducted to get the actual amount of material in this irregular longitudinal wall.

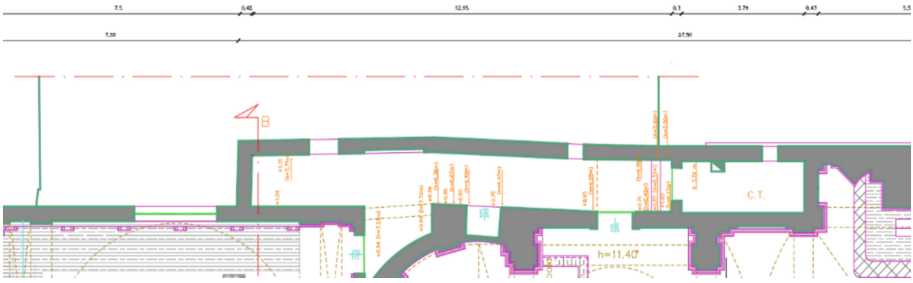

Fig. 2. Floor plan used for QTO of the B. V. della Cintura Church.

Calculation which determines the Gross Volume: L = 12.95m which is the wall length, the average height of the wall is estimated at H ≈11m and assuming a wall thickness of T = 0.8m, representing the typical thickness of an Italian rural church wall:

$$V_{total} = 12.95 \times 11 \times 0.8 \approx 114\,\mathrm{m}^3 \tag{1}$$

Calculation of Window Openings: The volume of the overall opening based on the window distribution given in the CAD drawings is approximately 14 m^3:

$$\mathrm{V_{net}} = 114 - 14 = 100\,\mathrm{m}^3 \tag{2}$$

When the space occupied by the window openings and multiplied by the brick density of 1800 kg/m^3 is subtracted and the total material mass of this unit established as approximately 180 tons. The detailed calculation parameters and resulting mass are summarized in Table 1.

Table 1. Summary of Geometric Dimensions and Mass of Building Components

Category	Parameters	Values	Unit	Remarks/Source
Geometry	Element length (L)	12.95	m	Based on CAD planar surveying
	Average height (H)	11,00	m	Based on drawing annotations
	Wall thickness (T)	0.80	m	Measured from existing masonry
	Gross Volume (V_{total})	114	m^3	L × H × T
Net Volume	Volume of window opening (A_{open})	14	m^3	Geometric extraction from CAD

(*continued*)

Table 1. (*continued*)

Category	Parameters	Values	Unit	Remarks/Source
	Net volume (V_{net})	100.00	m^3	Actual volume after deducting openings
Current Situation	Masonry density (ρ_m)	1,800	kg/m^3	Historical building construction codes
	Total masonry mass (M_m)	180.00	t	Used for LCA baseline calculation

4.3 Quantitative Comparison of Environmental Performance Across Repair Scenarios

In this work, three sets of repair schemes of technical gradients and protection philosophy of a selected 12.95-m exterior wall analysis unit were designed to compare the environmental performance and the structural resilience of diverse intervention strategies. Detailed geometric and material parameters are summarized in Table 2.

Option 1 (A1) - Baseline (Minimum Intervention):
This scheme follows the principle of minimum intervention. Its main measures include lime mortar grouting of existing cracks, partial removal of masonry, and necessary preventative maintenance. In this scheme, except for a very small amount of maintenance materials, the material condition of the original 180 tons of masonry is basically maintained. Although it has the lowest environmental load, it cannot provide additional structural safety guarantees in response to the potential seismic risk in the region.

Option 2 (A2) - Traditional Retrofitting:
This traditional reinforcement scheme incorporates a concrete ring beam with a 0.40m $\times$ 0.30m cross-section. Based on a concrete density of 2,400kg/m^3 and a reinforcement ratio of 100kg/m^3, the total mass increment (ΔM_{A2}) is calculated.

Option 3 (A3) - Advanced Reinforcement (FRCM):
Aligned with circular economy principles, this scheme adopts Fiber Reinforced Cementitious Matrix (FRCM) technology. A 15 mm thick high-performance cement mortar is applied to both sides of the 12.95 m l wall, embedded with carbon fiber mesh. After deducting the three window openings (total area 4.20 m^2), the net reinforced area (A_{net}) is 259.70 m^2. Following Italian engineering standards (CNR) [12], a material loss coefficient of $\alpha = 10\%$ is applied. With a fiber mesh unit weight (ω) of 250 g/m^2, the total incremental mass (ΔM_{A3}) is derived from the mortar matrix (M_{mortar}) and fiber mesh (M_{mesh}).

Table 2. Geometric Calculation and Material Inventory for Restoration Scenarios

Scenario	Core Formula	Parameters & Data Sources	Mass Result
A1: Baseline	$M_{base} = V_{net} \times \rho_m$	$V_{net} = 100\,m^3$	180,000 kg
		$\rho_m = 1800\,kg/m^3$	
A2: Traditional	$\Delta M_{A2} = M_{conc} + M_{steel}$	$M_{Concrete} = V_{concrete} \times \rho_{concrete} = 1.554 \times 2400 = 3729.6\,kg$ (1)	3,885 kg
		$M_{steel} = V_{concrete} \times \rho_{steel} = 1.554 \times 100 = 155.4\,kg$ (2)	
A3: Advanced (FRCM)	$\Delta M_{A3} = M_{mortar} + M_{mesh}$	$M_{mortar} = A_{net} \times t_{total} \times \rho_{mortar} = 259.70 \times 0.03 \times 1800 = 14023.80\,kg$ (3)	14,166.64kg
		$M_{mesh} = A_{net} \times N \times \omega \times (1 + \alpha) = 259.70 \times 2 \times 0.25 \times 0.10 = 142.84\,kg$ (4)	

4.4 System Boundaries for LCA Calculation

This section defines the LCA system boundaries for the north longitudinal wall unit.

A1: Baseline Scenario (Minimum Intervention):

Even though Option A1 is characterized as a maintenance-only approach, it consumes 540.0 kg of materials to deal with centuries of environmental degradation. These materials primarily consist of hydraulic lime (NHL) mortar for localized repairs of deteriorated joints and mineral-based reinforcing agents for strengthening weathered masonry surfaces. Also, 220.00 kg of tap water and 18.00 MJ of electricity to cover small machinery are also supplied to assist manual construction and mortar cleaning. The logistics and transportation are modeled based on localized procurement within a 20 km radius (Table 3).

Table 3. A1 Phase Environmental Load Basic Data Calculation

Option A1	Calculation Process	Amount	**Unit**
Hydraulic lime mortar (NHL)	$142.45 \times 0.07 \times 0.03 \times 1800\,kg/m^3$	540.00	kg
	Based on 3 cm grout depth & 7% damage rate		
Tap Water	M_{mixing} (1:4) + $M_{cleaning}(2\,kg/m^2)$	220.00	kg
electricity for small machinery	$0.25\,kWh/m^2 \times 20\,m^2$	18.00 (5.0 kWh)	MJ
logistics and transportation load	$(0.54 + 0.01 + 0.22)\,t \times 20\,km$	15.40	t·km

The obtained Inventory Data was input into the openLCA software platform and mapped to the Ecoinvent 3.10 database. The characterization of data presented in Fig. 3 was derived by setting up a life cycle model.

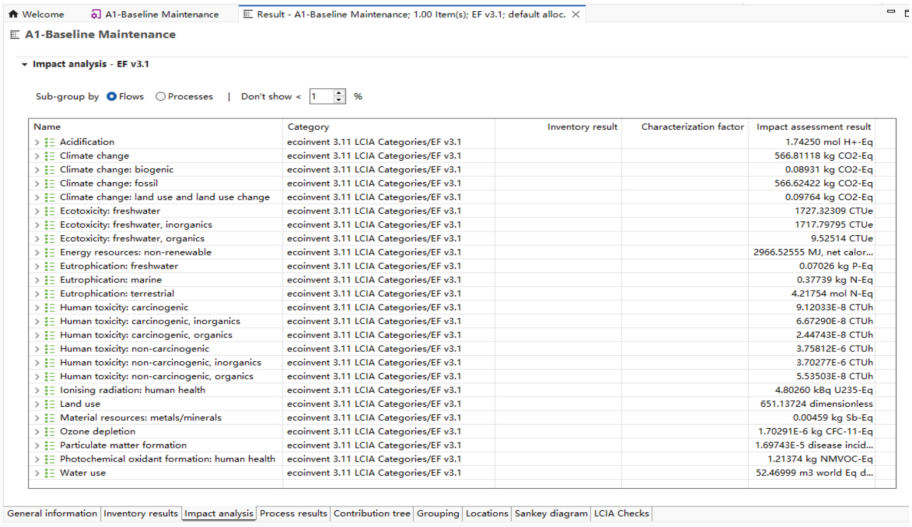

Fig. 3. The impact analysis of option A1

A2 - Traditional Retrofitting:

The basic features of option A2 involve the r structural reinforcement using reinforced concrete (RC). According to the reinforcement design requirements, this alternative will add a cumulative of 3729.60 kg of cast-in-place concrete (grade C25) and 155.40 kg of low-alloy steel reinforcement. The total mass of the added materials is estimated at 3.885 tons, representing 2.16% of the original wall's total mass. During construction, a total of 233.10 kg of tap water will be used, regarding the mixing of concrete, its curing, as well as the cleaning up of the base. One unit volume of mechanized construction (drilling and rebar installation, synthetic concrete pumping, and vibration) is estimated to consume 23.31 kWh (equivalent of 83.92 MJ) of electricity. According to the assumption of localized procurement (transport radius established at 20km), the total mass of all the concrete, rebar, and water applied in the construction is estimated, giving an alternative of 77.7 t·km of transportation turnover in the case of A2 (see Table 4).

Table 4. A2 Phase Environmental Load Basic Data Calculation

Option A2	Calculation Process	Amount	Unit
Cast-in-place concrete	1.554 m^3 × 2400 kg/m^3	3729.60	kg
Steel rebar	Reinforcement quantity corresponding to 1.554 m^3 of concrete (at 100 kg/m^3)	155.40	kg

(*continued*)

Table 4. (*continued*)

Option A2	Calculation Process	Amount	Unit
Tap water	1.554 m^3 × 150 kg/m^3	233.10	kg
	Concrete mixing (180 kg/m^3) + curing loss		
Construction power consumption	15 kWh/m^3 × 1.554 m^3 = 23.31 kWh	83.92(23.31)	MJ(kWh)
	Drilling and rebar installation/concrete vibration		
Logistics and transportation load	(3.73 + 0.16) t × 20 km	77.70	t·km

By establishing a LCA model, the final characterization results data shown in Fig. 4 were obtained.

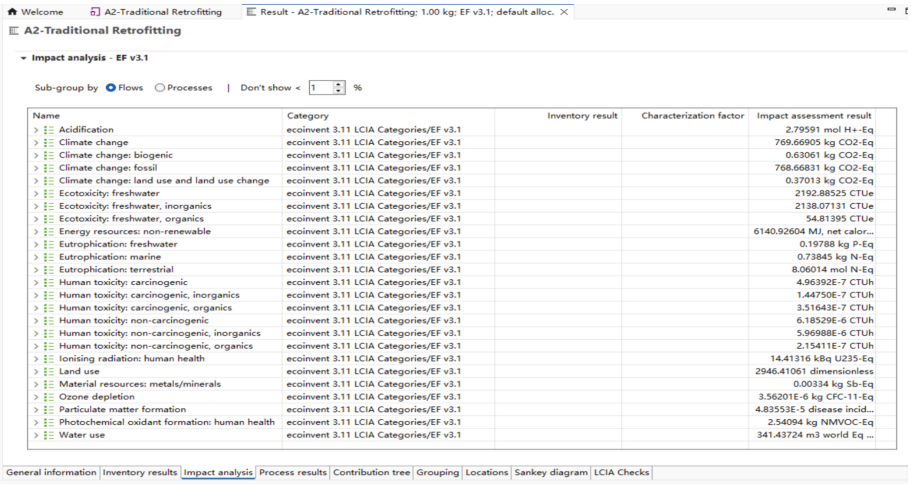

Fig. 4. The impact analysis of option A2

A3- Advanced Reinforcement (FRCM):

For Option A3, the FRCM is adopted to ensure double-sided reinforcement of the 180-ton masonry unit. Beyond enhancing structural ductility and seismic performance, this alternative creates a continuous reinforcement layer by applying fiber mesh and high-performance mortar to both interior and exterior surfaces. Accounting for double-sided window openings (25.20 m^2), the net reinforcement area (A_{net}) is 259.70 m^2. Based on a total double-sided thickness of 30 mm, 14,023.80 kg of mortar is required. The reinforcement phase utilizes alkali-resistant glass fiber mesh, requiring 142.84 kg to account for construction overlaps and a wastage coefficient of 1.1.

To support mortar mixing and substrate wetting, 2,524.28 kg of tap water is required (calculated at 18% of the mortar mass). Due to the intensive high-pressure water jet

cleaning and mechanical mixing involved in Scheme A3, construction power demand increases significantly to 311.64 kWh (equivalent to 1,121.90 MJ). Assuming localized procurement within a 20 km radius, the total transportation load—comprising mortar, fiber mesh, and construction water (approximately 16.69 tons)—is calculated at 333.60 t·km (see Table 5).

Table 5. Calculation of Environmental Inventory Data for Option A3

Option A3	Calculation	Amount	Unit
High-performance cement-based mortar	$259.70\,m^2 \times 0.03\,m \times 1800\,kg/m^3$	14023.80	kg
Alkali-resistant fiberglass mesh	$259.70 \times 2 \times 0.25\,kg/m^2 \times 1.1$	142.84	kg
Tap water	14023.80 kg × 0.18	2524.28	kg
	Calculated at 18% of the mortar mass (including mixing and wetting of the substrate)		
Construction power consumption	$1.2\ kWh/m^2 \times 259.70\,m^2 \times 3.6$	1121.90	MJ
	High-pressure water jet cleaning and mechanical agitation		
Logistics and transportation load	(14.02 + 0.14 + 2.52) t × 20km	333.60	t·km

By establishing the life cycle model, the final characterization results data shown in Fig. 5 were obtained.

4.5 Comparison of Restoration Scenarios

To evaluate the environmental performance of the different interventions, LCIA results for Scenarios A1, A2, and A3 are compared. Table 6 summarizes the key impact categories, including GWP, AP, and RU, for all three options.

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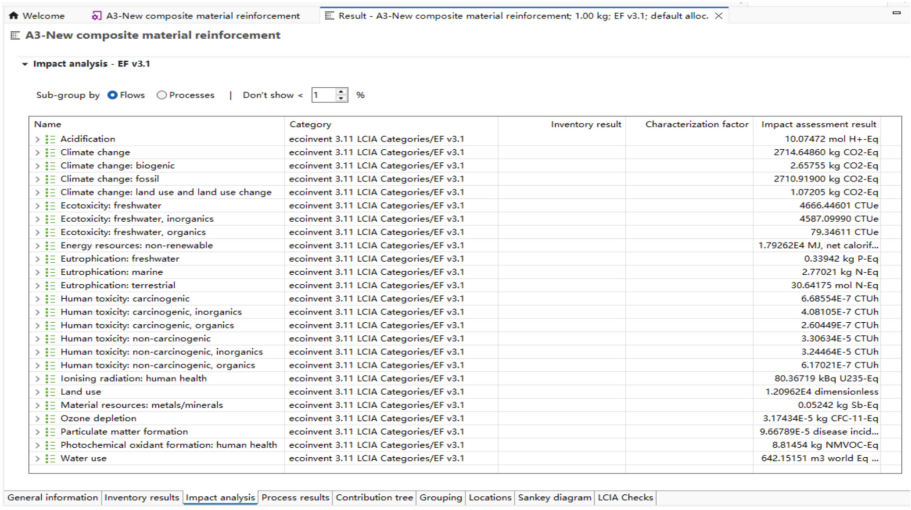

Fig. 5. The impact analysis of A3

Table 6. Summarize of LCIA results for all restoration scenarios

Impact Categories	Unit	A1: Baseline	A2: Traditional	A3: FRCM
GWP	$kgCO_2eq$	566.81	769.669	2714.649
AP	Mol H^+eq	1.743	2.796	10.075
RU	kgSbeq	4.59×10^{-3}	3.33×10^{-3}	5.242×10^{-2}

4.6 Decision Model Construction: AHP Weight Allocation and Comprehensive Evaluation

The core first step of the AHP method lies in hierarchical modeling. The systematic analysis of the natural correlation between decision-making goals and indicators of evaluation turns complex issues into a properly structured multi-level model. This model is performed top to bottom based on the following series of "objective layer-primary indicator -secondary indicator," and the structural framework in question is depicted below (see Table 7).

Table 7. AHP Hierarchical Framework

Target layer	Primary Indicators	Secondary Indicators
Selecting the optimal restoration strategy for historic church exterior walls	A. Heritage Conservation Value	A1 Reversibility

(*continued*)

Table 7. (*continued*)

Target layer	Primary Indicators	Secondary Indicators
		A2 Visual Compatibility
	B. Technical Structure Performance	B1 Enhancement Efficiency
		B2 Intervention Depth
		B3 Maturity Score
	C. Environmental Sustainability	C1 GWP (Carbon Footprint)
		C2 AP (Environmental Pollution)
		C3 Resource Use
	D. Economic Feasibility	D1Operation and Maintenance Costs
		D2 Material Lifespan

The weights of each evaluation indicator were given by the authors to provide expert judgments. The weighting process was performed by pairwise comparisons of the four primary criteria (A, B, C, and D) using Saaty's 1–9 scale. Individual judgment matrices were synthesized using the geometric mean method. This process resulted in the integrated comparison matrix for the primary indicators shown in Table 8. The values within the matrix reflect the relative importance of each criterion; for instance, the value of 1.6612 indicates that in this restoration context, Heritage Conservation Value (A) is assigned a moderate priority over Technical Structural Performance (B).

Table 8. Heritage Conservation Value - Economic Feasibility Assessment Integrated Matrix

Choosing the most sustainable strategy for restoring the exterior walls of a historic church	A Heritage Conservation Value	B Technical Structure Performance	C Environmental Sustainability	D Economic Feasibility
A. Heritage Conservation Value	1	1.6612	1.8015	2.7595
B. Technical Structure Performance	0.6020	1	1.3351	1.6438
C. Environmental Sustainability	0.5551	0.7490	1	1.2821
D. Economic Feasibility	0.3624	0.6084	0.7800	1

Table 9. The weight calculation results

Index	Weight	λmax	CI	CR
A1Reversibility	0.6025	2.0000	0.0000	0.0000 < 0.1Consistency passed
A2Visual Compatibility	0.3975			
B1Enhancement Efficiency	0.4014	3.0028	0.0014	0.0026 < 0.1Consistency check passed
B2 Intervention Depth	0.3966			
B3Maturity Score	0.2020			
C1GWP (Carbon Footprint)	0.5000	3.0007	0.0003	0.0007 < 0.1Consistency check passed
C2 AP (Environmental Pollution)	0.2012			
C3 RU	0.2987			
D1Operation and Maintenance Costs	0.4997	2.0000	0.0000	0.0000 < 0.1Consistency check passed
D2 Material Lifespan	0.5003			

Based on the calculation results of the integration matrix and weights for each indicator, the weights between the indicators at each level are summarized as follows in Tables 9 and 10.

Table 10. Summary of Weights for Selecting the Most Sustainable Historic Church Exterior Wall Restoration Strategies

Primary Indicator	Relative Weight (W_1)	Secondary Indicator	Relative Weight (W_2)	Over all Weight ($W_1 \times W_2$)
A. Heritage Conservation Value	0.3974	A1 Reversibility	0.6025	0.2394
		A2 Visual Compatibility	0.3975	0.1580
B. TechnicalStructurePerformance	0.2513	B1 Enhancement Efficiency	0.4014	0.1009
		B2 Intervention Depth	0.3966	0.0997
		B3 Maturity Score	0.2020	0.0508
C. Environmental Sustainability	0.2003	C1 GWP (Carbon Footprint)	0.5000	0.1002
		C2 AP (Environmental Pollution)	0.2012	0.0403
		C3 RU	0.2987	0.0598

(*continued*)

Table 10. (*continued*)

Primary Indicator	Relative Weight (W_1)	Secondary Indicator	Relative Weight (W_2)	Over all Weight ($W_1 \times W_2$)
D. EconomicFeasibility	0.1510	D1 Operation and Maintenance Costs	0.4997	0.0755
		D2 Material Lifespan	0.5003	0.0755

Finally, a comprehensive evaluation matrix was constructed by multiplying the overall weights of the indicators by the performance scores assigned to each restoration strategy (A1, A2, and A3). As shown in Table 11, Option A3 (FRCM) achieved the highest total score (7.5882), followed by A1 (7.0678) and A2 (6.4246).

Table 11. Comprehensive evaluation matrix for restoration strategies

Primary indicator	Secondary Indicators(comprehensive weight)	A1: Baseline	A2: Traditional	A3: Advanced
A.Heritage Conservation Value	A1 Reversibility (0.2394)	10	6	8
	A2 Visual Compatibility (0.1580)	10	9	7
B. Technical Structure Performance	B1 Enhancement Efficiency (0.1009)	1	4	9
	B2 Intervention Depth (0.0997)	10	7	6
	B3 Maturity Score (0.0508)	9	10	7
C. Environmental Sustainability	C1 GWP (0.1002)	3	5	7
	C2 AP (0.0403)	8	7	6
	C3 RU (0.0598)	9	6	8
D. Economic Feasibility	D1 O&M Costs (0.0755)	2	5	8
	D2 Material Lifespan (0.0755)	3	5	9
Total	**1.0000**	7.0678	6.4246	**7.5882**

4.7 Sensitivity Analysis

To verify the robustness of the decision-making results, a sensitivity analysis was conducted by fluctuating the weights of the primary indicators (A, B, C, and D). The results of the sensitivity analysis are illustrated in Fig. 6. The analysis demonstrates that despite

minor adjustments in the priority of environmental sustainability or economic feasibility, Option A3 consistently maintains its position as the most suitable strategy, with the exception of values of the weight of Heritage conservation larger than 0.6, where the A1 option gives better results. Nevertheless, the proposed AHP model confirms it statability in most of the cases, thus confirming the robustness of the proposed procedure (Fig. 6).

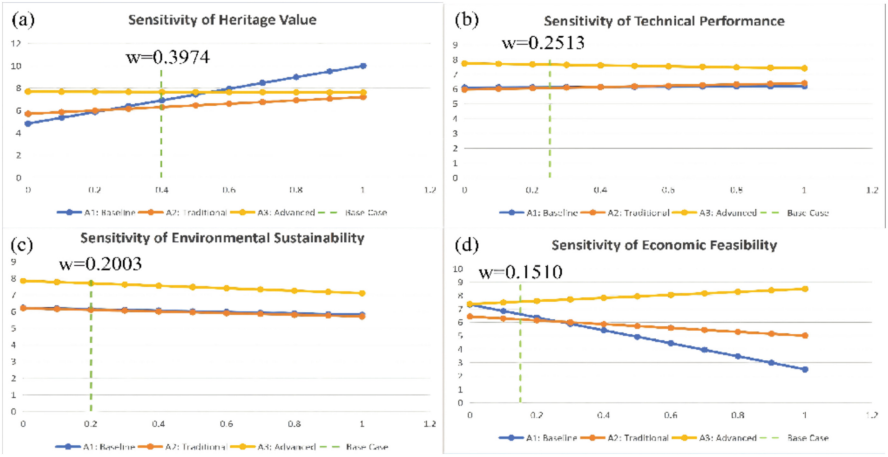

Fig. 6. Sensitivity analysis of the criteria weights for the restoration scenarios

5 Conclusion

This study constructed and validated a multi-dimensional assessment model for the restoration of historic buildings by integrating LCA and AHP. A major advantage of this model is its flexibility: it does not require HBIM model, but rather achieves quantitative analysis of the environmental performance and structural performance of restoration schemes through an integrated CAD-LCA-AHP approach, even with limited basic data. The case study of the Lady Mary of the Belt Church demonstrates that the FRCM reinforcement scheme significantly reduces GWP and AP while meeting structural safety and heritage preservation values, confirming it as the optimal strategy for green restoration of historic buildings. Sensitivity analysis was introduced to quantify the impact of fluctuations in expert weights on the results. The analysis shows that within the current expert consensus weights (e.g., heritage value $w = 0.3974$) and their significant fluctuation range, the scheme ranking remains highly robust. This significant safety margin strongly demonstrates the high reliability and application value of this assessment framework in addressing the uncertainty of subjective decision-making.

While this study confirms the potential of the CAD-LCA-AHP approach in the quantitative analysis of environmental performance, certain limitations remain. Current research focuses on a representative 12.95-m-long wall section and has not yet fully simulated the extreme changes in complex geometries such as the church dome and apse. Furthermore, due to the limited coverage of existing Environmental Declaration (EPD) databases for heritage conservation materials, evaluation indicators do not yet

encompass eutrophication and human toxicity. Future research will aim to expand the evaluation boundaries, utilize a more comprehensive background database to broaden evaluation dimensions, and validate the applicability of the framework across all spatial dimensions. Simultaneously, the research will explore integrating real-time monitoring data into deeper digital models to achieve dynamic sensitivity analysis, aiming to provide more universal and intelligent decision support for the sustainable restoration of cultural heritage under complex constraints.

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Mainstreaming the Ecosystem Services Values in the Context of Green Public Procurements

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Abstract. The Public Procurement serves as strategic instruments that can steer the sustainable transformative change of territorial transition. Its intrinsic value to be used actively for supporting the supply the Ecosystem Services (ES) globally remains underpinned and few attentional in the sectorial scientific literature. This contribution is oriented to investigate how Green Public Procurement (GPP) can serve as instrumental bridge to renewal traditional approach toward nature-positive paradigm that support the production for ES in multiple and diversified contexts. To tracking the underground principles that link procurement mechanism with assessment practices related to the ecosystem services, the expected outcome of the works consists in the proposal of an operational framework for integrating nature assessment in procurement outline. The study is supported also across the study of a demonstration case about the "100Parks of Rome" initiative, that represents an example of green infrastructure investment nature-positive pro ES production. The paper concludes with the description of main challenges that face during the implementation, and with the sharing of policy directions to follow for facilitating the mainstreaming the accounting of ecosystem services in nature-positive procurement procedures.

Keywords: Ecosystem Services · Green Public Procurement

1 Introduction

The global decline of nature footprint has significant implications not only for ecosystem integrity and connectivity, but also for the ecosystem services values that drive the transformation of societal and economic systems. The capacity of ecosystems to provide services that could restore, maintain and/or improve biodiversity, affects the resilience attitude of the economic-societal communities to face environmental risks and resulting impact [1]. The latter extend across multiple sectors, including (e.g.) well-being, water resilience, economic development, with substantial increasing of social cost of mitigation and restoration strategy actions [2].

Building nature-people communities for a positive and resilient green transition raises issues relating to biodiversity loss, and subsequently to economic security prosperity, social well-being, and environmental justice. Each of these challenges is interlinked, yet they are often addressed in isolation rather than in a complementary manner; a systemic, top-down and bottom-up approach is therefore required. From this perspective,

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 413–424, 2026.
https://doi.org/10.1007/978-3-032-30524-4_26

NbS could represent an innovative values-sharing platform, where multiple decision-making spheres engage in dialogue towards a common synthesis of knowledge, whilst maintaining their integrity [3].

IPBES highlights the need for new ways of thinking about economics that can account for non-instrumental and non-individual values, recognizing that they are incommensurable within conventional economic framing because they are difficult (or inappropriate) to incorporate into preference based trade-off analyses (e.g., cost–benefit analysis) or monetize [4]. A synthetic perspective on how to incorporate more diverse values in biodiversity economics - the area of economics that studies the role of nature, biodiversity and ecosystems in the production, consumption, valuation, allocation, and exchange of goods and services, how those economic processes affect nature, and the way they are institutionalized and governed - remains absent [5].

Addressing these interconnected challenges requires transformative change – a fundamental, system-wide reorganization of technological, economic, and societal systems [6]. This transformation involves shifts not only in policies and governance arrangements, but also in underlying societal values, economic incentives, and decision-making paradigms [7]. Achieving such change requires moving beyond fragmented, sector-specific interventions toward cross-fertilization knowledge paradigms that explicitly recognize the interdependence between ecological integrity, climate resilience and people-nature values [8]. Through complementarities, different knowledge systems can contribute to an enriched picture. The analysis of the enriched picture, including synergies and contradictions across diverse knowledge systems, can enhance the understanding of environmental conditions and change, and the potential for sustainable governance practices values based [9].

Despite their potential to be eligible as values-shared communities, the large-scale uptake of NbS across the EU remains constrained due to multi-sectorial value transfer boundaries. These are concerned with jeopardized governance and policy frameworks that address biodiversity, economic development, and well-being sectorally. These domains are often managed through separate policy processes and institutional structures, resulting in siloed decision-making that fails to capture the interactions between ecological processes, socio-economic dynamics, policy systems under the length of the mutual knowledge permeability. This fragmentation significantly hinders the effective integration of NbS as potential driver of interconnection across pluralistic knowledge systems in the fields of policy and decision-making [10].

The Public Procurement (PP) stands for a tool for encouraging nature-positive transition, by performing radical influences on markets dynamics, innovation trajectories and environmental targets achievement [11]. With this in mind, and with a view to encouraging the various stakeholders to play an active role in the transition to a greener economy, Directives at European level direct the Countries Members in integrating the sustainability measurement in public procurement mechanism toward the using of PP as strategical policy instrument oriented to contribute to broader goals.

On the basis of it, Green Public Procurement are proposed at internation level to substantiate the intent to mainstream the impact assessment on the environment giving attention to the minimization of waste production, lowering pollution emissions and

water quality standard. This is pursued referring to the life cycle of good and services, to integrate environmental considerations into procurement decisions process [12].

This document analyses the limitations of the current assessment of ecosystem services in the context of 'nature-positive' public procurement. The aim is to examine, from a theoretical perspective, the importance of integrating ecosystem service indicators into public decision-making to ensure sound governance practices (Sect. 2); with a view to supporting the transition from green public procurement to management approaches that have a positive impact on nature (Sect. 3), including through operational tools to be used to implement ecosystem service accounting during the procurement process. An urban regeneration initiative was examined as a case study demonstrating the attempt to incorporate the valuation of natural capital into the planning and regulatory framework relating to transformations in urban and peri-urban contexts Sect. 4).

2 Ecosystem Services Valuations in the Urban Governance

Ecosystem services refer to the goods and services that natural capital is capable of providing to people in the form of benefits that are beneficial to human health [13]. The significance of ecosystem services depends on the reference assessment context, as well as on the underlying structure of relationships between cross-sectorial fields [14]. Significant references in the scientific literature in this field associate ecosystem services with spatial planning and governance, treating them as drivers of sustainable land transformation [15]. Within this analytical framework, the aim is to guide land management and land-use policies with a view to ensuring, over time, the production and provision of pre-established service targets capable of fully meeting the demand for social well-being. To this end, a range of tools is being implemented to regulate the allocation of land-use designations in a manner compatible with the useful life of existing natural capital [16].

The application of ecosystem service assessment mechanisms within a policy and planning context results in a fragmented and complex picture. The study by Kremer et al. (2016) is noteworthy because it examines the disparity, particularly in an urban context, between decision-making processes and ecosystem service assessment mechanisms. This is mainly due to: *i*) difficulties in unambiguously defining the meaning of an ecosystem service that can be widely recognised by the scientific community in general in relation to the urban environment; *ii*) a lack of shared methods and standardised scientific databases to measure and analyse various types of data on the availability of ecosystem services in relation to different land-use types, depending on the intervention to be implemented; and *iii*) an inability to appreciate the benefits that natural resources provide over a short- to medium-term analytical timeframe [17].

It is useful to address the challenges associated with biodiversity conservation, sustainable land-use planning and natural resource management in order to create a green market, by drawing on frameworks at different scales. Some of these have been developed

with the aim of integrating the accounting of ecosystem services into the entire decision-making process. For example, the UN (2012) proposed the System of Environmental-Economic Accounting (SEEA) to guide public and private bodies in their decision-making when taking into account the provision of ecosystem services. To assist governments in creating and implementing coherent policies, the Policy Coherence for Sustainable Development Framework was established. Others, such as the Building System Carbon Framework (2020), aim to achieve net-zero emissions in the built environment. The Cooperation Framework (2022) defines the roles that the United Nations development system plays within a country and influences how the UN resources required both within and outside the country are organised (UN, 2022). Their differences stem from the different analytical frameworks used, rather than from the objectives they sought to achieve [18].

Nature-based Solutions (NbS) can simultaneously improve human well-being and biodiversity, but current frameworks are unable to account for this complexity. This highlights the potential drawbacks of applying the internationally published framework, even in the absence of a standardised operational strategy for environmentally responsible transformative change at multiple spatial scales [19]. The implementation of NbS at different levels of governance is influenced by land-use policies and practices, as well as by the regulations governing land conversion through the adoption of appropriate design measures. Among the tools that can influence the practical implementation of nature-positive investments in support of ecosystem services are codes of conduct for public procurement [20].

Public procurement acts as a channel for dialogue between territorial governance policies and the decision-making systems that regulate territorial transformation, based on the relationship between the public sector, the private sector and citizens. It serves as a tool for the exchange of knowledge between multi-value systems of an economic, social and environmental nature [21]. The system of interrelationships between multiple decision-making spheres is a distinctive feature of public procurement in relation to the instrument's purpose of regulating the flow of goods and services during the planning, design and implementation of territorial development actions [22].

Ecosystem services, as elements arising from the interaction between the human and natural systems, are in themselves potential drivers of ecological transition that should form the basis of public procurement. The latter may take the form of either green public procurement or public procurement that has a positive impact on the environment.

The first specifically concerns the design of new green spaces and/or the improvement of the existing ecosystem; the second, on the other hand, concerns the implementation of measures assessed on the basis of their potential impact on the environment [23].

How can public procurement become 'nature-positive' through greening initiatives? To what extent could ecosystem services be considered key factors in the evaluation of public procurement contracts? Are there any criteria and indicators that can be used as tools during the evaluation process and the monitoring phase?

To address the questions set out above, the following sections will provide a brief overview of green and nature-friendly public procurement as presented in the existing literature (Sect. 3). Subsequently, based on the analysis of a case study (Sect. 4), a suitable

framework will be outlined regarding the criteria and indicators to be used to support the evaluation of public procurement using an ecosystem-based approach (Sect. 5).

3 Green Public Procurement Nature-Positive

Green Public Procurement (GPP) is a regional policy tool promoted by European Union directives to restore ecosystems and support environmentally sound transitions. It is characterised by a focus on enhancing natural capital, with the aim of countering its excessive use for productive purposes [24]. Through the incorporation of new green elements or measures to protect ecosystems using nature-based solutions, green public procurement seeks to mitigate the environmental impact of productive activities in terms of pollutant emissions [25]. This significance of GPPs fits perfectly with the objectives on transition of the European Sustainable Finance strategy, namely low environmental impact purposes in compliance with the Do Not Significant Harm (DNSH) principle. Frequent references to GPPs refer to entrepreneurial initiatives in the production sectors, and few with reference to nature-based solutions aimed at restoring and defending existing ecosystems [26]. Especially in cases of industrial productivity, particular account is taken of the effects of production on the environment, focusing on the alteration of the climate balance by means of pollutants [27]. That is, within the context of GPPs, a single-value evaluation process is taken into account according to "input-output" logics between production factors and the outcome of production activities. The evaluation approach underlying GPPs is also reflected in the adoption of appropriate and coherent evaluation methods and tools, such as life cycle analysis, goal programming analysis techniques, and the use of minimum environmental criteria. LCA in particular is widely used in the context of GPPs in order to de-write the production process in the phases that distinguish it, and by associating the possible environmental impacts as well as the costs incurred with each [28–30] (Fig. 1).

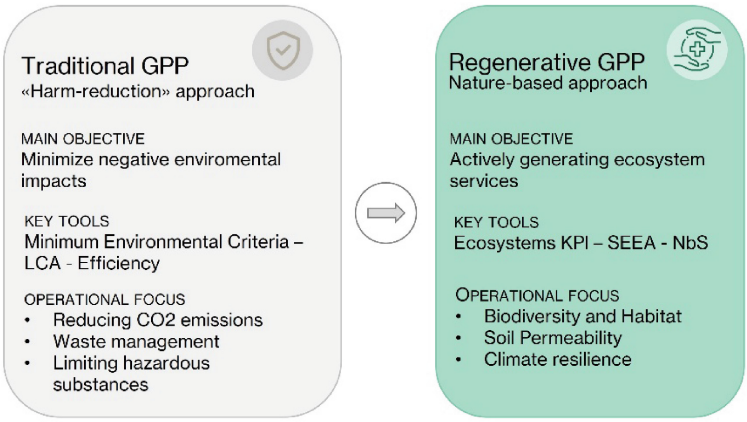

Fig. 1. From Traditional GPP to Nature-Positive GPP.

Although there is a focus on the life cycle of, for example, a production activity in the evaluation of GPP, it is limited to taking into account only air pollution-related disruptions. Extra-environmental aspects, which also are during the supply chain, are not considered. From an ecosystem perspective, this means that ecosystem services of regulation, support, supply, and culture are not judged equally and as elements to be brought in GPP evaluation processes. Therefore, a paradigm shift in GPPs is needed in the direction of nature-positive GPPs, that is, public procurement as a policy tool to aid the production of ecosystem services [31–33].

The scientific literature on ecosystem services and public procurement attempts to highlight the relational values that link economy, society, and the environment, according to the ES international classifications. These are attempts that explore their functional interdependencies, proposing evaluation metrics that are not standardized but dependent on the decision-making context of study. Productive performance variables, as well as environmental impact variables, often come into play, and metrics related to social aspects are unlikely to be found, except in cases where participatory practices are implemented. In the latter, in fact, information is often obtained, for example, on the potential likability of people for an element of existing natural capital, while also noting their willingness to pay for its protection [34]. As internationally recognized, several attempts have been developed to standardize the integration of ecosystem service values within the processes on which territorial development is based. Noteworthy among these is the United Nations (UN) System of Environmental-Economic Accounting (SEEA), which reevaluates the biophysical structure with economic appreciation. The bridge between ecosystem and economy occurs through monetization practices aimed at expressing the monetary significance of ecosystem services in relation to the characteristics of the production process. SEEA consists as an innovative regional policy instrument oriented towards nature-based solutions [35]. Through the accounting of ecosystem services, it serves as a useful strategic tool to guide development in an ecological and green direction towards the improvement of ecosystem conditions [36–39].

Despite the requirement to use minimum environmental criteria in public procurement, it is possible to detect a lack of a set of standard metrics that can be used in ecosystem-based GPPs. This is for reasons related to the difficulty of measuring certain intangible aspects of GPP, such as those related to sociability; the riskiness of pre-assessment practices without uncertain metrics; and the lack of immediate understanding of the relationship between GPP, economic development, financial convenience, and non-environmental impacts. In order to be able to make an initial contribution in the provision of standard metrics in the evaluation of GPPs from an ecosystemic perspective, i.e. taking into account ecosystem services, the aim is to provide empirical evidence of the possible metrics to be adopted in the case of nature-positive GPPs starting from the analysis and study of a demonstration case. The latter concern greening programme initiatives in Rome (Italy), in which case the municipality adopts multiple parameters to be used to evaluate the various public procurements with an ecosystem approach, as described in the following Sect. 4.

4 Putting into Practice Accounting for ES in GPP

In order to be able to take into account ecosystem services in green public procurement, it would be appropriate to have available standard metrics that can be used in the evaluation processes of public interest, especially those aimed at improving the greening footprint of the transformative context of interest. To this end, in order to provide an initial indication of which metrics could be used based on green public procurement evaluated from a nature-positive perspective, it is intended to start with the description and analysis of a pilot case, specifically the 100 Parks program in Rome, Italy. The approach to the issue of integrating the evaluation of ecosystem services in public procurement was chosen in light of the lack of standardization of the metrics to be considered during the analysis of project proposals. Hence the use of a bottom-up analytical approach starting from a case study. The study and content analysis of the case of interest were conducted by analysing the available public administration documentation that describes the characteristics of the initiative program and the requirements that projects must have at the submission stage.

In the following subsections, the demonstrative case (4.1) is outlined and the results of the content analysis are summarized (4.2).

4.1 Demonstration Case Description

The *100 Parks* Program of the City of Rome's municipal administration has as its primary objective the redevelopment of 100 urban and peri-urban green spaces, restoring their public use to the community. This program comprises a series of urban redevelopment initiatives to be implemented in the decade following 2024, the year in which the program's first 16 projects were funded. The initiatives involve urban parks as well as green spaces located in Rome's suburbs. Because green redevelopment encompasses the entire city, the *100 Parks* program encourages territorial development by building on existing natural capital and enhancing its characteristics. This also contributes to climate change mitigation, biodiversity restoration, and environmental justice, thereby avoiding socioeconomic disparities within a single urban area.

In 2024, the following 16 redevelopment projects were funded:

1. "Via Valsolda"
   The project involves the general redevelopment and creation of connections along the Aniene River and the open spaces, creating a new linear park serving the neighborhood's residents.
2. *Caio Sicinio Belluto Park*
   The goal is to enhance historical elements and strengthen ecological and physical connections between the various parts of the Aniene Reserve park and the Montesacro neighborhood.
3. "Via degli Alberini Park"
   The project involves the completion of slow-mobility paths and the creation of a path along the river.
4. *Madre Teresa di Calcutta Park*
   To improve the safe use of the park, the project includes the construction of a plaza with a multipurpose sports facility that will serve as a social hub.

5. *Green Area via M. Candia*
   The project involves the redevelopment of the existing area through the design of a children's play area.
6. "Parco degli Acquedotti"
   The project involves the redevelopment of the area, aiming to enhance the existing archaeological remains of considerable historical interest.
7. "Parco della Romanina"
   The project involves the creation of a cycle/pedestrian path connecting a large sports area and spaces for urban gardens.
8. "Giardino Pisino"
   The new garden project characterizes it as a space dedicated to children with play areas.
9. "Parco Tre Fontane"
   The project intends to enhance the park as a link between urban greenery and agricultural spaces, also strengthening the cycle/pedestrian network.
10. "Parco Cesare Pavese"
    The project involves the redevelopment of the vegetation, the system of paths, and the facilities.
11. "Parco dei Ravennati"
    The redevelopment project aims to preserve the characteristics of a historical-archaeological park and integrate them with the new needs of functional, equipped areas.
12. "Piazza Augusto Lorenzin"
    The project involves the redevelopment of the area to create rest areas.
13. "Villa Flora"
    The project's goal is to combine the enhancement of the historic garden with improved usability as a public park.
14. "Villa Veschi"
    The project aims to relocate the area within an ecological and environmental network.
15. "Parco della Cellulosa"
    The project involves the regeneration of the tree population, the restoration of the paths, and the installation of recreational facilities.
16. Lucchina Garden
    The project involves the redevelopment of the green area with new permeable paths, the creation of a playground, and a fitness area.

These are projects for the restoration of existing natural capital that involve the redevelopment of urban parks or even the reforestation of communication roads between parts of the same territorial context. This also aims to restore the ecological connection in the city over time by promoting the accessibility of the areas to residents and non-resident communities nearby. Through targeted actions, the creation of green infrastructure between distant urban areas is encouraged over time, thus implicitly promoting the development of intermediate areas within the green network.

4.2 Accounting Evidence of Ecosystem Services

La valutazione dei 16 progetti finanziati nel 2024 tiene conto di un approccio sistemico, ovvero sono tenuti in conto aspetti legati all'ambiente, ecologia, socialità ed economia. Nei GPP a base di ciascuna iniziativa sono assunti quali strumenti di valutazione delle proposte progettuali alcuni criteri afferenti rispettivamente alla sostenibilità ambientale, economica e sociale del progetto. Nello specifico, si tratta di criteri che possono trovare una loro collocazione semantica e finalistica nelle categorie sui servizi ecosistemici come proposte in ambito internazionale. The following Table 1 organizes the evaluation criteria derived from the analysis of the 16 projects proposed for the 100 Parks program, organized according to the four thematic categories of the classification proposed by *The Economics of Ecosystems and Biodiversity* (TEEB) on ecosystem services. The criteria are derived through a content analysis of the available documents relating to the 16 projects. The table shows the TEEB ecosystem services that are used as evaluation criteria for the 16 redevelopment projects. These criteria constitute a reference for implementing nature-positive GPPs with a view to promoting the ecological transition of urban agglomerations through the ES provision.

Table 1. Ecosystem Services Criteria for GPP nature-positive.

ES TEEB Categories	Ecosystem Services	ES Criteria
Provisioning	Food	
	Water	
	Raw materials	
	Genetic resources	
	Medicinal resources	
Regulating	Air quality regulation	●
	Climate regulation	●
	Moderation of extreme events	
	Regulation of water flows	●
	Waste treatment	
	Erosion prevention	
	Maintenance of soil fertility	
	Pollination	●
	Biological control	
Habitat	Maintenance of life cycles	
	Maintenance of genetic diversity	
Cultural	Aesthetic information	
	Opportunities for recreation and tourism	●
	Inspiration for culture, art and design	●
	Spiritual experience	
	Information for cognitive development	
	Existence, bequest values	

5 Conclusions

The ecological transition of a territory, such as consolidated urban agglomerations, requires the adoption of specific evaluation mechanisms aimed at promoting ecosystem-based territorial development. From this perspective, Green Public Procurement plays a central role in guiding the implementation of governance policies while respecting existing natural capital and the targets of the *New Restoration Law* and biodiversity conservation. The need to promote the restoration of existing natural capital requires evaluation metrics not strictly linked to the natural characteristics of ecosystems, but also to the ecosystem services they provide. Hence the search for appropriate evaluation criteria for green public procurement that reflect not only the biophysical conditions of natural assets, but also the benefits derived from them.

To contribute to this direction, an empirical content analysis of urban regeneration cases involving parks and green infrastructure in the city of Rome is conducted. The criteria derived from the documentary screening and compared with the ecosystem service categories proposed by the TEEB constitute evaluation tools to be used as the basis for green public procurement with an ecosystem services perspective.

To obtain results that can be generalized at the national scale, it is necessary to expand the set of case studies to include urban redevelopment initiatives for existing green areas. The next step in the research will consist of introducing appropriate biophysical-monetary accounting metrics corresponding to the evaluation criteria derived from the screening and comparison with the TEEB list of ecosystem services. This will be complemented by operational considerations on the use of appropriate multi-criteria evaluation tools useful in selecting and ranking the project alternatives gathered during the tender process.

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

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Post-Occupancy Evaluation of Reused Confiscated Assets: An Application in the Campania Region

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Abstract. Within public policies aimed at the reuse of the extensive real estate assets confiscated from organized crime, characterised by strong typological heterogeneity, the National Strategy for the Enhancement of Confiscated Assets through Cohesion Policies (2017) represents a relevant territorial development tool. Fundings are allocated to the renovation and adaptive reuse of properties for social and civil purposes, the strengthening of institutional capacity in confiscated assets management, and the promotion of legality and social inclusion. However, these interventions raise several evaluation issues. From an appraisal perspective, a key challenge concens the estimation of market-consistent rental values for publicly owned assets assigned to economic operators, given that such properties cannot be sold or mortgaged. Furthermore, in contexts characterized by high criminal intensity, contextual risk factors and negative externalities significantly affect real estate market performance. Despite numerous rehabilitation interventions, several confiscated assets, returned to the community, fail to meet local needs, sometimes becoming underutilized and resulting in a waste of public resources and, above all, important opportunities for territorial development. This inefficiency can potentially be overcome through more intense community involvement in decision-making processes, with the aim of identifying real problems and defining uses consistent with the needs of the territory. In this scenario, the paper explores the possibility of applying Post-Occupancy Evaluation (POE) as a support tool for public administrations, capable of helping both to define intervention priorities and to formulate improvement strategies. The application of the POE is proposed for a case study in the province of Caserta, in the Campania region (Italy).

Keywords: Post-Occupancy Evaluation (POE) · Confiscated Assets · Adaptive reuse

1 Introduction

Over the past few decades, European institutions have increasingly focused on the importance of developing effective legal and operational tools for the identification, seizure and subsequent confiscation of assets of illicit origin. Empirical studies show that assets

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 425–448, 2026.
https://doi.org/10.1007/978-3-032-30524-4_27

confiscated from organised crime constitute veritable investment portfolios, as demonstrated by the OCP (Organised Crime Portfolio) [1], which has enabled the mapping of the main investment sectors of the major criminal organisations active in Europe. The study found that the main countries affected by organised crime include Italy, Spain, Germany and the United Kingdom, with numerous sectors, assets and economic activities involved. In addition to the classic, now well-known illegal activities (tobacco, gambling, drug and arms trafficking, money laundering) and the relatively new ones (cybercrime, fraud, theft of medicines), the construction sector continues to be the most heavily involved in mafia activities, both due to its high labour intensity and the involvement of the public administration [2–3]. Within this sector, public works play a crucial role [4–7] particularly around public procurement [8, 9], where organised crime can exploit its capacity for corruption, intimidation and infiltration into the political and administrative spheres. In this sense, criminal investment in construction firms represents a more 'alarming' phenomenon than simple money laundering through restaurants or property, because it entails a more pervasive infiltration within the local political, economic and social community. The real estate sector – encompassing assets such as houses, villas, flats and other properties – is a prime area of investment for criminal groups, capable of generating high returns, as well as being well-suited to facilitating money laundering through the generation of seemingly legitimate income, such as rental payments. Furthermore, the ownership of such assets serves an operational and strategic function, as they can be used as logistical bases for illicit activities, storage facilities for illegal goods, or spaces facilitating the commission of further crimes [6]. For example, in Italy, real estate accounts for more than 50% of assets confiscated from organised crime over the last thirty years [10].

In southern Europe, they also contribute to the control of territory by international criminal organizations [10], strengthening their social and economic roots. Finally, the ownership of real estate, particularly high-value properties, also takes on symbolic and social status value, reflecting the power and prestige of criminal groups. In this scenario, the confiscation of assets is not only a repressive measure but also a fundamental tool for dismantling the economic foundations of organised crime and returning these resources to the community.

At European level, the regulatory framework governing the confiscation of assets has developed progressively through a range of instruments designed to strengthen harmonisation and cooperation between Member States, with the aim of making the financial fight against organised crime more effective. In this context, Directive 2014/42/EU [11] represented a fundamental step, outlining a comprehensive model for the asset recovery process, which includes the identification and tracing of illicit assets, their freezing or seizure, management aimed at preserving their value, confiscation and, finally, the transfer and reuse of assets, including for public or social purposes. On this basis, an evolving concept of confiscation has gradually gained ground, including at the international level, no longer limited to the purely punitive dimension, but understood as an instrument of restorative justice and social development. This approach is further reinforced by the recent Directive (EU) 2024/1260 [12], which introduces a more advanced regulatory framework, explicitly promoting the social reuse of confiscated assets and fostering greater integration among the institutional actors involved. However, despite significant

regulatory progress, substantial differences persist between Member States in terms of implementation: whilst some legal systems, such as Italy's, represent an advanced model of social reuse, others, such as Belgium and Germany, still have systems predominantly geared towards the liquidation of assets and their allocation to state budgets, although innovative local examples of reuse are emerging. Similarly, in France there has been a recent regulatory shift favouring the allocation of confiscated assets to public bodies and associations, marking a gradual transition from sale to social reuse. In this context, the effectiveness of European policies will depend largely on the Member States' ability to implement the new directive consistently, developing integrated models based on institutional cooperation, the efficient management of assets and their enhancement for the benefit of communities [13]. From this perspective, the public and social reuse of confiscated assets takes on a central role, as highlighted by the 2025 UNICRI report [14], which, in line with the principles set out in the United Nations Convention against Transnational Organised Crime and the United Nations Convention against Corruption, emphasises the value of reuse as a lever for inclusion, social cohesion and democratic strengthening.

Within this European context, Italy has a long-standing tradition of asset confiscation, which is regarded as a highly effective tool, particularly in the fight against organised crime [15], with a particularly advanced and comprehensive model based on a dual approach: on the one hand, there is a procedure based on a criminal conviction; on the other, there is a special procedure known as precautionary confiscation in the case of criminal organisations. This procedure was designed to tackle organised crime without being bound by traditional methods. The latter is particularly effective and is applied to individuals convicted of mafia-type offences, where the value of their assets is disproportionate to their legitimate income and they are unable to prove their lawful origin. This confiscation does not require a link between the asset in question and the specific offence but is based on an assessment of the danger the individual may pose to society and the disproportionate nature of their assets.

The Rognoni-La Torre Law of 1982 [16] was the first Italian legislative act aimed at combating the illegal activities and investments of organised crime, followed subsequently by the Anti-Mafia Code [17], which brings together and coordinates the body of legal provisions and instruments for the prevention and suppression of the mafia phenomenon. Of paramount importance in this context is the role played by the National Agency for the Management and Disposal of Assets Seized and Confiscated from Organised Crime (ANBSC), whose primary objective is to return assets confiscated from organised crime to the community. The Agency is a public body with organisational and accounting autonomy, subject to the supervision of the Ministry of the Interior and responsible for the integrated management of assets throughout the entire procedural process.

This process, implemented through public tenders, agreements with local authorities or entrustment to the third sector, is of strategic importance not only in terms of law enforcement, but also in symbolic and socio-economic terms, transforming illicitly accumulated assets into collective resources capable of promoting the rule of law, social cohesion and regional development. In particular, the management of confiscated businesses poses complex challenges in terms of maintaining production and safeguarding

employment, requiring targeted measures for revitalisation or conversion that preserve the economic and social value of the assets, whilst avoiding the risk of dispersing productive capital. When assets such as property, businesses, land or money are seized from mafias, clans or criminal organisations, it is the ANBSC that takes charge: it does not merely hold them in custody, but administers them, develops their potential and assigns them to public bodies or associations for social purposes. A confiscated asset can thus become a school, a cultural centre, an agricultural cooperative or a shelter, and this process is of immense value, transforming damage into redemption, and illegality into opportunity [18].

Analysing the objectives and actions set out in the ANBSC Strategic Programme means delving into the heart of the work of an institution that is one of the main tools for combating organised crime in Italy. It is not simply a matter of seizing an asset, but of restoring its dignity, function and value through a process involving the State, local institutions, associations and citizens. To achieve this aim, the Strategic Programme is structured around a series of priority actions: constant monitoring of the state, an efficient allocation procedure and the strengthening of collaboration between public and private entities. The ANBSC works to streamline the bureaucratic procedures leading to the final allocation of assets, seeking to prevent properties or businesses from remaining unused for too long due to administrative delays or legal difficulties [12, 19]. The national picture of confiscated assets, updated with data from the ANBSC's Single National Platform as of February 2025, shows a clear concentration in the South, where 73% of the total is located, compared with 15% in the North and 12% in the Centre. In total, there are 42,110 confiscated assets (property and businesses, both allocated and under management), with the highest number in Sicily (15,675 assets), followed by Campania (6,443) and Calabria (5,095); Lazio (3,853) and Lombardy (3,068) follow, confirming the now nationwide scale of this phenomenon, as can be seen in Fig. 1.

The reuse of assets confiscated from organised crime has effects that go beyond the purely financial dimension, significantly impacting the quality of the social fabric and the relationship between citizens and institutions. From this perspective, the conversion of properties, businesses and movable assets seized from mafia networks into spaces for public, social and productive purposes represents not only a form of collective redress, but also a concrete mechanism for territorial regeneration [20]. The impact of these processes is evident, on the one hand, in the creation of employment opportunities, the provision of services of general interest and the return of community spaces to local communities; on the other hand, in the creation of strong symbolic value, as places once associated with criminal power are transformed into bastions of legality and inclusion. In this sense, initiatives such as those developed in the Caserta area demonstrate how the development of confiscated assets can help to strengthen citizens' trust in institutions, highlighting the state's capacity not only to combat criminal activity but also to translate the outcomes of judicial action into tangible benefits for the community. Transparency in procedures, the involvement of local authorities, the third sector and civic networks, as well as the continuity of activities carried out in reused properties, are essential elements to ensure that reuse does not remain a mere formality, but becomes a sustainable process for generating public value, social cohesion and the consolidation of a culture of legality. Indeed, there is a growing spread of management entities at national level, with

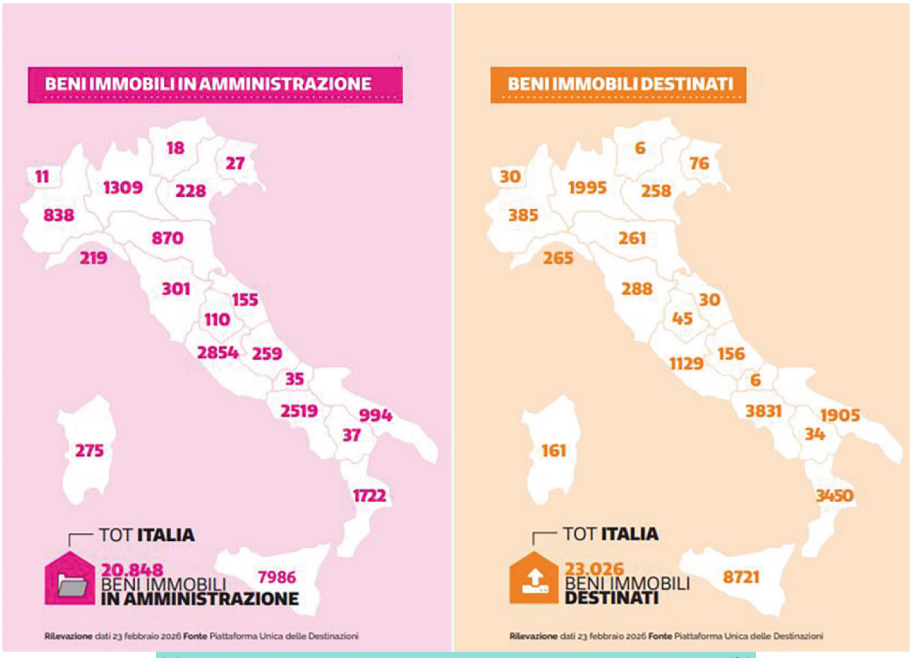


Fig. 1. Map of confiscated assets in Italian territory: on the left (a), real estate assets under Italian administration are shown; on the right (b), real estate assets confiscated and already destined for Italy are reported. Source: [13]

a particular concentration in the southern regions. The most recent data show that 384 management entities operate in Sicily, 205 in Campania, 193 in Lombardy and 154 in Calabria. In terms of type, assets allocated for social purposes consist mainly of residential units (39.8%), followed by villas and multi-unit buildings (17.3%), agricultural or building land (16%) and commercial or industrial premises (10.8%). These assets now serve as genuine social infrastructure, within which activities with a significant local impact are developed: 57.6% of organisations operate in the welfare and social policy sector, 23.2% in cultural, educational and tourism promotion, and 9% in the agriculture and environmental sustainability sectors. In this way, the reuse of confiscated assets is increasingly seen not merely as a restorative measure, but as a public policy capable of fostering processes of inclusion, social innovation and regional development [21].

In Campania, 55% of assets have already been allocated, whilst 45% are still under management: this figure appears more favourable for properties (59% allocated and 41% under management in the South) than for businesses, for which significantly lower allocation rates are recorded. The 6,443 confiscated assets in the Campania region are heavily concentrated in the province of Naples (3,534 assets, accounting for 55% of the total), followed by Caserta (1,841, 29%), Salerno (870, 13%), Avellino (126, 2%) and Benevento (72, 1%). The distribution at municipal level appears particularly widespread: 216 municipalities (39% of the total of 550) host at least one confiscated asset, with a

higher incidence in the provinces of Naples (70 out of 92 municipalities) and Caserta (60 out of 104), followed by Salerno (48 out of 158), Avellino (22 out of 118) and Benevento (16 out of 78) [22]. In Campania, the phenomenon of the confiscation and reuse of assets seized from organised crime is of particular significance, both due to the sheer scale of the operation and the strong symbolic value it conveys in the process of the community reclaiming the territory.

In this context, the reuse of confiscated assets stands out as one of the most effective tools for upholding the rule of law, capable of transforming illicit assets into resources for the public good. Civil society plays a decisive role, contributing both through the direct management of these assets and by promoting awareness-raising initiatives and lobbying institutions. Interaction between public and private social actors is often decisive for the success of reuse projects, as demonstrated by numerous local initiatives. Among these, the case of the Agrorinasce Consortium, active in the Caserta area, stands out as a well-established example of integrated governance of confiscated assets. The Agrorinasce Consortium, in collaboration with the ANBSC and the participating municipalities, publishes periodic analytical lists of confiscated assets in the area, which detail not only the structural characteristics of the properties but also their intended use and the current progress of the works. Over time, this mapping and monitoring work has enabled the conversion of properties previously linked to organised crime into spaces serving new social functions, including co-working spaces, community gardening centres and sports facilities [23]. A similar approach has also been adopted for assets earmarked for social housing initiatives and urban regeneration projects, in which the value of the properties is assessed not only in economic terms but also in relation to the impact generated on the local social fabric [24]. The body of empirical evidence analysed demonstrates that the Italian model for the management of confiscated assets goes beyond the mere seizure of illicit assets, constituting a system capable of promoting processes of conversion and reuse geared towards the public interest. From this perspective, confiscated assets are not merely the result of repressive action, but become active instruments of development, capable of generating social and economic value and contributing significantly to processes of territorial regeneration.

2 The Case Study: The Social Chocolate Shop “Dulcis in Fundo” in Casal Di Principe

In this scenario, the Province of Caserta is at the centre, an area particularly exposed to the presence of organised crime and, at the same time, an important laboratory for social reuse policies [25]. The criminal scenario in Campania is characterised by the presence of a multiplicity of Camorra groups, which show significant differences depending on their respective areas of influence. These include historically rooted Camorra organisations, alongside smaller, predominantly family-based criminal groups. According to Legambiente’s Ecomafia Report, in 2024 environmental crimes in Italy exceeded 40,000 cases (+14.4%), with an illicit turnover of over 9.3 billion euros. Campania is the region most affected by this phenomenon, followed by Puglia, Sicily and Calabria, which together represent a significant share of crimes. The most affected sectors are the construction and

waste sectors, while the role of environmental corruption as a link between illicit activities and organised crime is also increasing [3]. The provinces of Naples and Caserta remain the territories with the highest and most qualified mafia density, where large Camorra cartels and the most structured criminal groups are present. In these provinces, frequent cases of interference in public administration are found, aimed at influencing decision-making processes relating to public procurement, a sector of criminal interest. In the province of Caserta alone, approximately 25 municipalities (out of 104) have been dissolved due to proven infiltration by organised crime; many municipalities have been placed under special administration several times, demonstrating the deeply rooted nature of the phenomenon [26]. In 2024, the 240 anti-mafia seizures carried out in Campania, concentrated above all in the provinces of Naples and Caserta, highlight the growing capacity of Camorra organisations to adapt, increasingly oriented towards the diversification of their activities and infiltration into legal markets. The construction and real estate sectors appear to be the most exposed, followed by sectors such as waste management, environmental services, and other economic sectors, indicating an expansion of criminal strategies aimed at profit and territorial control.

In the province of Caserta, historically centred on the area of Casal di Principe, the mafia phenomenon takes on distinctive and deeply entrenched characteristics. Evidence gathered from asset seizures highlights the significant economic and financial clout of local criminal groups, which are active not only in traditional illicit trafficking but also in sophisticated forms of criminal enterprise. These organisations are in fact able to exercise monopolistic control over key segments of the legal economy, as well as to systematically infiltrate public procurement through corrupt and collusive practices, facilitated by well-established networks of relationships with institutional actors and businesspeople. The data reveal a large concentration of confiscated assets in the municipalities of the Agro Aversano and the Costa Domiziana, where municipalities such as Castel Volturno (206 assets), Trentola Ducenta (203), Santa Maria la Fossa (128) and Casal di Principe (124) record the highest numbers [10].

Similarly, the adoption of specific local regulations remains limited, indicating that governance remains fragmented and inconsistent. In this context, exemplary management practices take on particular significance, including those promoted by the Agrorinasce consortium [27], which has played a central role in the recovery and enhancement of numerous confiscated properties, facilitating their use for productive, social and social-healthcare purposes. The prevalence of productive uses, particularly in the agricultural sector, highlights how the reuse of assets can contribute not only to their symbolic return to the community but also to the creation of economic and employment opportunities. The municipality of Casal di Principe is one of the areas in the province of Caserta with the highest number of confiscated assets already allocated to public and social uses. The process leading to this result has developed progressively over time: starting in 1999, the year in which the first seven properties were allocated, there has been steady growth, with an average of around 3.6 properties allocated annually between 1999 and 2020 and a significant peak of 16 allocations in 2007. In recent years, partly thanks to the operational strengthening of the National Agency for Seized and Confiscated Assets (ANBSC), there has been a further increase in the number of assets allocated. Casal di Principe also stands out for several good administrative practices: it is one of the

few municipalities in the province to have published a complete and up-to-date list of confiscated assets within its territory and to have adopted specific regulations for their management. These regulations provide for various possible uses: institutional, social, for housing emergencies, and even economic and productive purposes, with the provision that any profits are reinvested in social activities or in the recovery of further assets not yet allocated [28]. In this context, the reuse of confiscated assets plays a central role in territorial regeneration strategies. A region seeking to free itself from the presence of organised crime and counter its potential reorganisation must necessarily invest in culture, education and civic participation. The distinctive feature of the initiative launched in Casal di Principe lies precisely in its ability to combine these objectives with the practical enhancement of confiscated assets, transforming them into tools for social development, inclusion and the promotion of legality. This context includes the case study of the social chocolate shop "Dulcis in Fundo" [29], located in the municipality of Casal di Principe, an area heavily affected by organised crime but now at the heart of significant social regeneration initiatives. The property in question was confiscated from a Camorra member, following a court order, representing a typical example of illicitly accumulated assets subsequently returned to the community. The process of revitalising the property began with its entrustment to Agrorinasce and its designation as the "Casa delle Associazioni", as part of a wider urban regeneration project funded by the Campania Region. Subsequently, in 2011, part of the property was allocated, via a public tender, to the Davar social cooperative, which launched a social enterprise project aimed at the employment inclusion of people with disabilities. After a period marked by bureaucratic delays, the facility became operational in 2016 with the opening of the social chocolate workshop "Dulcis in Fundo", also supported by co-funding from the Fondazione con il Sud.

The significance of this case study lies not only in the economic and productive aspects of the initiative, but above all in its symbolic and social value: an asset seized from a member of organised crime is transformed into a space for inclusion, training and civic participation. The chocolate shop provides a safe environment in which people with disabilities can acquire professional skills, develop independence and actively participate in the social and economic life of the local community. The experience of 'Dulcis in Fundo' demonstrates how the reuse of confiscated assets can contribute to the development of local development models based on legality, solidarity and social innovation. The conversion of a property that belonged to a member of organised crime into a place of social production and workplace inclusion represents a concrete example of 'restitution' to the community, capable of generating not only economic value but also cultural and symbolic value, thereby strengthening citizens' trust in institutions and the justice system. Thus, the proliferation of numerous examples of the reuse of confiscated assets in the Caserta area testifies to the value of such initiatives as tools for territorial development and social cohesion.

Although the formal allocation of assets does not necessarily equate to their full and effective use, there is a clear need to examine in greater depth the issue of how these assets are utilised for the benefit of the community, analysing their ability to meet local needs and generate lasting impacts [20]. It is essential to identify and adopt appropriate analytical approaches and evaluation tools capable of measuring the performance of

confiscated assets in a structured and comparable manner, in order to guide enhancement policies more effectively and improve management practices.

3 Methodology

It is well known that the mere allocation of confiscated assets and their return to the local community cannot guarantee their effective automatic valorization. Furthermore, in some cases, reassigned assets, despite being intended for public use, do not meet with the consensus of the community, especially when their new function does not address the real needs expressed by the local territory. When there is no alignment between need and intended use, or the actors managing the asset are not fully capable of fulfilling their role, the assets remain underutilized for long periods, losing the possibility of improving the territorial context and proving inefficient. Existing policies aimed at valorizing confiscated assets are, however, mainly focused on the "aesthetic" valorization of the asset, favoring public funding for building renovation interventions. This framework, mainly aimed at the physical rehabilitation of recovered assets, has at times relegated to a secondary role the definition of use functions, the involvement of local stakeholders, and the development of projects consistent with the actual needs of the territory. Experience has instead show that effective valorization requires the mobilization of territorial resources, the activation of participatory processes, and the involvement of specific expertises in the design of interventions with a strong social impact. When an asset returned to the community fails to meet users' expectations or needs, it risks falling back into conditions of disuse and abandonment, thereby becoming a waste of public resources and opportunities for territorial development. This highlights the need to strengthen both ex-ante analyses, aimed at intercepting real demand in the territorial area, and ex-post evaluations of the interventions implemented. Furthermore, the management of the recovered assets is never definitive, but rather subject to cyclical renewals regulated by the Anti-Mafia Code [17], upon request by the managing entity, which must be approved by the municipal administration following due verification. However, such assessments of project continuation are generally based on verifying the maintenance of the asset's intended social use and on anti-mafia checks - aimed at confirming the absence of criminal infiltration. The actual evaluation of the performance of recovered assets therefore remains excluded from these mandatory control processes, which, in any case, do not preclude conditions of underutilisation or inefficiency.

From this perspective, Post-Occupancy Evaluation (POE) represents a particularly effective tool, as it places the user at the centre of the assessment of an intervention or service; this is why the methodology has been widely debated, predominantly within academic contexts. It is generally described as a systematic process of collecting and analysing data relating to building performance following occupancy [30]. This process aims to assess such performance through the comparison between predefined performance criteria and the actual, current perceptions of direct or indirect users. In both architectural and managerial contexts, POE is regarded as a valuable learning tool - typically aimed at improving design and management quality - useful for both designers and those responsible for building management [31, 32]. The evolution of POE, from early assessments primarily focused on the technical aspects of building performance to the

integration of social, psychological, and managerial dimensions, reflects the dynamic and complex nature of the relationship between users and the built environment [33, 34]. It can therefore be understood as an interdisciplinary research methodology aimed at understanding and improving the interaction between buildings, technical performance, and human needs. In termini operativi, l'analisi preliminare dell'ambiente costruito implica il riconoscimento e l'identificazione sia delle criticità che degli aspetti positivi che caratterizzano il bene oggetto dell'analisi [35, 36].

From an operational point of view, the preliminary analysis of the built environment involves recognising and identifying both the critical issues and the positive aspects that characterise the asset under investigation [37, 38]. In this regard, the literature identifies several evaluation dimensions: technical and funcional, with particular attention to materials, construction techniques, and the structural and funcional elements of the building; and socio-behavioural, based on observation and user feedback [39, 40]. Similarly, evaluation may include varios equally important aspects for measuring building quality performance, focusing both on users' opinions regarding performance and on the purely technical characteristics of the building [41]. In recent decades, studies on the perception of the built environment have gained increasing relevance, highlighting the central role of user experience in assessing spatial quality. More recently, POE studies have assumed a new perspective and greater importance for designers, developers, and clients [42–44], also in relation to growing awareness and sensitivity towards environmental sustainability, building energy eficiency and user comfort [45]. Among its possible fields and scales of application, POE is also employed in the evaluation of the performance of public buildings [46–49] for assessing building quality.

During the management phase - which is assuming an increasingly important role in the building process – POE enables the monitoring of the durability of the built environment throughout its life cycle and supports the planning of maintenance interventions, structural upgrades, and energy efficiency improvements. These activities are particularly relevant in the case of public buildings or assets intended for collective use, which are designed to have a long duration. In this sense, POE can be configured as a highly useful operational tool for public administrations, capable of systematically supporting decision-making processes throughout the entire life cycle of the asset. Through the structured collection of data relating to user experience, POE makes it possible to identify functional, managerial and perceptual criticalities in public-use buildings, detecting both physical and structural dysfunctions and those related to spatial organisation-such as accessibility, usability, and the quality of services provided-thus enabling a more efficient allocation of public resources.

A further field of application concerns the adaptive reuse and the valorisation or rehabilitation of existing building. In this context, POE can help check the coherence between the actual physical-spatial characteristics of a property and its newly intended functions, reducing the risk of incompatibility between container and content, and increasing the probability of successful valorisation interventions [50]. It is therefore possible to provide for the application of the POE also in the context of confiscated assets, where it can assume a dual role. When applied ex ante, it allows for the establishment of priority criteria for resource allocation, integrating technical analyses with the real needs expressed by the local context. When applied ex post, it allows for the assessment of user satisfaction

and the measurement of the effectiveness of the recovered asset's intended use. Moreover, through continuous monitoring over time, it becomes possible to identify early signs ot underutilisation or disengagement, thereby anticipating processes of decline and supporting the adoption of corrective strategies, including service enhancement or functional reconfiguration aligned with the evolving needs of users.

Regardless of the field of application, the process of applying the Post-Occupancy Evaluation methodology follows a well-defined framework, which can be broadly summarized in the phases illustrated in Fig. 2. Each phase was explored individually in Sects. 4 and 5, through the practical example of implementing the POE to the case study.

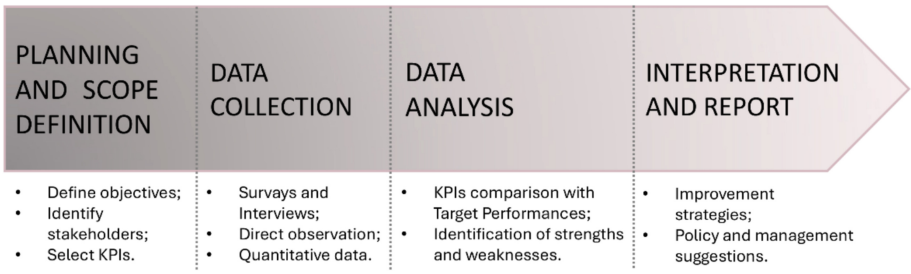


Fig. 2. Main phases of the Post-Occupancy Evaluation methodology. Source: author's elaboration.

4 Application of Post-Occupancy Evaluation to the Case Study

Starting from the assumption that this methodology can be employed as a tool capable of systematically collecting information on the performance of recovered assets, while at the same time being applicable to assets characterised by highly diverse uses, there emerges a need to make the evaluation process as objective, structured, and easily replicable as possible. Accordingly, this contribution - through the application of POE to the case study of the social chocolate shop "Dulcis in Fundo" - proposes the development of a set of standardised territorial indicators, organised into measurable dimensions, capable of integrating quantitative data with qualitative information derived from users' experience. The aim is to propose a clear operational model applicable across multiple cases, indipendently of the intended use of the recovered assets, thereby strengthening comparability between different experiences and supporting more informed decisions in terms of management, reuse, and valorisation.

Stage 1: Planning and Scope Definition. In the initial phase, the methodological framework was structured to ensure coherence between objectives, areas of analysis, and measurement tools, through a series of key steps:

– the primary objective of the POE application was identified as the evaluation of the overall performance of the confiscated asset, including its capacity to generate social, economic and territorial value within its reference context.
– The stakeholders to be involved in the evaluation process were identified, to simultaneously consider heterogeneous and complementary perspectives. In particular, the main actors included the asset manager, the employed workers and volunteers

involved in daily activities, partner associations and enterprises collaborating with the asset, as well as end users who benefit from the spaces and services provided.
– Three thematic areas were defined, corresponding to the main macro-domains of performance evaluation. For each area, specific aspects of analysis were identified, selected based on their ability to describe conditions of use, perceived quality and the effectiveness of asset management.
– These specific aspects were operationalised through the development of a set of Key Performance Indicators (KPI), designed according to criteria of objectivity, measurability and replicability. The aim was to define KPIs capable not only of supporting the analysis of the case study under consideration, but also of being applied in analogous contexts, thereby enabling comparisons and encouraging further applications of the methodology. The set of indicators is summarised in Fig. 3.

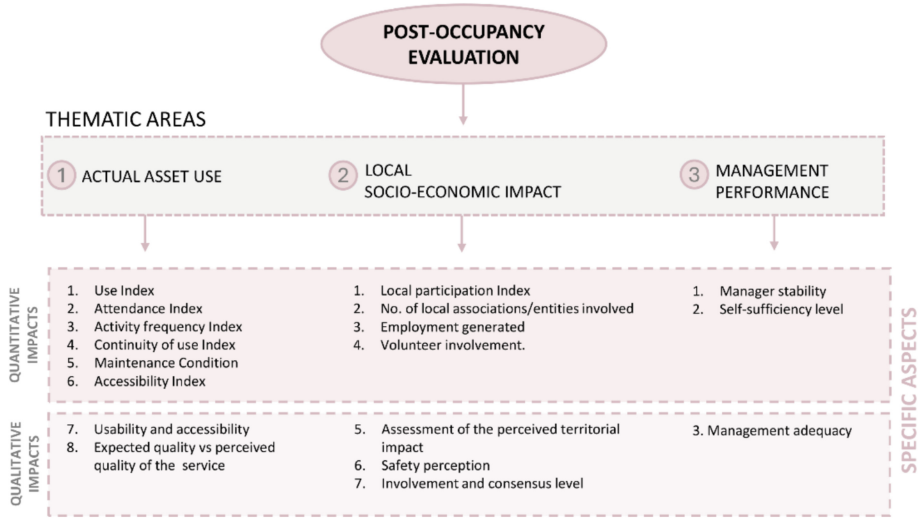


Fig. 3. Chart of the Thematic Areas and Specific Aspects of the Performance Evaluation of a Confiscated Asset. Source: author's elaboration.

Stage 2: Data Collection. This activity represents a crucial step in the overall POE application process, as it is aimed at constructing as robust and comprehensive an information base as possible. At this phase, the operational methods are defined to capture, in an integrated way, both the objective performance of the asset - and those related to its managementand the perceptions and expectations of its users. With reference to the specific case study, quantitative data were collected through direct on-site monitoring activities, aimed at observing both the implementation of activities within the asset and the state of conservation and maintenance of the building. These observations were complemented by quantitative data provided by the asset manager, which contributed to completing the information framework with managerial and operational elements. The quantitative data were collected through interviews with direct and indirect users of the asset and subsequently synthesised in the tables presented in Figs. 4, 5 and 6.

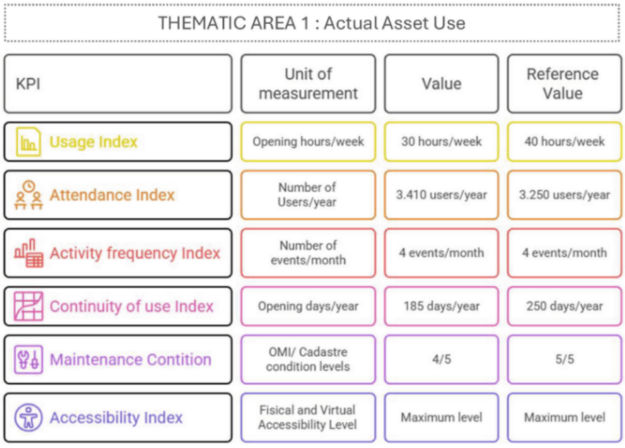


Fig. 4. Representative figure of the comparison between the current values – relating to the asset under examination – and the reference values, in relation to the specific aspects (quantitative impacts) of Thematic Area 1: Effective Use of Resources. Source: author's elaboration.

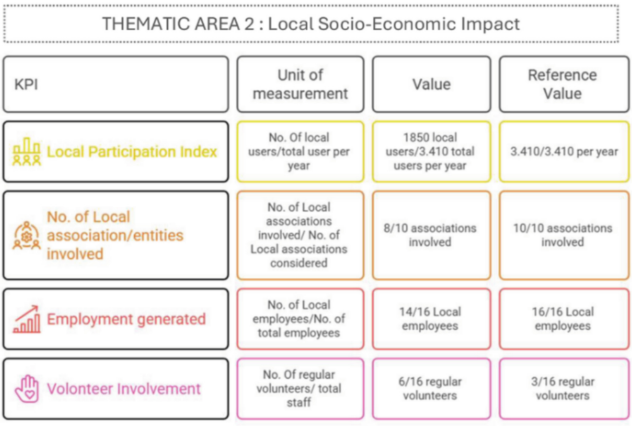


Fig. 5. Representative figure of the comparison between the current values – relating to the asset under examination – and the reference values, in relation to the specific aspects (quantitative impacts) of Thematic Area 2: Local Socio-Economic Impact. Source: author's elaboration.

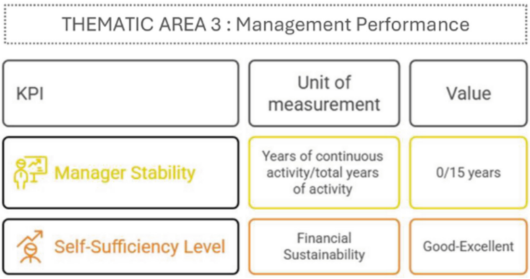


Fig. 6. Representative figure of the comparison between the current values – relating to the asset under examination – and the reference values, in relation to the specific aspects (quantitative impacts) of Thematic Area 3: Management Performance. Source: author's elaboration.

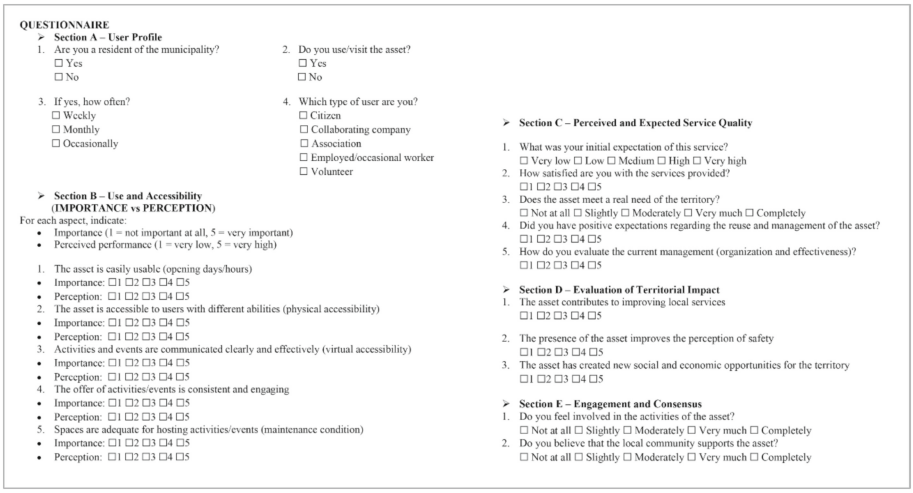
The reference values were established as follows:

- Usage Index: the reference value of 40 h/week was set in accordance with the maximum standard weekly working hours in Italy, as defined by Legislative Decree No. 66 of 8 April 2003, Art. 3 [50].
- Attendance Index: the reference value for the number of users per year was calculated as 15% of the total resident population (21,298 inhabitants). A maximum fluctuation up to 21,500 individuals was considered, also including non-residents who frequent the municipality during daytime hours. This reflects an average level of community engagement in local activities.
- Activity Frequency Index: similarly, the reference value for the number of events per month was established to reflect a moderate level in the quantity of activities offered.
- Continuity of Use Index: the reference value of 250 days/year was based on the standard number of working days in a calendar year in Italy.
- Maintenance Condition: the reference value for maintenance status is based on the official classification of building maintenance conditions in Italy. Based on the OMI Database Manual:

  Maintenance States: 1 = poor/to be refurbished; 2 = fair; 3 = moderate; 4 = good; 5 = excellent.
- Accessibility Index: the reference value for accessibility was defined according to three predefined levels, combining the requirements set out in Presidential Decree No. 503/1996 [51] for the removal of architectural barriers in public spaces, buildings and transport, with the degree of virtual accessibility, depending on the adequacy of communication and promotion of activities. The levels are defined as follows: L1 = Maximum Level (full physical and virtual accessibility; L2 = Medium Level (full accessibility either physical or virtual); L3 = Low Level (no full arcessibility).
- Volunteer Involvement: the reference value of three volunteers was also calculated as a proportion of the total resident population.

In parallel, a qualitative survey was developed, based on the direct user experience. A structured, closed-ended questionnaire was designed to collect subjective evaluations regarding expected and perceived quality, as well as the impacts of the asset within its territorial context. All indicators relating to the specific aspects of the analysis were included in the questionnaire. The questionnaire, presented in Fig. 7, was administered

to the previously identified stakeholders, who expressed their views both through the completion of paper forms on site and via the digital platform Google Forms, thereby ensuring greater accessibility and participation in the data collection process.



QUESTIONNAIRE

➢ **Section A – User Profile**

1. Are you a resident of the municipality?
   ☐ Yes
   ☐ No
2. Do you use/visit the asset?
   ☐ Yes
   ☐ No
3. If yes, how often?
   ☐ Weekly
   ☐ Monthly
   ☐ Occasionally
4. Which type of user are you?
   ☐ Citizen
   ☐ Collaborating company
   ☐ Association
   ☐ Employed/occasional worker
   ☐ Volunteer

➢ **Section B – Use and Accessibility (IMPORTANCE vs PERCEPTION)**

For each aspect, indicate:
- Importance (1 = not important at all, 5 = very important)
- Perceived performance (1 = very low, 5 = very high)

1. The asset is easily usable (opening days/hours)
- Importance: ☐1 ☐2 ☐3 ☐4 ☐5
- Perception: ☐1 ☐2 ☐3 ☐4 ☐5

2. The asset is accessible to users with different abilities (physical accessibility)
- Importance: ☐1 ☐2 ☐3 ☐4 ☐5
- Perception: ☐1 ☐2 ☐3 ☐4 ☐5

3. Activities and events are communicated clearly and effectively (virtual accessibility)
- Importance: ☐1 ☐2 ☐3 ☐4 ☐5
- Perception: ☐1 ☐2 ☐3 ☐4 ☐5

4. The offer of activities/events is consistent and engaging
- Importance: ☐1 ☐2 ☐3 ☐4 ☐5
- Perception: ☐1 ☐2 ☐3 ☐4 ☐5

5. Spaces are adequate for hosting activities/events (maintenance condition)
- Importance: ☐1 ☐2 ☐3 ☐4 ☐5
- Perception: ☐1 ☐2 ☐3 ☐4 ☐5

➢ **Section C – Perceived and Expected Service Quality**

1. What was your initial expectation of this service?
   ☐ Very low ☐ Low ☐ Medium ☐ High ☐ Very high
2. How satisfied are you with the services provided?
   ☐1 ☐2 ☐3 ☐4 ☐5
3. Does the asset meet a real need of the territory?
   ☐ Not at all ☐ Slightly ☐ Moderately ☐ Very much ☐ Completely
4. Did you have positive expectations regarding the reuse and management of the asset?
   ☐1 ☐2 ☐3 ☐4 ☐5
5. How do you evaluate the current management (organization and effectiveness)?
   ☐1 ☐2 ☐3 ☐4 ☐5

➢ **Section D – Evaluation of Territorial Impact**

1. The asset contributes to improving local services
   ☐1 ☐2 ☐3 ☐4 ☐5
2. The presence of the asset improves the perception of safety
   ☐1 ☐2 ☐3 ☐4 ☐5
3. The asset has created new social and economic opportunities for the territory
   ☐1 ☐2 ☐3 ☐4 ☐5

➢ **Section E – Engagement and Consensus**

1. Do you feel involved in the activities of the asset?
   ☐ Not at all ☐ Slightly ☐ Moderately ☐ Very much ☐ Completely
2. Do you believe that the local community supports the asset?
   ☐ Not at all ☐ Slightly ☐ Moderately ☐ Very much ☐ Completely

Fig. 7. Structured, closed-ended questionnaire for collecting qualitative data. Source: author's elaboration.

5 Results

It should be noted that the POE methodology does not constitute a static and definitive evaluation; rather, it fosters a cyclical process of learning and continuous improvement. Therefore, the results presented in this section should be considered reliable at the present phase, as they reflect performance at the time of application.

Stage 3: Data Analysis. The information collected during the Data Collection phase was analysed and processed in this step of the process. Regarding the analysis of quantitative impacts - based on the assessment of specific aspects that can be objectively measured - the comparison between the previously defined reference values and those observed for the asset under examination produced the results summarised in Fig. 8.

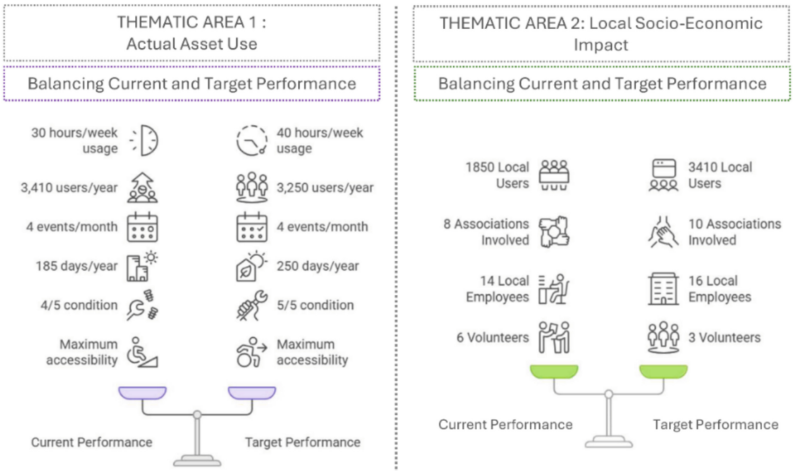


Fig. 8. Synthetic graphical representation comparing the established reference values (Target Performance) with the values detected for the asset under examination (Current Performance), with reference to Thematic Area 1 and Thematic Area 2. Source: author's elaboration.

The balanced representation visually highlights the deviations between current performance and reference benchmarks. For Thematic Area 1, relating to the "Actual Use of the Asset", a general misalignment emerges between its current and potential use, particularly with respect to weekly hours and annual opening days. However, it should be noted that the activity operates throughout the year, except for the summer months (June, July, and August). Given that the facility is a chocolate workshop and considering the high summer temperatures typical of this area of the country, the manager's decision to limit its temporal use is understandable to preserve product quality. Other indicators within this thematic area are aligned with the established standards-such as the number of monthly events and maintenance condition-or exceed performance targets, as in the case of the annual number of users and the level of physical and virtual accessibility, suggesting a strong capacity to attract users despite limited temporal availability. As regards Thematic Area 2, which concerns the "Local Socio-Economic Impact", the comparative analysis reveals a more complex situation. On the one hand, a significant gap is observed between the number of local users involved annually - primarily those who work, collaborate, or provide regular voluntary service and the total number of annual users. This suggests the need to strengthen territorial embeddedness and to develop innovative strategies for engaging local communities. On the other hand, the number of volunteers involved appears highly positive, representing a distinctive feature of a management model grounded in strong civic participation. This significant level of voluntary engagement, combined with the stability of the managing entity - whose activity has continued uninterrupted for fifteen years - and a solid degree of economic self-sufficiency, outlines a framework of excellent qualitative performance.

About the analysis of qualitative impacts - based on the evaluation of specific aspects related to user perception and the comparison between expected and perceived quality for each aspect - the results are presented in Figs. 9, 10, 11, 12 and 13.

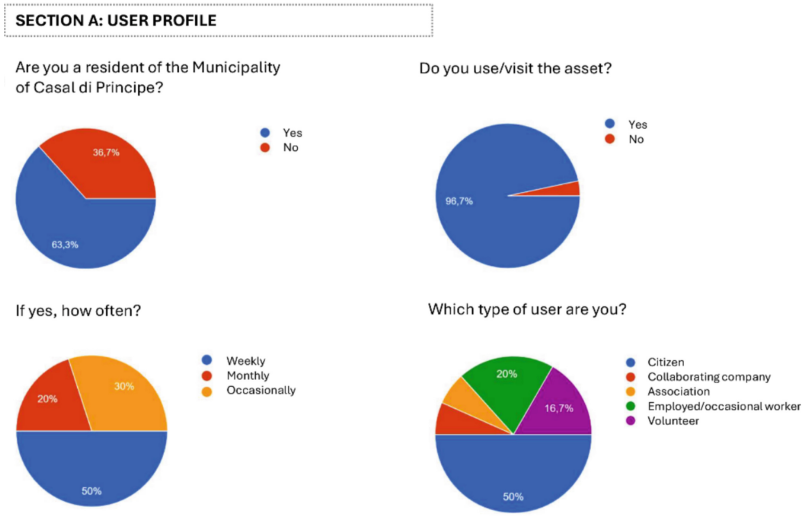


Fig. 9. Graphical representation of the questionnaire results compared to Section A: User profile. Source: author's elaboration.

Most of the users involved in the interviews were individuals who currently attend or have previously attended the social chocolate workshop, as respondents were required to express judgements primarily based on direct experience of the service and the asset. The stakeholders involved in the survey, depending on their user category, engage with the asset in different ways and were therefore able to provide diverse and complementary perspectives on its use and perception. Below in the Figs. 10, 11 and 12 are the graphically processed survey results, as required by the Stage 4: Interpretation and Report.

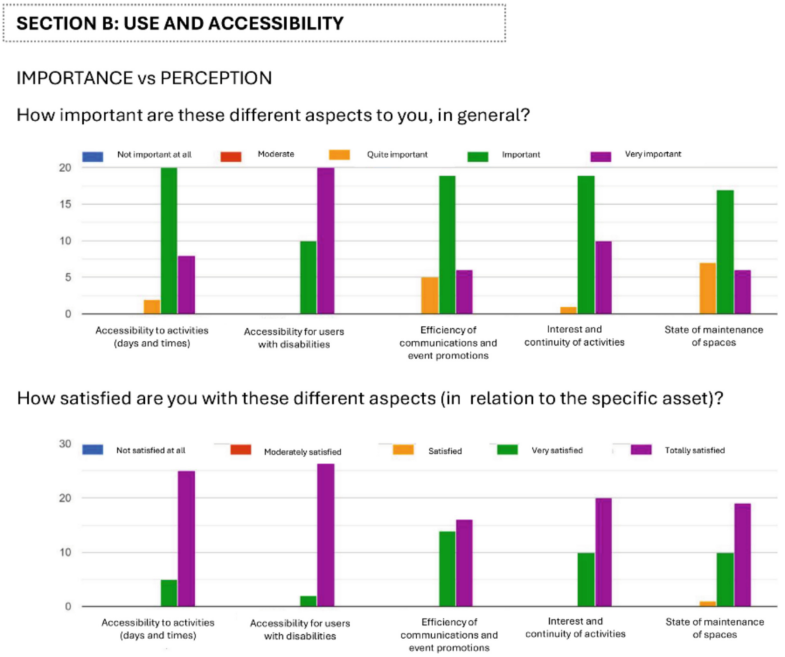


Fig. 10. Graphical representation of the questionnaire results compared to Section B: Use and Accessibility. Source: author's elaboration.

In the Section B of the questionnaire, users were asked to provide a combined assessment. For each specific aspect, they assigned a score from 1 to 5 both in terms of its importance at a general level, irrespective of the specific case and in terms of their level of satisfaction derived from its use in relation to the asset under consideration. Overall, the graphs indicate a positive outcome, with no significant gaps between expected and perceived quality across the performance dimensions considered. Users' expectations are either met or fully satisfied by the actual performance of the asset. Particularly noteworthy is the comparison between expected and perceived quality in relation to accessibility for users with diverse abilities, which highlights the exceptional inclusiveness of both the service and the use of the asset.



Fig. 11. Graphical representation of the questionnaire results compared to Section C: Percived and expected service quality. Source: author's elaboration.

The findings of the Section C of the questionnaire reveal an excellent level of user satisfaction regarding the services provided and the quality of asset management. The overall valuation of the asset, depending on the services offered, exceeds users' expectations. The presence of the good in the area is perceived as an added value, with a positive impact that far exceeds expectations.

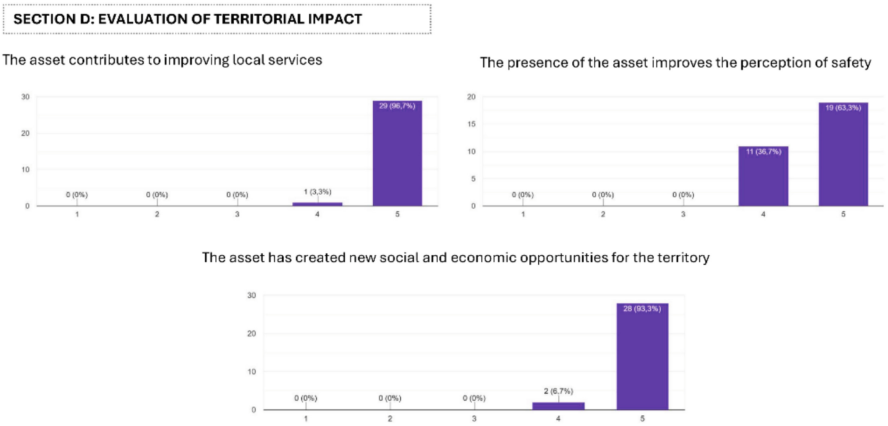


Fig. 12. Graphical representation of the questionnaire results compared to Section D: Evaluation of territorial impact. Source: author's elaboration.

Similarly, Section D of the questionnaire produces positive results. The territorial impact of the asset is excellently assessed, especially in relation to its ability to generate employment, social, and economic opportunities, especially given the complex and precarious socioeconomic balance of the area.

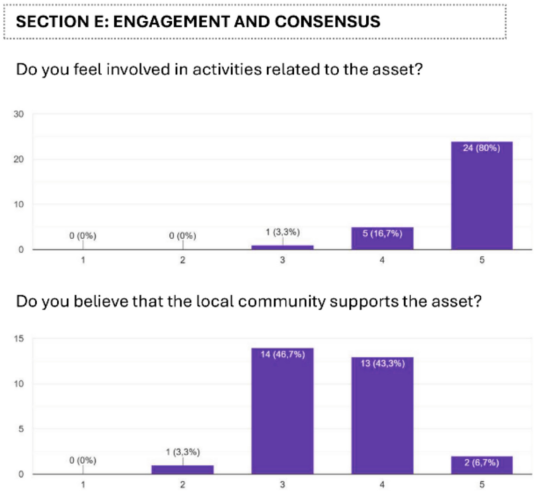


Fig. 13. Graphical representation of the questionnaire results compared to Section E: Engagement and Consensus. Source: author's elaboration.

The results of Section E of the questionnaire are more fragmented, especially compared to the analysis of the level of local community consensus. Direct users, who therefore know the asset and assiduously frequent it, by actively participating in the proposed activities, have obviously developed a strong sense of belonging to this project of inclusiveness and solidarity. Neverthenless, the level of consensus among the broader local community is less positive, suggesting a lower involvement predisposition and participation in the proposed activities. However, it is important to consider, once again, the complexity of the social context, in which organised crime continues to generate a shadow and influence the residents'lives, particularly older residents.

6 Conclusions

The study highlights how the reuse of confiscated assets in the Caserta area represents an area of intervention with high socio-economic potential, capable of generating positive effects in terms of local development, social inclusion and the strengthening of a culture of legality. The repurposing and return of confiscated assets to the community, as well as being a valuable tool for territorial management, creates opportunities, strengthens the sense of community and contributes to a development process that puts people at the centre [52]. The case study of the social chocolate shop 'Dulcis in Fundo', situated in a socially complex context such as the municipality of Casal di Principe, confirms how

the conversion of an asset seized from organised crime can result in a virtuous cycle, capable of generating economic, social and symbolic value for the local area.

The findings in this case highlight an excellent alignment between the asset's formal designated use and its actual utilisation, likely due to the significant social impact on the local area and the high level of user engagement with the service. However, it was only through an assessment of the actual impacts – and thus following the asset's real-world use – that it was possible to determine the effectiveness of the designated use. The research therefore highlights that designation alone is not sufficient to guarantee adequate performance; rather, a paradigm shift is required that places the assessment of actual use and the impacts generated at the centre, which translates into the necessary monitoring of assets over time. The application of the Post-Occupancy Evaluation (POE) methodology to the case study demonstrated the validity of an integrated approach, capable of combining quantitative indicators and users' qualitative perceptions.

On the one hand, there has been excellent performance in terms of service quality and management, as well as the site's accessibility and appeal. However, on the other hand, there are some critical issues, particularly regarding the site's roots in the local area and the broader involvement of the local community. In this regard, one of the main operational recommendations that has emerged concerns the need to strengthen engagement strategies, including through the active involvement of partner associations and local networks, to broaden participation and consolidate the bond between the site and the community.

In terms of methodology, the POE proves to be an effective and flexible tool for the evaluation of confiscated assets. The proposed set of KPIs can be adapted to different contexts and to assets with diverse intended uses, enabling not only the measurement of managerial efficiency and effectiveness, but also supporting more informed decision-making processes. In particular, the possibility of applying this model in an ex-post phase allows for the assessment of the assets' performance, including in view of the renewal of concessions, facilitating corrective measures or potential repurposing initiatives. Furthermore, the comparability between different cases paves the way for prioritising public interventions, which is particularly relevant in contexts characterised by limited resources.

The proposed methodology does, however, have certain limitations, mainly linked to the subjective nature of qualitative assessments, which may be influenced by individual interpretations of desire/need and by variations in perception. Nevertheless, this limitation can be mitigated by integrating quantitative data and by expanding the survey sample, to obtain statistically more robust results.

In conclusion, the research suggests that the methodology should be extended to other similar case studies, to build a broader and more consolidated empirical basis. Comparing different experiences of reuse would make it possible to identify recurring patterns, strengths and systemic weaknesses, as well as to promote the most effective practices as replicable models. In this sense, Post-Occupancy Evaluation can help transform the assessment of confiscated assets from an episodic and descriptive practice into a structured and continuous process, geared towards improving performance and ensuring the long-term sustainability of enhancement policies.

Acknowledgments. The authors would like to thank the social chocolate shop "Dulcis in Fundo" for its availability, as well as all the users involved, who offered their time and made their valuable contributions during the interviews.

Attributions. The authors jointly conceived and contributed to the contribution. Conceptualization: Y.R., D.M., F.F. Data curation: Y.R. Investigation: Y.R., D.M. Validation: Y.R., D.M., F.F. Methodology: Y.R. Supervision: F.F. Writing—original draft, Y.R., D.M., F.F. Writing—review and editing: Y.R., D.M., F.F. All authors have read and agreed to the published version of the manuscript.

Disclosure of Interests. The authors declare no conflict of interest.

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An Integrated Methodological Framework for Urban Well-Being Assessment: An Application to the City of Siracusa (Italy)

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Abstract. In recent years, the concept of urban well-being and quality of life has emerged as a central theme for the planning agenda. Orienting urban planning toward enhancing urban well-being, while properly considering its complexity stemming from its multi-dimensional nature, calls for appropriate knowledge bases and assessment tools to support decisions on actions toward urban livability. Based on these premises, the paper proposes an integrated methodological framework for urban well-being assessment, which leads to the definition of an Urban Well-Being (UWB) composite indicator. The proposed framework integrates a "quantitative" and "data-based" approach with a "qualitative" and "perception-based" one, thus overcoming the mere data-based approach to the theme and providing a comprehensive assessment of well-being and its distribution mechanisms within an urban area. The framework's preliminary application to Syracuse - a mid-sized city in the Sicily Region (Italy) – demonstrates its potential as a decision support tool, together with its limits and future research challenges to effectively orient urban policies towards greater equity, awareness, and quality of life.

Keywords: Methodological framework · Urban · Well-being · Assessment · Planning

1 Introduction

In recent years, the concept of urban well-being and quality of life has emerged as a central theme for the planning agenda [1, 2]. The growing attention towards the livability of urban spaces reflects the awareness that the progress of a city cannot be merely measured in terms of economic or physical development but must consider the overall well-being of resident citizens [3, 4]. From this perspective, the quality of urban life emerges as a complex theme, influenced by the interweaving of different dimensions: accessibility to services and daily opportunities, environmental conditions, safety and health, infrastructural facilities, social cohesion, and the equity in the distribution of rights and opportunities [5]. The COVID-19 pandemic has amplified the debate on the importance of living in healthy, well-served, and human-scale urban environments [6].

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 449–466, 2026.
https://doi.org/10.1007/978-3-032-30524-4_28

Therefore, the academic and planning debate has paid growing attention to metrics and tools to support the integrated assessment of urban well-being [7]. Resting on the recognition of the inadequacy of traditional economic indicators (i.e., the GDP) in capturing the multi-dimensional nature of well-being [3], different institutional initiatives have dealt with alternative approaches for urban well-being assessment. In Italy, initiatives such as the BES (Equitable and Sustainable Well-being) [8, 9] or the annual rankings of provinces, based on their quality of life, reflect the need to meet the demand for assessment tools and indicators to measure urban well-being [10]. These assessment tools, properly considering the multi-dimensional nature of urban well-being and the specificities of different urban environments, can offer a valuable contribution to the design of policy oriented to urban livability.

Based on these premises, the paper aims to provide an integrated methodological framework to assess well-being at the urban level, thus providing a robust knowledge ground to support "catered" urban planning decisions geared towards promoting justice and livability in cities. Specifically, by integrating an objective, data-driven component with a subject, perception-based one, the proposed assessment framework not only enables a multi-dimensional assessment of the distribution of well-being at the urban scale, but also provides some hints about the experiential dimension of access to services.

The paper moves from providing an overview of the theoretical planning models geared toward triggering urban quality of life and well-being, together with their critical issues in Sect. 2. Starting from a systematic literature review process about urban well-being assessment, Sect. 3 proposes an integrated methodological framework for the definition of an urban well-being composite indicator. Section 4 presents the application of the proposed framework to a case study - the city of Syracuse in the Sicily Region (Italy) – and its results in terms of distribution of urban well-being.

In Sect. 5, these results are assumed as the basis to discuss the opportunities, limits, and future research efforts related to implementing and spreading the proposed methodological framework as a decision-support tool for social equity in urban planning.

2 Urban Well-Being: Conceptual and Planning Foundations

The concept of well-being has accompanied human reflection since ancient times and, over the centuries, has progressively transformed from a philosophical ideal to a multidimensional construct used in social sciences and public policies [11]. In classical philosophies, two main orientations are distinguished: a hedonistic vision of "good living", centred on pleasure and the reduction of pain, and a eudaimonic vision, which interprets happiness as personal fulfilment and virtuous life. With modern utilitarianism, this concept also assumes a collective dimension: the idea of maximizing happiness for the greatest number of people introduces a criterion of social evaluation that anticipates, in embryonic form, future aggregate measures of well-being [3].

In the twentieth century, and in the post-war period, the concept was further consolidated and entered institutional definitions. A decisive step, in this sense, is the definition of health adopted by the World Health Organization in 1946, which identifies it in the state of complete physical, mental, and social well-being, rather than in the simple absence of disease [12]. This definition shifts the focus towards a positive and integrated

conception of living conditions, highlighting that "being well" depends on the intertwining of bodily, psychological, and relational dimensions. In recent decades, research has further expanded this framework, placing increasing attention on subjective well-being. Psychological and economic studies have shown that increasing income, beyond a certain threshold, does not automatically translate into an increase in declared happiness [13], thus stimulating new investigations on life satisfaction and the quality of daily experience. Positive psychology, which developed in the early 2000s, has strengthened this orientation, shifting the focus to factors such as resilience, optimism, and personal fulfilment [11]. However, the interdisciplinary expansion of the concept has brought along the difficulty of defining it unequivocally: well-being is recognized as a multidimensional concept, but, consequently, each discipline has proposed different readings and metrics for it [11].

Coming to the urban dimension of well-being, the growth of urbanization in the 20th and 21st centuries has made it increasingly clear that cities are not only places of opportunity, but also environments that produce pressures and vulnerabilities: high density, traffic, pollution, noise, lack of space, socio-spatial imbalances, and unequal access to resources. Since the 1970s, studies in environmental psychology and urban planning have analysed the impact of the built environment on the quality of life, showing how housing overcrowding and poor availability of green space can increase stress and reduce life satisfaction. On the contrary, pedestrian areas, public green spaces, and spatial opportunities for social interaction are recognized as generating positive relationships and psychophysical health [14]. Such a recognition paves the way for an integrated approach to the challenge of promoting urban well-being, which acts both on the physical dimension of cities (i.e., by improving air quality, accessibility to services, safety, mobility) and on residents' perception sphere (i.e., by strengthening their perception of safety, sense of community, attachment to places) [1].

By embracing this perspective, urban well-being can be understood as the city's ability to offer healthy, safe, stimulating, and inclusive living conditions, considering both physical morphologies and social processes that affect residents' life patterns. Consequently, urban well-being can only stem from striking a balance between environmental, social, and economic factors, while facilitating citizens' participation and sense of belonging.

The recognition of the link between urban space and well-being has led the planning debate to develop theoretical reference models to be implemented towards more liveable, inclusive, and just cities. Among these, three paradigms emerge as particularly relevant: the "15-min city", the "City of needs", and the "Just City" (see Table 1). While proposing different accents, they converge on the idea that urban planning must assume well-being and spatial justice as explicit objectives.

The "15-min city", promoted by Carlos Moreno, proposes a polycentric and proximity reorganization, in which most of the daily functions are accessible on foot or by bicycle in a short time [10]. Given its dual attention to individual well-being and collective welfare, this model is at the center of the international urban planning debate on the future of metropolitan areas [15].

According to it, travel time is not only a functional objective, but a lever of quality of life: it reduces stress, gives back time, strengthens local sociality, and reduces dependence on the car, with environmental benefits. The model is based on some recurring design dimensions: adequate density, short distance, functional and social diversity, and the integration of services and technologies that reduce the need for travel. From this perspective, proximity becomes a resource of well-being if it is pursued with attention to equity between neighbourhoods. However, its implementation requires addressing different challenges: it requires integrated planning, investments in soft mobility, and a cultural change in lifestyle habits.

The paradigm of the "City of needs", instead, has emerged in the academic and political debate as a critical counterpoint to the neoliberal city oriented towards markets and consumption. Several scholars have focused on the need to ground planning decisions on the real needs of the inhabitants, especially the weakest social groups [16]. The starting point for this model implementation is identifying fundamental needs: living with dignity, working with stability, accessing essential services, living in healthy neighbourhoods equipped with spaces for social interaction, and feeling safe and recognized. The model calls for planning to become an instrument of care and rebalancing, especially in territories affected by precariousness and marginality. Mapping social and territorial needs, thus, becomes an operational precondition for targeted interventions: understanding where health facilities, schools, public transport, and civic spaces are lacking; recognizing housing conditions and unexpressed needs; activating participatory processes to offer context-specific planning responses. In this sense, well-being is not read as an abstract urban metric, but as the city's ability to reduce discomfort and inequalities, promoting empowerment and cohesion.

The "Just City", theorized by the American political scientist and urban planner Susan S. Fainstein in her book "The Just City" (2010), proposes a normative-evaluative framework that makes the main objective of planning [5]. From this perspective, a city can be said to be "just" if it pursues equitable outcomes in the distribution of resources and opportunities, ensures democratic decision-making processes, and recognizes diversity as an urban value. Three principles constitute the normative core of the "Just City": equity, democracy, and diversity. Equity indicates a more equitable distribution of resources, services, and benefits of urban life among all social groups. Democracy is intended as the possibility for citizens to control their living environment. Finally, a "Just City" encourages and maintains urban diversity, understood both as socio-economic and ethnic mixing in neighbourhoods, and as a variety of uses and urban environments. However, these principles are not always convergent: a participatory process can produce localistic and unequitable outcomes, while diversity policies can trigger dynamics of exclusion or social replacement. For this reason, equity assumes a priority role, since well-being should not be evaluated as an average, but also in terms of distribution, by carefully recognizing who benefits from urban advantages, who remains excluded, and the contribution of spaces to reproducing or mitigating inequalities.

The resulting challenge for architects, urban planners, and policymakers, stemming from the willingness to implement these three paradigms in urban planning, lies in translating these principles into effective and integrated actions able to consider and properly balance the multiple interests and objectives at stake.

Table 1. Comparison of three urban models addressing well-being and spatial justice (Authors' elaboration)

Model	View of well-being	Planning logic
15-min city	Proximity to daily services	Polycentric and adaptive, focused on proximity
City of needs	Improving living conditions for disadvantages groups	Inclusive and participatory, centered on urban fragilities
Just city	Fair distribution of resources and social inclusion	Normative, oriented toward substantively just outcomes

Addressing this challenge requires building up solid knowledge bases, enabling the capture of the complexity of urban well-being, thus calling for the definition of integrated and context-sensitive assessment tools.

3 Assessing Urban Well-Being: An Integrated Methodological Framework

3.1 Investigating Evaluation Approaches to Urban Well-Being: A Systematic Literature Review

The willingness to orient planning efforts toward promoting well-being and quality of life in urban areas by recognizing its multi-dimensional and complex nature calls for a sound knowledge base and appropriate methodological support to build it.

From this perspective, the paper proposes an integrated methodological framework to assess well-being at the urban scale, while focusing on its distribution mechanisms across different areas.

Building up such an integrated methodological framework requires analysing the landscape of existing scientific literature on urban well-being assessment. To this aim, the framework construction rests on a systematic literature review, conducted through the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol [17]. The choice to adopt this protocol meets the need to ensure traceability and transparency in the literature review process, avoiding subjective biases in the selection of scientific sources.

The application of the PRISMA protocol required, as the initial phase, the identification of the preliminary set of scientific sources to be reviewed. The bibliographic research was carried out by keywords on the Scopus scientific database and the Google Scholar search engine. The keywords string used is: "urban well-being" OR "urban well being" OR "urban wellbeing" AND "assessment" OR "evaluation" OR "index" AND "Quality of life" OR "Life quality" on Scopus; "urban well-being", "index", "quality of life" on Google Scholar. This preliminary step led to the identification of 82 sources as potentially relevant. It should be noted that, in this phase, no rigid limit was placed on publication time to include both recent research and seminal studies in the field.

However, most of the articles identified have been published in the last fifteen years, revealing a growing recent interest in the urban well-being theme.

Of the 82 articles, 4 were duplicates and were eliminated. The remaining 78 were subjected to a screening phase, based on reading the title and abstract. During this phase, 63 articles were excluded, as they not directly address the topic of urban well-being assessment. Indeed, many of the excluded papers focus on "specific" topics such as the presence of urban green, environmental sustainability of buildings, improvement of the living conditions for elderly people, or on general theoretical approaches, without proposing an operational framework for measuring urban well-being.

At the end of the screening phase, 15 articles were selected and subjected to a subsequent phase of suitability assessment based on their full-text reading. In this phase, 5 articles were excluded for three main reasons: impossibility of accessing the full-text; significant methodological overlap with other studies already included; lack of an in-depth discussion about an assessment framework.

The final corpus, consisting of 10 papers, therefore, represents the set of the most relevant scientific contributions for the research purposes. These papers were analysed to understand: their methodological ground for the assessment task, the reference metrics or dimensions for the evaluation, and their fields of application (see Table 2).

The comparative analysis of the selected studies, despite their differences in terms of case study location and methodological approach, returns some recurring reference dimensions for the assessment of urban well-being:

- The environmental dimension is considered in almost all studies, both in terms of environmental physical quality (pollution, green spaces, environmental services), and as ecological sustainability measured through indicators of resource consumption and emissions [20, 27].
- Health and safety are further cornerstones, often accompanied by measures related to access to health services and personal protection [27].
- A central role is played by the socio-economic dimension, with indicators relating to income, employment, and material living conditions [23].
- Housing conditions, transport opportunities, and accessibility to urban services also recur as relevant dimensions, together with relational and community aspects, such as civic participation, social cohesion, and interpersonal trust [20]. Several studies also include the cultural dimension and leisure, revealing a broad interpretation of the urban well-being concept [26].

From a methodological point of view, a convergence towards structured multidimensional approaches is observed, often inspired by consolidated frameworks such as the Better Life Index [9], and towards the use of composite indices to synthesize the different dimensions [21]. Integration of objective indicators and subjective measures of satisfaction is also widespread, recognizing that urban well-being cannot be captured solely through measurable data nor only through individual perceptions [18, 27].

Overall, the analyzed corpus of literature confirms the multidimensional nature of urban well-being and the need for assessment tools capable of combining methodological solidity, comparability, and attention to the specificities of the addressed urban environment.

Table 2. Relevant studies addressing urban well-being assessment (Authors' elaboration)

Authors (Year)	Ref	Methodological ground	Relevant metrics/dimensions
Das (2008)	[18]	Survey-based empirical study; objective + subjective QOL; factor analysis; reliability test (Cronobach's alpha)	27 objective variables (physical, economic, social conditions); Subjective satisfaction on same domains (Likert 5); overall QOL question (pre/post)
Schleicher (2021)	[19]	Mixed methods; participatory adaptation of OECD Better Life Index (BLI); Workshop (qualitative coding) + citizen survey; descriptivist stats + regression	12 priority dimensions (income, jobs, housing, infrastructure, safety, culture, education, environment, health, civic participation, community, subjective satisfaction)
Stern & Kissinger (2025)	[20]	Comparative multi perspective framework ("three-legs"); secondary quantitative data; rankings + standardisation (0–100); domain averages	3 thematic dimensions: (i) conventional (income, education, health, etc.); (ii) integrated (social/cultural/environmental + SDGs/BLI/CIW-type domains); (iii) socio-environmental (strong sustainability)
Sarra & Nissi (2020)	[21]	Spatial composite indicator; BES-based dataset; geographically weighted PCA + DEA-BoD for endogenous weights; index normalised	11 well-being dimensions + 64 indicators (UR-BES): human + ecosystem well-being (health, education, environment quality, work, safety, social relations, leisure, landscape heritage)
Hadj Kilani (2022)	[22]	Critical review of selected studies (secondary review); comparison of quantitative, qualitative, and mixed approaches	Recurring dimensions across reviewed papers: urban environment (physical + social), services, perceived safety, traffic/transport, cultural opportunities
Vuković, Koriugina, & Nekhorosheva (2022)	[23]	Comparative review of international city well-being rankings; indicator mapping across ranking systems	8 global rankings; indicators grouped into six well-being spheres; most frequent: environment and work; housing and health moderately frequent; leisure and finance less frequent

(*continued*)

Table 2. (*continued*)

Authors (Year)	Ref	Methodological ground	Relevant metrics/dimensions
Dobrowolska & Kopczewska (2024)	[24]	GIS-based fine-scale index; Objective assessability / amenities approach aligned with "15-min city"; weighted scoring + normalization	QOLI based on 8 categories (shopping, dining, education, healthcare, sport, transport, nature, other)
Tiran (2016)	[25]	Survey-based subjective QOL; SEM (MIMIC) + hierarchical multiple regression; model fit indices	Residential satisfaction (home, neighbourhood, city) + overall QOL as latent variable; general life satisfaction/happiness; domains affecting satisfaction include economic well-being, family life, social relations
Ferentz et al. (2020)	[26]	Composite sustainability indicator integrating QOL, well-being and happiness; multi-instrument survey; arithmetic aggregation	SDI Curitiba = mean of three tools: WHOQOL-BREF (4 domains), UWI (45 urban variables), GNH (9 domains); Likert 5
Ghaffari, Pirttikangas, & Gilman. (2025)	[27]	Review paper; taxonomy of indicators, methods and data sources	Multidimensional determinants (health, environment, economy, social factors, services)

3.2 An Integrated Methodological Framework for Urban Well-Being Assessment

The comparative analysis of the literature highlights a convergence towards multidimensional approaches to urban well-being assessment. Together with it, the analysis reveals the opportunity to integrate data-based measures of physical quality of the built environment with subjective dimensions related to residents' perception [26]. Based on this evidence, the research proposes a methodological framework (see Fig. 1) to assess urban well-being by integrating the two emerging approaches: a "quantitative" and "data-based" approach and the "qualitative" and "perception-based" approach. Such a framework allows for overcoming a merely data-driven approach to urban well-being and is consistent with the underlying rationale of the urban capability approach, as it complements the assessment of service availability with residents' perception, which reflects their effective opportunities to access and benefit from existing services [28, 29].

Concerning the "quantitative" and "data-based" approach, the integrated methodological framework provides a spatialized Urban Well-Being (UWB) composite indicator by adapting the methodology proposed from the QOLI (Quality Of Life Index) assessment in the city of Warsaw [24]. The choice of this methodology lies in its structural

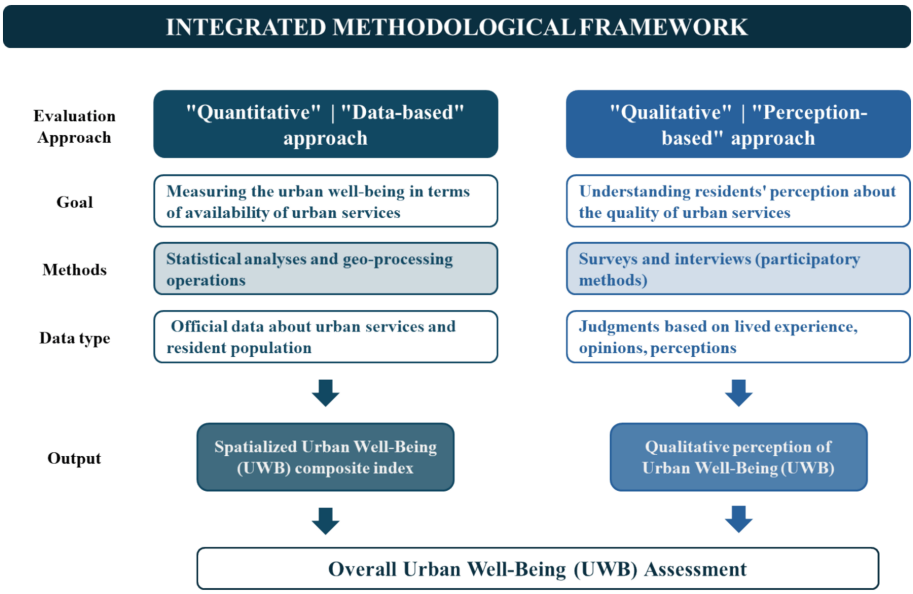

Fig. 1. Methodological framework for the assessment of urban well-being at the urban scale (Authors' elaboration)

clarity, replicability, and consistency with the logic of urban proximity. The "qualitative" and "perception-based" approach, instead, rests on a direct survey methodology [18, 26].

By integrating the two approaches, the proposed framework may provide a broader reading of the urban well-being phenomenon, which captures both the structural conditions of the urban environment and how they are experienced by inhabitants.

Turning to the implementation of the methodology for the "quantitative" assessment, the UWB indicator is assessed at a sub-municipal level, by considering, as an elementary spatial unit for the evaluation, a square cell of 1 km square, since it allows dividing the built environment into "spatial units" consistent with the logic of the 15-min city. The UWB assessment considers the urban services/amenities present in each cell, and those located in the 8 adjacent cells (first-order neighbourhood) by introducing a spatial weighting mechanism that attenuates the border effects [24].

More in detail, following Dobrowolska & Kopczewska (2024) [24], seven categories of urban services/amenities have been defined, as the most relevant for urban well-being: Restaurant, Transport, Health, Education, Sport, Shopping, and Nature. Within these categories, the different typologies of amenities are differently weighted based on their contribution to the quality of life of the resident population: greater weight is given to basic services, satisfying primary needs, while advanced or additional services are given a lower weight. To this aim, the amenities/urban services, within each category, are classified into a hierarchy of sub-levels of importance - primary, secondary, tertiary, and additional - reflecting the priority of the different types of services based on their relevance and frequency of use by the population. For each category, thus, the specific UWB sub-index is defined as the sum of the single contribution of the four levels of

services (Eq. 1):

$$icat = icat, \text{prim} + icat, \text{sec} + icat, \text{third} + icat, \text{add} \tag{1}$$

The index *icat*, prim captures the contribution of primary services to urban well-being for the specific spatial unit, and is defined as follows (Eq. 2):

$$icat, \text{prim} = \left[\frac{n(cell)cat, \text{prim} + Wnb \bullet n(nb)cat, \text{prim}}{Q3cat, \text{prim}} \bullet S_{\text{prim}} \right] \tag{2}$$

where:

- $n(cell)cat$, prim is the *per capita* number of primary services located within the cell;
- $n(nb)cat$, prim is the *per capita* number of primary services available in the 8 neighbouring cells;
- *Wnb* is the proximity weight of neighbouring services, accounting for their reduced accessibility compared to services located within the cell: it is placed equal to 0.5;
- $Q3cat$, prim is the third quartile of the distribution of per capita primary services across the urban area, used as a normalizing factor[1];
- $S_{\text{prim}} = 9$ is a scaling factor used to rescale the index to the desired range (0–9).

The index *icat*, sec captures the contribution of secondary services to urban well-being. It is computed using a binary approach with distance penalty: for each service category, only one amenity is considered. Based on this assumption, the index is defined as follows (Eq. 3):

$$icat, \text{sec} = \begin{cases} 0.3 if there is at least one secondary service within the cell \\ 0.15 if there is a secondary service in at least one neighbour.cell \\ 0 in the other cases (no secondary services) \end{cases} \tag{3}$$

The tertiary level index *icat*, third, considers the presence of two type of tertiary services for category and, like the second level index, is defined as (Eq. 4):

$$icat, \text{third} = \begin{cases} 0.4 if both services are represent within the cell \\ 0.3 if both services are in the neighbour.cells and one is in the cell \\ 0.2 if both services are represent within the neighbour.cells \\ 0.1 if only one service is in the nieghbour.cells \\ 0 in the other cases (no tertiary services) \end{cases} \tag{4}$$

Finally, the additional services index *icat*, add captures the variety of additional services, while imposing an upper bound (0.3) to prevent diversification from compensating for the absence of essential services. Its calculation is based on the following equation (Eq. 5):

$$icat, \text{add} = \min\{Wadd \bullet n(cell)cat, \text{add} + Wnb \bullet W\text{add} \bullet n(nb)cat, \text{add}; W\text{add}, max\} \tag{5}$$

[1] The third quartile was selected as the normalization factor to provide a robust and relevant benchamark. Unlike other standardization procedures (min-max standardization), which can be strongly influenced by extreme values or outliers, Q3 represents a high but representative level of service provision within the urban context.

where:

- $n(cell)cat$, add is the number of distinct types of additional services available within the cell;
- $n(nb)cat$, add is the number of distinct types of additional services available in neighboring cells;
- Wadd is the base weight assigned to each type of additional service within the cell (set to 0.1);
- Wadd is the proximity weight applied to additional services located in neighboring cells (set to 0.5);
- Wadd, max is the maximum cap imposed on the additive component (0.3).

The UWB sub-index, defined for each category and given by the sum of the four components (Eq. 1), thus, can range between 0 and 10. The Overall UWB index, defined at the cell spatial unit, can be derived as simple arithmetic mean of the 7 categorical sub-indices (Eq. 6):

$$UWBcell = \frac{iedu + ihealth + irest + ishop + isport + itrans + inat}{7} \tag{6}$$

This composite UWB index, also ranging between 0 and 10, provides a synthetic measure of the level of urban livability of each area. It should be noted that, as an average, the UWB index attenuates the extreme values of the individual categories: for example, a cell with higher service provision in some categories but deficiencies in others will obtain a balanced average score. The UWB index, therefore, must be read together with the categorical sub-indices: if the former offers a general and comparative overview across different urban areas, the latter allows identifying in which specific aspects an area excels or is deficient.

Given the proposed framework design, this "quantitative" assessment is integrated with a "perception-based" assessment component, defined through a questionnaire administered to residents. The questionnaire is structured in accordance with the 7 service categories of the UBW quantitative index and requires respondents to rate the quality of each service category on a 0–10 scale. This choice allows direct comparability between objective scores and individual perceptions.

By so doing, the proposed approach combines objective metrics of accessibility and availability of services with subjective assessments expressed by citizens. The comparison between the two levels makes it possible to identify any convergences or misalignments between "measured" and "perceived" well-being, strengthening the interpretative robustness of the analysis and providing operational support for planning decisions oriented towards the fair and sustainable improvement of urban livability.

4 Application Prospects: Insights from the Case Study of Siracusa (Italy)

4.1 Introduction to the Case Study

The desire to test the opportunities of the proposed methodological framework in assessing urban well-being and guiding planning choices calls for its application to a case study, identified in the city of Syracuse.

Syracuse is a city of about 120,000 inhabitants and extends over a municipal territory of over 200 km^2. It is in the south-east of Sicily, in Southern Italy, and it is a city with a rich historical heritage, from the Neapolis archaeological park to the historic center of the island of Ortigia, flanked by modern neighbourhoods and less dense peripheral areas. It belongs to the realm of medium-sized Italian cities, and its territorial variety offers a significant testing ground for the UWB methodology, allowing to assess urban well-being through indicators of accessibility to services both in consolidated central areas and in marginal areas. More in detail, the city of Siracusa is approached to test its distance from the theoretical models of the "15-min city", the "Just City", and the "City of Needs" [5, 10, 16]: based on the UWB index assessment, indeed, it is possible to understand the provision and distribution of urban well-being across different areas. Indeed, if an urban area perfectly adhered to the 15-min model, each cell would record high and similar UWB values. Applying the index to Syracuse, thus, allows for verifying the presence of imbalances in well-being distribution, while identifying "deficient areas" to orient planning actions.

4.2 The Proposed Methodological Framework Implementation

The implementation of the framework in the case of Syracuse first required the construction of a geo-database consistent with the spatial structure proposed for the UWB index assessment. The geo-referenced information about the different typologies of urban services included in the assessment was retrieved from Open Street Map (OMS), an open-source map service, which allows replicability of the model to other territories, up-scaling, and continuous updating.

Data were processed through the QGIS software. In an initial phase, urban services were filtered according to the 7 categories of the UWB (restaurants, transport, health, education, sport, shopping, nature), defining correspondence rules between OSM tags and the hierarchical structure of the index (primary, secondary, tertiary, and additional levels). At the same time, Istat demographic data were integrated to express the number of services in *per capita* terms.

The entire municipal territory was divided into a regular grid of 1 km by 1 km cells, generated in GIS and projected in the UTM WGS84 system (EPSG:32633). Through join and spatial intersection operations, each cell was associated with: the number of services per category and level; the resident population; and the services present in the 8 adjacent cells, to consider proximity and possibility to access services beyond the geometric boundary of the single unit [24].

Once the territorial database was structured, the category sub-indices were calculated by applying the formulas presented in Sect. 3.2, combining the *per capita* number of primary services, the presence of secondary and tertiary level services, and the additional contribution. The 7 sub-indices were finally aggregated using a simple arithmetic mean (Eq. 6) to obtain the overall value of the UWB index for each cell [24]. The process has made it possible to translate raw geospatial data into comparable synthetic indicators, making it possible to analyse the territorial patterns of urban quality of life in the case study.

4.3 Results

The analysis of the UWB Index for the municipality of Syracuse highlights a marked center-periphery gradient, with significantly higher values in the central urban areas and progressively lower values moving away from the urban core.

UWB per cell values vary from a maximum of about 9 (on a scale of 0–10), located in the heart of the urban area, such as Ortigia and Neapolis, to values close to zero in sparsely served low-density rural areas. The average UWB value is approximately 2.2, with a standard deviation of 2.4, reflecting a strong imbalance between a few very advantaged areas and a large part of the territory with deficient endowments. However, this average value is influenced by the inclusion of numerous marginal, agricultural or almost uninhabited cells, devoid of urban services, which lower the overall value without necessarily representing conditions of urban distress. However, the main emerging result is the already mentioned uneven distribution of urban well-being. Specifically, the north-eastern quadrant, coinciding with the compact coastal city, has better living conditions than the western inland hinterland, characterized by scattered settlements and predominantly agricultural functions. Peripheral localities, such as Cassibile (15 km south from the center) and Belvedere (8 km north-west), suffer from less accessibility to services, having to depend largely on the major center.

The "quantitative" results (see Fig. 2) can be explained by the heterogeneous urban morphology of Syracuse. Ortigia and the surrounding historical fabric play a leading role, concentrating cultural, commercial, and administrative functions, as well as consolidated public services. Semi-central neighbourhoods (Grotta Santa, Akradina, Santa Lucia, Neapolis) benefit from the proximity to the center, showing medium-high conditions. Conversely, peripheral districts developed through recent expansions or as detached villages display weaker urban well-being conditions. Epipoli represents an emblematic case: a predominantly residential area lacking structured local centralities and proximity services. Overall, this results in a polarized urban structure: a strong multifunctional center, a semi-central belt with a medium availability of services, and an outer ring characterized by low accessibility.

In addition to the "quantitative" evaluation, the "perception-based" assessment, based on a questionnaire to the residents, returned 54 responses. Consequently, as a first application, the analysis focused on the three neighbourhoods with the largest numbers of responses - Akradina (10), Neapolis (9), and Scala Greca (8) - thus ensuring a minimum, albeit limited, basis for comparison between the "quantitative" UWB index and its subjective counterpart (see Fig. 3) (Table 3).

The comparison between the two indices reveals a weak correlation between the "data-based" measure of urban well-being and the "perception-based" measure. In some cases, a certain level of coherence can be observed: for example, the lack of green spaces detected in Akradina and Scala Greca corresponds to moderately low levels of residents' satisfaction. In other cases, significant deviations emerge. The case of transport services is particularly evident: despite high "quantitative" scores, residents express lower satisfaction, suggesting that the mere presence of infrastructure does not automatically guarantee a positive perception, as factors such as frequency, reliability, and quality of experience have a decisive impact. Different is the case of local commercial

Table 3. Sample responses on subjective satisfaction by service category for the neighbourhood of Akradina (Authors' elaboration)

Respondent	Neighbourhood	Healthcare services	Education	Sport facilities	Shops and services	Nature	Public transport	Catering services
A	Akradina	2	6	6	8	5	4	6
B	Akradina	6	6	6	7	3	1	3
C	Akradina	4	4	4	6	2	1	1
D	Akradina	10	10	10	6	3	4	4
E	Akradina	6	6	7	7	5	2	6
F	Akradina	5	7	5	7	3	4	7
G	Akradina	5	7	5	7	3	4	7
H	Akradina	7	5	4	5	3	7	5
I	Akradina	7	5	6	7	5	5	5
L	Akradina	5	5	4	7	8	5	8

services: although these services' density is low in some areas, satisfaction remains on average sufficient, likely due to behavioural adaptations and reliance on nearby districts.

Overall, the comparison between the two dimensions confirms that urban well-being cannot be interpreted exclusively through quantitative indicators. Experiential aspects, individual expectations, and daily practices influence the perception of well-being. The integration between objective data and subjective evaluations is therefore fundamental for a more complete reading and for guiding planning interventions aimed at reducing territorial imbalances.

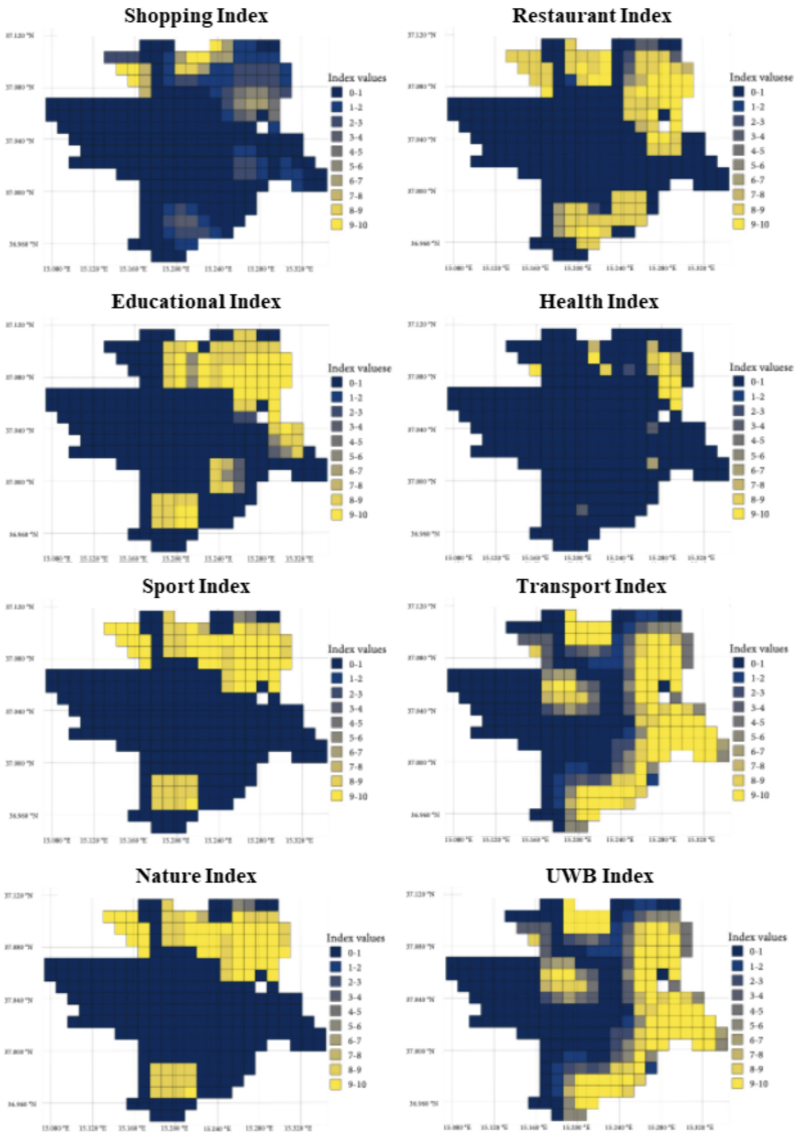

Fig. 2. Categorical sub-indices and UWB index for Siracusa municipality (Authors' elaboration on ISTAT and Open Street Map data)

5 Discussion and Conclusions

The paper addresses the issue of urban well-being through an integrated approach, with the aim of supporting planning decisions and orienting them toward spatial equity. The proposed methodological framework, based on integrating a "quantitative"/"data-based" assessment procedure and a "qualitative"/"perception-based" approach to the evaluation task, allows a complete and sensitive reading of urban dynamics and urban well-being

distribution mechanisms. The comparison between the results from the two assessment approaches, when applied to the Syracuse case study, reveals the opportunities of an integrated approach, highlighting that the quality of life does not always coincide with the mere availability of services. In some areas, there is consistency between the two assessment components' results; in others, significant deviations are recorded, confirming that qualitative factors, individual expectations, and practices significantly affect perceived well-being [22].

Furthermore, the application to Syracuse highlights the framework's potential in detecting intra-urban inequalities in well-being distribution. Historical areas and semi-central areas, with a higher density of services, show UWB higher values than those of peripheral areas, thus outlining an evident center-periphery gradient. The spatial support to the assessment allows for visualizing these imbalances and identifying fragile areas in terms of accessibility to services, thus providing a useful, albeit not exhaustive, tool for orienting urban policies at the municipal level from an equity and responsibility perspective.

However, it is necessary to recognize the intrinsic limits of the proposed framework and its output. The "quantitative" UWB index, by its nature, focuses on the proximity to services, neglecting complex subjective or social variables such as urban safety, social cohesion, air quality, or overall perception of quality of life [30]. Furthermore, the effectiveness of the model depends largely on the availability and quality of georeferenced data, which in medium-small urban contexts may be incomplete or inhomogeneous.

These limitations suggest research development prospects. First, the index can be enriched with new indicators that fill the current gaps (for example, indicators capturing further "dimensions", such as urban safety, air quality, noise, etc.) [31]. Secondly, the "qualitative" assessment component, currently proposed at its early stage and based on a participatory process, can be strengthened by involving citizens not only in the evaluation phase, but also in defining and weighting the dimensions considered. Another future development of the framework may investigate the adoption of alternative tessellation methods, such as hexagonal grids, which offer advantages in terms of isotropy and uniform neighbour relationships, thus assessing the sensitivity of results to the choice of spatial units.

Finally, applying the proposed methodological framework to other urban areas would provide additional evidence about its knowledge contribution from a comparative perspective, while testing its opportunities for scalability. These future research prospects, indeed, could strengthen the knowledge-generation potential of the framework, thus deploying its potential as a decision support tool to orient urban policies towards greater equity, awareness, and quality of life.

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A Mass Appraisal DSS for the Assessment of the Cost-Effectiveness of Flood Mitigation Interventions

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Abstract. This study presents a mass appraisal decision support system (DSS) and computational framework for the assessment of avoided flood damages and the evaluation of flood-risk-mitigation measures at the regional scale. The proposed approach integrates hazard assessment, exposure quantification, and vulnerability analysis to estimate damage to assets and industry in the status quo ("as-is") and post-intervention ("planned") scenarios. Avoided damage estimates are combined with intervention costs to derive a cost-effectiveness index of the investment undertaken, which remains consistent across different types, scales, and locations of interventions, and enables a coherent comparison of alternative solutions within a unified framework. This makes the approach particularly suitable for screening and ranking multiple mitigation options in complex territorial systems. The framework is applied to a levee breach scenario along the Piave River (northern Italy), where two alternative locations of the same intervention are evaluated. Results show a significant reduction in expected damages and clearly highlight the higher effectiveness of one solution compared to the other.

Keywords: Flood hazard modeling · Damage assessment · Cost-effectiveness

1 Introduction

Climate change is generating significant modifications in hydrological and meteorological regimes worldwide and across the European Union, including the amplification of extreme rainfall events, the intensification of storms, and the progressive rise in mean sea level. These drivers are producing, at both national and regional scales, an escalation in the occurrence probability and severity of flood phenomena. Floods are among the most common disasters in Europe [1, 2]. According to the European Environment Agency, over the period spanning 1980 to 2023, flood-related events across EU Member States resulted in the loss of 4,226 lives and generated annual average economic losses estimated at EUR 7.8 billion [1]. Notably, exceptional damage levels were recorded in 2021 and 2023, with total losses rising to about EUR 48.2 billion in 2021 and EUR 25.7 billion in 2023 [2]. Furthermore, national-scale impacts were particularly significant in Italy, where flood events in 2024 produced overall damages worth EUR 10 billion [2]. In

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 467–482, 2026.
https://doi.org/10.1007/978-3-032-30524-4_29

addition to causing injuries, mental trauma and deaths, floods impact property, infrastructures, and services, which can be destroyed or severely damaged. The unpredictability and magnitude of intense rainfall events represent a primary driver in flood risk management, which necessitates the deployment of reliable monitoring and prediction systems, and the design of resilient hydraulic systems and flexible risk mitigation approaches, aimed at safeguarding communities and critical infrastructure prone to flood hazard. It is expected that, in the next decades, flood risk and related economic loss will increase in Europe [1]. Consequently, enhancing the resilience of territories and implementing effective strategies to reduce hydrogeological risk have become central objectives in Governments' agendas and risk management policies.

Under these evolving boundary conditions, public decision-making assumes a strategic role in ensuring sustainable and technically sound planning. In this respect, Directive 2007/60/EC, better known as the Floods Directive on the assessment and management of flood risks, requires EU countries to: *i)* identify all areas potentially prone to significant flood hazard; *ii)* map the extension of these areas and the assets and population exposed within; *iii)* implement adequate and coordinated measures to reduce flood risk in these areas. Moreover, it is worth mentioning that Directive 2007/60/EC emphasizes the rights of citizens to access the above information and contribute their opinions throughout the planning process.

The intrinsic complexity of public decision processes, characterized by the interaction of multiple stakeholders, heterogeneous interests, and potentially competing objectives, requires the adoption of structured, transparent, and scientifically sound decision-support systems. Populations require, indeed, strengthening the legitimation, accountability, and transparency of public decision-making processes devoted to the design, ranking, and selection of flood risk mitigation interventions [3–5]. The structuring of robust decision-aiding processes and the provision of advanced and sound decision support systems are, consequently, essential to rule out arbitrariness in decision-making and assist planners and policy-makers in evaluating alternative risk mitigation measures and managing flood risk under increased uncertainty on hydrological patterns due to climate change, operational constraints, and an ever-stringent lack of financial resources.

In this paper, we propose a parsimonious decision support system (DSS), namely a simplified, low-variable methodological framework to evaluate the cost-effectiveness of alternative interventions (by type and/or location) to reduce damage in areas prone to flooding. We provide an assessment index based on avoided damage by comparing the status quo ("as-is" scenario) and the scenario after the intervention has been undertaken ("planned" scenario). In detail, our approach integrates hazard, exposure, and vulnerability into a mass appraisal valuation, and computational framework aimed at supporting decision-making at the regional scale. In other words, we couple advanced hydrodynamic modeling to define hazard scenarios with a mass appraisal procedure to assess damage to assets and industry potentially caused by floods in the status quo and post-intervention scenarios, respectively. Formal models permit improving the accountability of decision-making processes and pose the basis for participatory decision-making; by contrast, they can induce a possible loss of global insight and involve a cost for using them. The main objective of our contribution is to provide decision-makers with an assessment model that is robust; nonetheless, it includes a reasonable number of state

variables, and is fed via the largest possible number of open source or easily accessible data. On the one hand, data scarcity represents, *de facto*, a major issue, particularly in areas with limited monitoring of infrastructures. On the other hand, information needs to prove theoretical soundness and operational completeness: information and knowledge need to be exploited consistently and coherently, and need to be meaningful and useful for the final user and/or the purpose they have been designed and constructed for [4, 6].

The remainder of the paper is organized as follows. Section 2 briefly presents the related literature; Sect. 3 introduces materials and methods to clarify the methodological fundamentals of the proposed approach and data used for the modeling; Sect. 4 provides and discusses an illustrative example to prove the potential and the ease of use of the proposed approach; finally, Sect. 5 concludes.

2 Related Literature

In recent years, the increase in the frequency and intensity of flood events has been mainly attributed to climate change, urbanization, and land-use modifications. About 4% of floodplains and 40% of urban areas are covered by surfaces that do not allow water to seep into the ground, and about 12% of the EU's population lives in floodplains [1, 7]. This context challenges policy makers and governments to adopt advanced tools for flood risk assessment and support in decision-making [8–10].

In this respect, it can be observed in the literature an advancement from traditional deterministic models toward integrated approaches combining hydrological and hydraulic models, socio-economic analyses, and artificial intelligence (AI). This evolution has led to the development of multidisciplinary frameworks aimed at improving the design and successful implementation of flood risk mitigation strategies [11]. Traditional flood risk assessment models are based on the physical simulation of runoff and inundation processes, and allow the estimation of water depth, flood extent, and flood propagation time. They have recently included in the modeling open-database for simulating fluvial dynamics and socio-economic impacts to improve the assessment of potential damages and support land-use planning activities [12]. The introduction of probabilistic models in this domain has enabled the consideration of climate uncertainty and the simulation of multiple flood scenarios that, in turn, have improved the robustness of decision-making processes. Specifically, the integration of climate change projections into flood modelling represents one of the main current research directions in this field [13] meant to improving the assessment of extreme event probability of occurrence and enhancing resilience-based planning strategies [14].

According to the existing literature, the development of innovative DSS, which integrate hydraulic models, geographic information systems (GIS), and socio-economic data represents one of the major research interests in flood risk management. Nonetheless, the edge of research on DSS includes the integration of advanced tools (e.g., deep learning algorithms, urban digital twins), and multiple criteria evaluation models. The former contributes to supporting policy makers in infrastructure investment planning and improve allocation of resources [15], and the latter to prioritizing interventions based on infrastructure resilience, social vulnerability, and effectiveness of risk mitigation measures [10, 16]. It is worth mentioning that the recent deployment of AI has positively

impacted flood prediction, mapping of flood-prone areas, and damage assessment via machine learning [11, 17] and deep learning techniques [15, 18, 19], which are also becoming widely adopted to increase transparency and understanding of decision models and improve institutional acceptance, which are fundamentals when modeling is used to support policy-making and strategic planning [19].

A well-established strand of literature focuses on the assessment of economic losses caused by flood events. Starting from the seminal contribution by Merz et al. [20], many reviews have been recently conducted, as reported by Romali et al. [21] and Olesen et al. [22]. Most studies focused primarily on direct damages to buildings and urban areas [23–25]. In addition, recent studies have also reported modeling errors generated by less accurate or improper procedures of data aggregation [26–29] and the lack of high-resolution damage models. Consequently, the development of reliable valuation frameworks to assess economic losses remains a priority research area.

Finally, as it emerges from the literature, regardless the tremendous advancement in research mentioned above, data limitation and availability remain still a critical challenge in this domain, as obviously incomplete datasets may reduce the reliability of model outputs [12, 21, 30].

The aim of this paper is to contribute to filling some of the existing gaps in the literature, primarily identified in the provision of multidisciplinary and integrated valuation approaches and standardized DSS, which can be easily scaled and implemented also in areas where data scarcity is particularly limiting a robust damage assessment.

3 Methods

The valuation approach we propose can be structured into the following sequential steps (Fig. 1).

1) The first step involves the identification of the hazard-impacted area, defined as the spatial extent where the intervention is expected to modify hazard conditions.

For any return period relevant from a hydraulic perspective, we assume that the extension of the area is equal in the "as-is" and "planned" scenarios, with the only difference being the hazard level, which may change due to the intervention. This ensures that the spatial domain under investigation is comparable in the two scenarios. The area must be sufficiently extensive to capture all the relevant effects of the intervention while remaining reasonable in scope. In the case of floods, it basically corresponds to the inundated area in the "as-is" condition.

2) The second step involves the assessment of hazard, exposure, and vulnerability.

Within the impacted area, the hazard indicates the potential to generate damage. It can be expressed either in terms of physical variables (e.g., water depth and flow velocity in the case of floods), or as discrete hazard classes. Hazard is estimated through dedicated analyses carried out during the design phase. In the case of floods, they include two-dimensional (2-D) hydraulic modeling that provides spatial distributions of water depth and velocity. For the "as-is" scenario, they are also available from existing hazard maps (e.g., flood maps provided within the EU Floods Directive), while dedicated analyses are required for the "planned" scenario. This approach allows for areas characterized by certain hazard levels in the "as-is" scenario to be reassigned to lower or zero hazard

in the "planned" scenario. The approach also accounts for residual hazard in case the intervention does not fully eliminate flood hazard for a given return period.

Exposure is defined as the economic value of assets located within the hazard area, including buildings, infrastructures, and population, and it is assessed based on the same underlying hypotheses in the "as-is" and "planned" scenarios. Exposure evaluation first considers the spatial distribution and the number of assets, which are derived from existing cartographic and statistical sources. For example, buildings are characterized based on their location, footprint, and functional category. The economic value of assets is then assigned according to homogeneous categories based on local data. For example, building values are estimated using official property databases, considering the municipality and urban zone, while commercial and industrial activities are evaluated using sector-specific data, such as classifications based on economic activity and average revenue.

Vulnerability quantifies the proportion of the exposed asset that is expected to be damaged under a given hazard intensity. It is a function of hazard characteristics (e.g., water depth and flow velocity), and varies spatially according to hazard distribution. The same framework is applied to both the "as-is" and "planned" conditions, with differences arising only from changes in hazard levels. Specifically, vulnerability is expressed as a value between zero (no damage) and one (total loss), and it is estimated through damage functions relating hazard intensity to expected damage for different asset categories, including buildings and industrial structures. These functions are typically derived from literature or empirical data, even though vulnerability can be conservatively assumed equal to one for the damaged items.

3) The third step includes the assessment of damage in the hazard-impacted area.

Damage depends on hazard, exposure, and vulnerability. For each spatial unit $(x,y)_k$ and asset category i, damage is estimated as:

$$D_{i,(x,y)_k} = E \cdot V(H) \tag{1}$$

where E is the economic value of assets of category i in $(x,y)_k$, and $V(H)$ is the vulnerability associated with the hazard level H. Total damage is obtained by summing across the spatial units and the asset categories:

$$\mathrm{D} = \sum_{\mathrm{i}} \sum_{k} D_{i,(x,y)_k} \tag{2}$$

This calculation is performed separately for both the "as-is" and the "planned" scenarios, namely $\mathrm{D}_{as\text{-}is}$ and $\mathrm{D}_{planned}$.

The benefit B obtained from the intervention is defined as the reduction in damage:

$$B = \mathrm{D}_{as-is} - \mathrm{D}_{planned} \tag{3}$$

4) The fourth step includes the definition of a cost-effectiveness index and its calculation to provide a project ranking from the most to the least cost-effective.

The cost-effectiveness index I_{CE} is defined as the ratio between the avoided damage and the costs of the intervention C:

$$I_{CE} = \frac{\mathrm{D}_{as-is} - \mathrm{D}_{planned}}{\mathrm{C}} = \frac{B}{\mathrm{C}} \tag{4}$$

This index provides an objective measure of the intervention's effectiveness in terms of avoided damage and construction costs.

The general framework can be extended to consider multiple events over the service life T_U of the infrastructure. Each event is associated with an annual exceedance probability p_j (where $j = 1,\ldots,n$), and the probability domain is discretized into intervals Δp_j (i.e., the discretized annual exceedance probability interval associated with p_j). In the "as-is" and "planned" scenarios, the total damages over T_U, denoted as $\overline{\overline{D}}_{\text{as - is}}$ and $\overline{\overline{D}}_{\text{planned}}$, respectively, are given by:

$$\overline{\overline{\mathrm{D}}}_{\text{as - is}} = \overline{D}_{\text{as - is}} \cdot \mathrm{T_U} = \left(\sum_{\mathrm{j}} \mathrm{D}_{\text{as - is,j}} \cdot \Delta \mathrm{p_j} \right) \cdot \mathrm{T_U}$$

$$\overline{\overline{\mathrm{D}}}_{\text{planned}} = \overline{\mathrm{D}}_{\text{planned}} \cdot \mathrm{T_U} = \left(\sum_{\mathrm{j}} \mathrm{D}_{\text{planned,j}} \cdot \Delta \mathrm{p_j} \right) \cdot \mathrm{T_U} \tag{5}$$

where $D_{as\text{-}is,j}$ and $D_{planned,j}$ denote the damage associated with the probability level p_j and $\overline{D}_{as\text{ - }is}$ and $\overline{D}_{planned}$ are the expected annual damages in the "as-is" and "planned" scenarios [31].

The benefit and cost-effectiveness index can be calculated as in Eqs. (3) and (4).

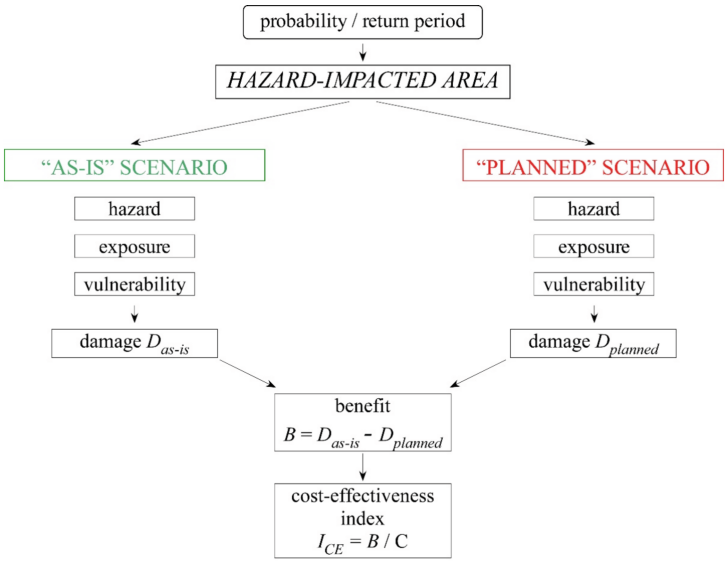

Fig. 1. Conceptual map of the proposed approach (workflow).

4 Application Example

As an application example, we consider a flood scenario induced by levee breaches. We assume a hypothetical intervention designed to prevent levee collapse at two potential breach locations, named B1 and B2. In the "as-is" state, the damage scenario corresponds

to the envelope of maximum water levels from both possible breaches. In the "planned" scenario, the intervention is implemented at one of the two locations, effectively excluding that breach from contributing to damage estimation. For the sake of simplification, we consider only a return period of 30 years (i.e., $p = 1/30 = 0.033$).

This example is meant to illustrate the potential of the valuation framework and the user-friendly procedure implemented for calculating the cost-effectiveness index I_{CE} and for ranking the two potential locations of the same intervention from best to worst in terms of cost-effectiveness. The extension of the framework to diverse and multiple interventions is straightforward and follows the same computational framework.

In addition, for the sake of simplification and according to the objective of the present section mentioned above, we considered only damages to buildings and industry as a proxy for damage. Nonetheless, this approach can be extended to include other types of losses to cover the full range of direct and indirect loss to tangible and intangible assets generated by floods.

4.1 Study Area

The study area is located in the Veneto Region (northeast of Italy), in the municipality of San Donà di Piave, adjacent to the Piave River. The Piave River, 230 km in length, has an average flow of around 100 m3/s and can convey discharges up to ~ 2700 m^3/s during flood events. In the study area, the river spans around 100–200 m in width and is separated from the surrounding floodplains by continuous levees approximately 6 m high. The terrain slopes southeast, with elevations ranging from 5 m above sea level near the northern levees to below 0 m in the southeastern portion.

Elevation data are derived from LiDAR surveys conducted between 2004 and 2009 by the Italian Ministry of the Environment and Energy Security, providing both a digital surface model (DSM) and a digital terrain model (DTM) at a spatial resolution of ~ 1 m. These data are available from the online atlas Geoportale Nazionale (https://gn.mase.gov.it/portale/home, accessed on 29 March 2026).

4.2 Hydrodynamic Model

The flood hazard scenario in the study area is simulated using the 2-D hydrodynamic model '2DEF', which enables a physics-based representation of river flow, levee failures, and the inundation of adjacent areas in a coupled framework. The model solves a modified form of the shallow water equations that incorporates wetting–drying processes [32], and it employs a mixed Eulerian–Lagrangian approach for momentum conservation [33].

The equations the model solve are:

$$\begin{aligned}
&\frac{\partial h}{\partial x} + \frac{1}{g}\frac{\mathrm{d}\left(\frac{q_x}{Y}\right)}{\mathrm{d}t} + \frac{q_x|\mathbf{q}|}{K_s^2 H^{10/3}} - Re_x = 0 \\
&\frac{\partial h}{\partial y} + \frac{1}{g}\frac{\mathrm{d}\left(\frac{q_y}{Y}\right)}{\mathrm{d}t} + \frac{q_y|\mathbf{q}|}{K_s^2 H^{10/3}} - Re_y = 0 \\
&\eta(h)\frac{\partial h}{\partial t} + \nabla\mathbf{q} = 0
\end{aligned} \tag{6}$$

where h represents the water level, g is gravity, t is time, Y is the volume of water per unit area, H indicates an equivalent water depth that is useful for describing partially wetted areas [31], η is the portion of wetted area per unit area, K_S is the Strickler roughness coefficient, $\mathbf{q} = (q_x;q_y)$ is the vertically integrated velocity, and $(Re_x;Re_y)$ are the dimensionless Reynolds stresses in the horizontal plane.

To efficiently represent rural floodplains, the model couples 2-D triangular elements with 1-D channel elements for the minor drainage network, that is not explicitly resolved by the 2-D representation. Special 1-D elements also allow modeling hydraulic structures, pumping stations, and levee breaches caused by overflow or piping.

The 2DEF solver has been successfully applied to simulate both river flows [34–36] and urban flooding [37–40]. In the present case, the model was used to simulate the Piave River from Nervesa della Battaglia to the Adriatic Sea. The computational domain covers approximately 589 km^2, with a flexible unstructured mesh whose elements range from ~ 500 m in rural areas to less than 100 m in urbanized zones. Model calibration and validation were performed against multiple gauging stations along the river in previous studies [41].

For the present analysis, a realistic flood event with a return period of 30 years was considered, based on the local Basin Authority assessment. The event has a total duration of 98 h, with a peak discharge of approximately 3000 m^3/s at $t = 50$ h.

The simulation incorporates hypothetical levee breaches to evaluate potential flooding under both "as-is" and "planned" conditions, providing a consistent framework for assessing the effectiveness of proposed interventions. The breaches were initiated after the flood peak had passed, at $t = 70$ h. To represent the breach, the levee crest elevation was reduced by 90% of its height on the floodplain side over a 30-min period. The breach width was assumed to be 230 m, corresponding approximately to the riverbed width at points B1 and B2. The 2D model, including the surrounding floodplain, then simulates the propagation of the resulting flood wave across the area (Fig. 2).

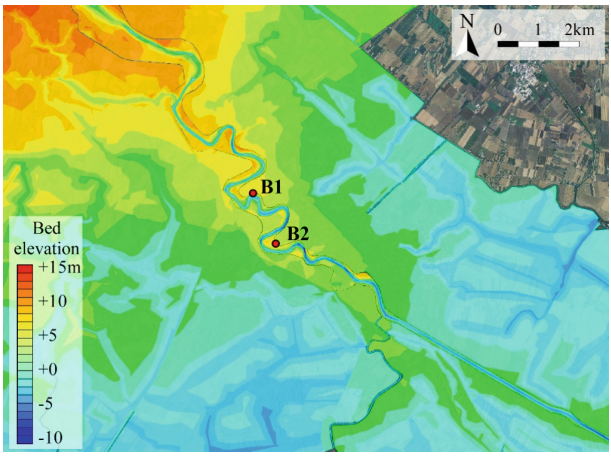

Fig. 2. Study area: bathymetry and identification of levee breach locations

4.3 Hazard Scenarios and Hazard-Impacted Area

Hazard scenarios are constructed based on the hydrodynamic simulations for both the "as-is" and "planned" conditions. In the "as-is" condition, the hazard is defined by the envelope of the maximum flow depths and velocities associated with the two potential breach locations (B1 and B2), as illustrated in Fig. 3a. In the "planned" conditions, two alternative scenarios are considered: P1, in which breach B1 is prevented, and P2, in which breach B2 is prevented, and the hazard scenarios are defined accordingly, as shown in Fig. 3b and Fig. 3c.

The hazard-impacted area is then identified based on the inundated extent obtained from the "as-is" condition, which represents the maximum spatial extent of flooding across the considered scenarios. This area covers a surface of 26.6 km^2 and is delineated by the red line in Fig. 3. It is subsequently used as the reference domain for the analysis.

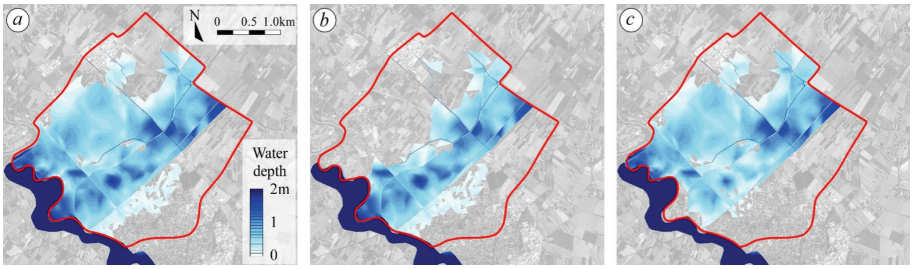

Fig. 3. Water depth predicted by simulations with the 2D hydrodynamic model for the "as-is" (a) and the "planned" scenarios P1, P2 (b,c).

4.4 Assessment of Damage to Buildings

Damage to buildings is assessed by combining information on exposure, hazard, and vulnerability. First, buildings located within the hazard-impacted area are identified and

characterized (Fig. 4a). Building footprints are extracted from the regional technical cartography (CTR), providing information on both the spatial location and the ground floor area of each building. In addition, the total floor area of the buildings is estimated based on the footprint area and the number of floors as described in [36], starting from the Digital Surface Model (DSM) obtained via the Geoportale Nazionale (see Sect. 4.1), and assuming an average inter-floor height of 3.5 m.

Property market data and value are derived from available open-source datasets. In particular, the unit market value (EUR/m^2) for different building typologies and locations, is here derived from the real estate market database provided by the Italian Real Estate Market Observatory (Osservatorio del Mercato Immobiliare, OMI) of the Italian Revenue Agency, and it is assigned to each building in the hazard-impacted area, as illustrated in Fig. 4b. The market value is used as it is more readily available and consistently accessible at the regional scale compared to construction cost data.

The estimation of direct damage is then performed by combining hazard and exposure information through a vulnerability function. For each building polygon, a lumped impact parameter for hazard, named W, is computed based on local hydraulic conditions (water depth Y and flow velocity U), according to the formulation proposed by Lazzarin et al. [42]:

$$\mathrm{W} = \frac{Y}{3.5}\left[1 + 0.3\left(\frac{U}{\sqrt{gY}}\right)^2\right] \tag{7}$$

This parameter is used as input to a damage function that expresses the relative damage as a function of hazard intensity. For the present application, the vulnerability (i.e., the relative damage) is computed following [42], where different vulnerability functions are defined depending on the building typology and number of storeys. For example, for masonry single-storey buildings, which are the most common in the study area, the vulnerability function is:

$$V(W) = \frac{1}{1 + 2.1/W} \tag{8}$$

For each building, the relative damage is first estimated based on the local hydraulic conditions and then converted into absolute economic loss by multiplying it by the total floor area and the assigned unit value. Finally, the damage to residential buildings is obtained by summing the contributions of all buildings within the hazard-impacted area. The spatial distribution of relative damage for the considered event is shown in Fig. 4c-e for the considered scenarios.

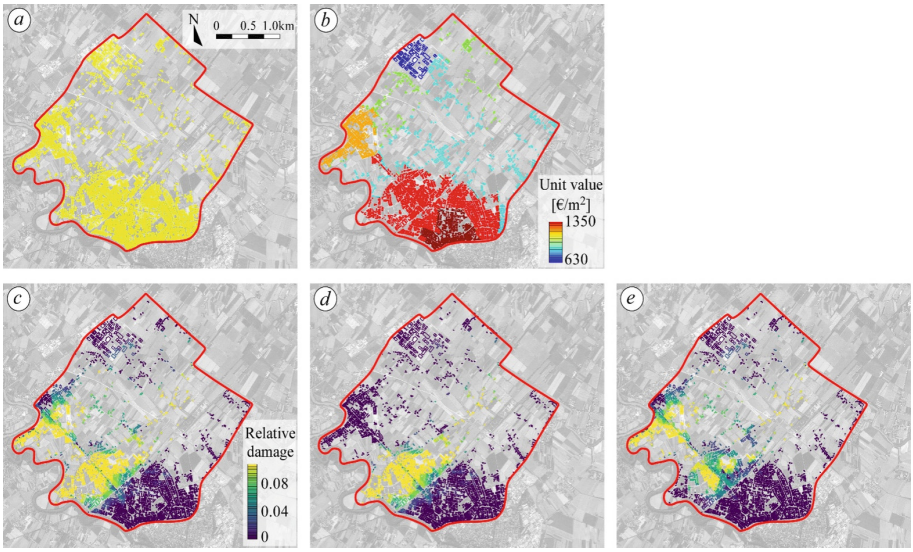

Fig. 4. Relative damage to buildings: (a) identification of building polygons from CTR; (b) evaluation of unit values; relative damage for the "as-is" (c), and the "planned" scenarios P1, P2 (d,e).

4.5 Damage to Industry

Damage to industry is also considered, accounting for economic losses associated with business interruption. In this study, damage to industry is estimated in terms of loss of daily revenues due to business interruption.

Assets are first identified within the hazard-impacted area by extracting polygons classified as *building* = *industrial* from the OSMAND database.

The economic loss associated to business interruption is quantified by estimating the average daily revenue for manufacturing activities (ATECO sector C) in the hazard-impacted area, according to data derived from the dataset of the Statistics Department of the Veneto Region, namely the Sistema Statistico Regionale. This value, subsequently combined with information derived from C.STAT (a data browsing platform designed by Unioncamere and the Guglielmo Tagliacarne Research Center of the Chambers of Commerce), is equal to 6,565 Euros per day (reference year 2021). Based on the average size of industrial buildings within the study area, this value is normalized to a unit value of 6.09 Euros/m^2/day.

Damage is then evaluated by combining hazard and exposure information. Given the high uncertainty associated with damage estimation, a conservative assumption is adopted by setting vulnerability equal to one. Consequently, only assets affected by flooding contribute to damage assessment (with relative damage equal to one), while unaffected assets are assigned zero damage, as illustrated in Fig. 5.

For the simulated event, the average flood duration is assumed to be 7 days, consistently for both the "as-is" and "planned" scenarios. Total damage is finally obtained by summing the contributions of industry units in the hazard-impacted area.

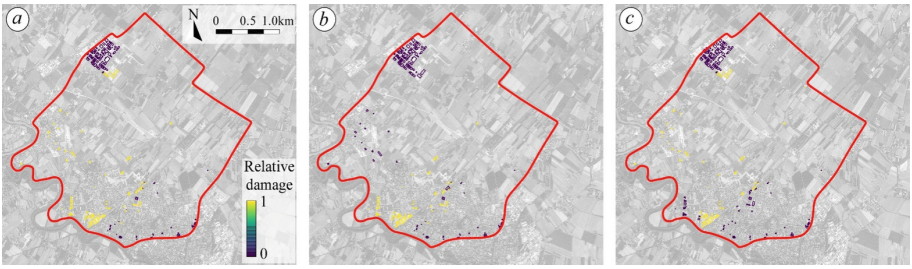

Fig. 5. Relative damage to industry for the "as-is" (a) and the "planned" scenarios P1, P2 (b,c).

4.6 Cost-Effectiveness Index

Total damages are determined for both the "as-is" and "planned" scenarios by summing the contributions evaluated in the previous steps and are reported in Table 1. Total damage is then calculated by considering a probability level equal to the return period of the hydrological event (i.e., 30 years). As previously mentioned, the total benefit is defined as $B = D_{as\text{-}is} - D_{planned}$, i.e., it is coincident with the avoided damage resulting from intervention implementation.

To determine the cost-effectiveness index, I_{CE}, it is necessary to estimating the intervention construction costs. In the present example, the levee reinforcement intervention has a length of approximately 230 m, corresponding to the extent of the considered breach. The unit cost per linear meter is estimated at 7,278.27 Euros/m, based on parametric evaluations derived from similar levee reinforcement works along the Piave River [43]. The resulting total construction cost is EUR 1,674,002.10. This value is the same for both the planned scenarios, as the present analysis compares alternative locations of the same intervention. However, for different types of interventions, construction costs may vary. Nonetheless, the proposed framework remains applicable.

Finally, the cost-effectiveness index is computed as the ratio between avoided damage B and construction costs C. The obtained values are EUR 16.75 and EUR 13.35 for the "planned" conditions P1 and P2, respectively. This indicates that, for every euro invested, approximately EUR 16.75 and EUR 13.35 of flood damages are avoided per single flooding event. Therefore, in this illustrative example, the intervention corresponding to scenario P1 is preferable, as it yields a higher index I_{CE}. This result reflects the lower residual damage associated with P1 compared to P2.

Table 1. Summary of estimated avoided damage, intervention cost, and probability, and benefit/cost ratio index for each scenario.

	"planned" scenario P1	"planned" scenario P2
$D_{as\text{ - }is}$	75,029,203.74 Euros	
$D_{planned}$	46,997,728.88 Euros	52,675,575.80 Euros
Probability	1/30 = 0.033	
B (avoided damage)	28,031,474.85 Euros	22,353,627.93 Euros
Length of the infrastructure	230 m	
Unit cost of the new structure	7,278.27 Euros/m	
C	1,674,002.10 Euros	
I_{CE} index	16.75	13.35

5 Conclusion

This study presented a rapid computational framework for estimating avoided flood damages in regional systems, with a specific application to levee breach scenarios along the Piave River in northern Italy. The framework integrates hazard assessment, exposure quantification, and vulnerability analysis to estimate both direct and indirect damages under "as-is" and "planned" conditions. The approach enables the evaluation of intervention benefits in terms of annualized avoided damages and provides a benefit index that can be effectively used to rank flood risk mitigation measures of different types and/or in different locations.

The application of the framework to a hypothetical levee reinforcement intervention demonstrated its capability to discriminate between alternative intervention locations, providing an objective and quantitative measure of expected benefits. In the presented example, the proposed intervention significantly reduced both direct damage to buildings and indirect losses for industrial activities. One location was clearly identified as preferable, yielding a higher benefit index and indicating greater economic efficiency.

Although tested on a single case study, the proposed framework is scalable and can be adapted to different flood-prone contexts and risk-mitigation interventions. It can provide, consequently, a valuable and easy-to-use DSS to support decision-making in regional flood risk management and policy design. Its flexibility allows the inclusion of multiple scenarios, alternative design solutions, and varying levels of data availability, making it particularly suitable for rapid and preliminary assessments of flood mitigation strategies.

Nonetheless, the limitations of the proposed framework should be mentioned: we focused primarily on direct damage to buildings and industry, and we assumed a fixed impact area. Compared to micro-scale approaches, which indeed requires extensive data availability, the adopted mass appraisal framework is less sophisticated due to data aggregation and the underlying simplifying assumptions. In addition, the results may be

sensitive to the choice of vulnerability (damage) functions, which needs further investigation. To further enhance the applicability of the proposed framework in integrated regional planning, future developments may be devoted to accounting for multiple hazards, cascading effects, and the full range of direct (e.g., to crops, livestock, infrastructures) and indirect (e.g., to industry and health) damages as well as intangible damages (e.g., psychological distress, loss of trust in authorities, impacts on cultural heritage and ecosystems) caused by flood events.

6 Disclosure of Interests.

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

Acknowledgments. The authors acknowledge financial support by the Veneto Region (project MCDA grant n. CUP H16F22000400002).

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Assessment of the Current State of Urban Redevelopment Areas and Their Environmental Impacts: An Analysis to Support the Strategic Environmental Assessment (SEA)

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Abstract. In metropolitan areas that have encountered various transformation processes and have a complex urban history, there are often undeveloped or abandoned areas, a result of the rapid and continuous change in cities. For this reason, in urban redevelopment and planning processes, it is important to consider these spaces as potential areas for development and to start with them, as they represent urban voids that should be viewed as a key element in the creation of redevelopment strategies. In this context, the Strategic Environmental Assessment (SEA) procedure becomes mandatory in order to evaluate the environmental impact of transformation strategies. This study proposes a working framework to support the SEA in defining strategies and actions for the development of degraded areas. The method applied consists of two distinct phases.

In the initial phase, an analysis of the present state of the territory was developed to assess the current situation, ongoing dynamics, and critical issues to be resolved. This analysis integrated SWOT analysis and Geographic Information System (GIS) tools. In the subsequent phase, the environmental impact of the proposed strategies was assessed. This assessment was based on the results of the initial analysis, and it was conducted by developing coaxial environmental impact matrices.

Keywords: SWOT analysis · Strategic Environmental Assessment · Geographic Information Systems · Environmental Impact Matrices · Urban planning

1 Introduction

During the last few decades, environmental issues have taken on increasing importance in planning processes, requiring ever greater integration and harmonization between environmental protection objectives and the socioeconomic development dynamics [1, 2]. This growing attention is reflected in the European context, where environmental policy has progressively acquired a more prominent role over time [2, 3]. In this framework, the European Union introduced, through Directive 2001/42/EC, a key instrument: Strategic Environmental Assessment (SEA), a procedure aimed at integrating environmental

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 483–499, 2026.
https://doi.org/10.1007/978-3-032-30524-4_30

considerations into planning and programming processes. Specifically, the progressive consolidation of European environmental legislation has led to the establishment of an increasingly structured system of principles and rules, designed to ensure high levels of protection and to integrate environmental requirements into various sectoral policies [3, 4]. This instrument applies to plans and programs likely to have significant environmental impacts, based on the premise that the implementation strategic policy decisions may produce significant environmental effects, which must therefore be assessed in advance [1]. The aim is thus to ensure high levels of sustainability in these processes, guiding transformations towards solutions that ensure adequate environment protection [3, 4].

In the Italian context, the SEA framework was introduced by D. Lgs. 3/04/2006, n. 152 (Environmental Regulations), thereby establishing the SEA procedure for plans and programs at the national level [1].

Alongside SEA, additional environmental assessment procedures further contribute to integrating environmental considerations into specific contexts, following specific procedural methods. These include the Environmental Impact Assessment (EIA) and the Appropriate Assessment (AA), both introduced at European level and subsequently transposed into Italian law. In particular, the EIA, introduced by Directive 85/337/EEC, aims to assess the impacts arising from individual projects, whereas the AA, introduced by Directive 92/43/EEC, is applied to any plan, project, or other measure that may have a significant impact on Natura 2000 sites, i.e. areas of high ecological value.

From this perspective, environmental assessment tools play a significant role in urban transformation processes as well, guiding decisions toward more sustainable solutions that prioritize the environmental quality of local contexts, especially in urban areas that have already been transformed or are in a state of decline. In such cases, planning decisions can have a significant impact on environmental balances and the quality of urban space. These areas often represent vestiges of urban transformation processes that have altered the functions and dynamics of cities over time. Despite their current perception as areas of urban decline and substandard quality, through processes of regeneration and repurposing, these districts harbor significant development potential. By facilitating the establishment of social gathering spaces and services within the city, these districts can contribute to the enhancement of the urban environment [5].

This case study, which analyzes a municipality in northern Italy, focuses on the effects of urban transformation processes on the presence of numerous abandoned areas within the city. These areas, which can be characterized as urban voids, have a detrimental impact on urban value and quality. Consequently, there is an imperative to revitalize and repurpose these spaces [6]. In order to address this issue, the areas in question were analyzed individually to assess their current state and establish a knowledge base for developing future design proposals aimed at their reuse. Concurrently, an environmental assessment was conducted within the framework of the SEA, incorporating its principles and functions.

The objective of this study is therefore to propose a methodological approach that is practical and applicable to similar contexts and situations, based on an in-depth analysis that allows for the interpretation of the current state of the territory and an understanding of its ongoing dynamics to create scenarios for future transformations and assess

their impacts, with a particular focus on environmental factors. The analysis was conducted using the SWOT method integrated with the STEEP approach. This methodological framework was selected to analyze the current situation and identify strengths, weaknesses, opportunities, and threats. These elements were considered in the analysis, which was informed by the main socio-economic, technological, environmental, economic, and political dimensions. Subsequently, the results of the analysis of opportunities and threats were used to construct strategic visions. These visions were evaluated from an environmental perspective through the creation of coaxial environmental impact matrices.

This paper is structured as follows: Sect. 2 describes the SEA process, explaining the main methodologies incorporated into the assessment and highlighting the most representative regional experiences; Sect. 3 describes the methodological framework used as the basis for the analysis; and Sect. 4 presents the application of the methodology to the case study, outlining the results and concluding remarks.

2 Strategic Environmental Assessment

The SEA process consists of a series of stages designed to ensure that the assessment process is comprehensive and fully integrated with the planning process [7], from the definition of objectives through to the monitoring of environmental impacts. The procedure is designed to ensure broad public participation throughout the entire process, which enables better environmental outcomes to be achieved as a result of shared, informed and sustainable decisions [1, 7].

The SEA begins with a screening phase, which aims to determine whether a plan or program is likely to have significant environmental impacts and therefore needs to be subject to the SEA procedure [8, 9]. This is followed by the scoping phase, the central stage of the process, during which the scope and methodology of the investigation are defined, and the likely significant environmental effects are assessed. During this phase, the Environmental Report is drawn up; this document will accompany the relevant plan or program and contains the information necessary to identify, describe and assess the potential environmental effects arising from its implementation [8, 9]. This is followed by the assessment and decision-making phase, which involves the adoption and approval of the plan or program, and, finally, the phase of monitoring environmental impacts, which entails defining the methods and indicators for evaluating the effects resulting from the implementation of plans or programs [8, 9]. The indicators must therefore provide information on the state and dynamics of a territory, which is essential for supporting decisions based on constantly updated data [9, 10]. Through monitoring, SEA ensures that the planning process is continuous and cyclical, allowing for the verification, reconsideration and/or reorientation of planning choices implemented on the basis of the results obtained [11].

During these stages, various techniques and methodologies are employed to support the decision-making process, although there are no universally valid or standard methods [8, 12]. In this context, several established approaches have been applied, each serving specific functions at different stages of the process [13].

Among these, SWOT analysis is frequently used to carry out context analyses, providing an assessment of the current situation by identifying problems or opportunities and classifying them as strengths, weaknesses, opportunities and threats [8].

Tools used to support the decision-making process also include consistency analysis models, such as correlation matrixes [8]. These matrixes enable the internal and external consistency of the plan to be evaluated by analyzing the degree of correlation between objectives, actions and environmental components. This makes it possible to identify inconsistencies or discrepancies, thereby supporting revisions and adjustments [14].

Methodologies for identifying potential environmental impacts may also be employed; these are used in the initial stages of the assessment to support subsequent analysis and monitoring activities. They enable the identification of certain or potential interactions between the actions associated with plans or programs and the environmental system. The main ones include checklists, impact matrixes and networks [13].

Checklists are structured lists of environmental, project and impact factors that are useful for an initial systematic survey of possible interactions and for establishing the information framework for the main impacts to be analyzed [13].

Environmental impact matrixes are analytical tools that link actions to environmental components, enabling identification and, in some cases, the assessment of the significance of potential effects [13]. An example of a quantitative impact matrix is the Leopold matrix [15], which lists 100 planned project actions in columns and 88 environmental components affected by these actions in rows; at their intersection, an assessment is assigned, ranging from +10 (extremely positive impact) to −10 (very negative impact).

Finally, networks, or impact chains, correspond to cause-and-effect relationship diagrams that represent the interactions between actions and environmental components in a more systematic and structured manner, also highlighting indirect and cumulative effects [13].

Other methods used, derived from a combination of the methods mentioned above, may include, for example, coaxial matrixes, grid-based tools that integrate environmental impact matrixes and networks to enable the relationships between causal factors of impact, environmental components and potential impacts to be analyzed and evaluated in a logical sequence [13].

Following the impact identification phase, the impacts are estimated. This assessment aims to estimate the significance of the changes induced by the implementation of plans or programs on the environmental system, by using a set of indicators capable of describing changes in environmental components and their causes [13]. One of the most widely used models for organizing environmental information is the DPSIR model (Drivers, Pressures, State, Impact, Response), developed by the European Environment Agency (1999) [16], which allows indicators to be structured according to a causal chain linking human activities, pressures exerted, environmental conditions, impacts generated and societal responses, thereby providing an integrated and systemic understanding of environmental dynamics[17, 18].

Finally, the comparison of alternative scenarios and the support for selecting the most sustainable option are entrusted to methodologies such as multi-criteria analysis, which enables the integration of heterogeneous dimensions into a structured decision-making process [19, 20]. Several approaches and techniques for multi-criteria analysis

have been developed in the literature [21] which can be applied to various contexts, specifically designed to assist the decision-maker in identifying the solution that best minimizes environmental impacts and, at the same time, is optimized from a technical and economic perspective [21].

Integration with GIS tools is particularly important in supporting the application of these methodologies, as it enables the analysis and representation of georeferenced data and the construction of knowledge frameworks useful for a comprehensive interpretation of territorial components [14, 22].

In the presence of a plurality of established approaches and methods, and in the absence of a regulatory framework defining the methodological aspects of SEA, a differentiated methodological and operational framework has progressively emerged at the national level [1]. Within this context, regional authorities have developed different approaches through the adoption of their own regulations, guidelines and operational tools [1, 23]. Some of these experiences stand out for their level of methodological structuring and can be regarded as good reference practices. Among these, notable examples include the cases examined within the ENPLAN project (*ENPLAN Guidelines – Environmental Assessment of Plans and Programmes*, 2004), such as Emilia-Romagna and other regional contexts that have adopted specific assessment models. This overall framework highlights how SEA can be understood as an inherently flexible tool, open to a variety of methodological approaches.

3 Methodology

The proposed methodology provides knowledge and interpretive support during the ex-ante phase of the SEA, in which it is necessary to assess the environmental context of the study area and define the objectives, goals, and priorities of future actions. As these are currently abandoned or disused areas, it is essential to assess their environmental condition in order to develop focused actions that improve the current situation and enhance the value of the territory.

In this regard, the methodology comprised two distinct phases. The first phase focused on analyzing the current situation in order to gain a thorough understanding of the factors that characterize the areas. The second phase aimed to assess the potential environmental impacts of these changes.

The SWOT analysis was used as the evaluation method for the first part of the study, as it allows for the detailed identification of the positive and negative factors influencing the area and its potential for transformation.

After gaining a thorough understanding of the area, development scenarios were defined for the second phase based on the results of the SWOT analysis. This was done to assess their potential environmental impact, as required by the SEA process. This involved creating coaxial environmental impact matrices based on the opportunities and threats identified in the SWOT analysis, in order to assess the types and extent of potential environmental impacts, and to determine the sustainability of the planned interventions.

3.1 SWOT Analysis

SWOT analysis is a decision-making tool designed to improve the effectiveness of decision-making processes [24]. Its primary objective is to identify the Strengths (S), Weaknesses (W), Opportunities (O) and Threats (T) related to complex issues [25]. When integrated with the SEA process, SWOT analysis provides a clear and interactive way to highlight the key characteristics of the context in short and long term. It serves as a tool for both strategic and environmental impact assessments of plans or programs. The aim is therefore to assess the current state of a territory by identifying the factors that define and influence it, whether endogenous or exogenous [26].

Specifically, the strengths and weaknesses of the case study are endogenous factors, that is, factors related to the current situation or expected in the near future. In contrast, opportunities and threats represent exogenous factors; that is factors or dynamics that influence the study area, but which are still potential in terms of their occurrence and effect. Examples include events and conditions that could potentially have a positive or negative impact on the territory [27].

SWOT analysis can be applied at various stages of the SEA process. During the *ex-ante* phase, it can be used to better integrate the plan or programs from a sustainability perspective. During the *in-itinere*, it can be used to verify compliance with previously defined sustainability objectives and make adjustments as needed. Finally, during the *ex-post* phase, it can be used to justify and interpret the results obtained. If necessary, it can also be used to explain any changes made to the initial choices [28].

In order to make the analysis more comprehensive by taking into account the various components that characterize the territorial system, the SWOT analysis is supplemented with the STEEP method, an acronym referring to the dimensions analyzed: Social (S), Technological (T), Environmental (E), Economic (E), and Political (P) [29]. This approach enables systematic analysis to be carried out, taking into account the various sectors that characterize the local context, thereby facilitating the creation of the SWOT-STEEP matrix.

By integrating the STEEP approach, it is possible to identify and analyze the dynamics of the study area in a more structured way. This systematic methodology allows for comprehensive consideration of all factors that may influence the area's transformation and development processes [30].

In order to provide a clearer, integrated approach that helps decision-makers choose actions and strategies, the assessment of complex decision-making problems requires the integration of decision-support tools with spatial components [31].

Visualizing trends identified through analytical models in a spatial context improves understanding of their geographic distribution. This enables development of strategies better suited to the local context, which can address negative aspects or highlight positive elements.

In this study, the SWOT analysis was integrated with a spatial analysis conducted using GIS systems to create a graphical representation of the elements identified during the analysis and transform qualitative factors into spatial data. The integration of these two methods made it possible to easily understand the dynamics at play within the

relevant territorial context. An integrated interpretation of analytical and spatial information provides thematic maps that support and assist decision-makers and stakeholders in selecting planning and transformation strategies [32].

3.2 Coaxial Matrix

A preliminary analysis of the area's current state provides a foundation for understanding the potential environmental impacts of the transformation.

The aforementioned impacts can be defined as alterations to the environmental system that result from the interaction between an external agent and the specific aspect of the system that is affected [33]. Their evaluation can be carried out by constructing two-way matrices that take into account the environmental factors and design strategies into which the activity has been broken down; the intersection of these factors represents a potential interaction between them [34].

A series of coaxial environmental impact matrices have been developed, thereby constituting a theoretical extension of Leopold's matrix framework. As previously mentioned, the coaxial matrices are based on the same principle; however, they consist of multiple entries, thereby allowing for the correlation of causal impact factors, environmental components, potential changes, and human activities vulnerable to impact.

A co-axial matrix is defined by its capacity to accommodate a variable number of entry points, with the potential for both qualitative and quantitative data representation. In the first case, value judgments (symbols or colors) are entered; in the second, numerical values are assigned to the intersections.

For the case study analyzed, the co-axial matrix was constructed based on the DPSIR model [16], which describes the cause-and-effect interactions between environmental components and the socioeconomic system. The elements of the model are the Driving forces, the dynamics that activate the transformation processes; the Pressures, the effects of the driving forces on environmental components; the State, the changes induced in environmental components; the Impacts, the consequences resulting from the change in state; and the Responses, actions necessary to compensate for or mitigate the impacts [16].

These elements are outlined as follows to construct the matrix for the case study: Driving forces represent the factors that influence the territorial system (e.g., urban planning policies, the transportation system, the availability of green spaces…). Pressures refer specifically to the pressures imposed on environmental components (e.g., land consumption, water and noise pollution…). The State assesses changes in the environmental components under consideration (e.g., water, air, soil and subsoil, waste, noise, biodiversity…). The Impacts describe how environmental components are altered by changes (e.g., effects on water quality, on soil…). The Responses consider urban planning and regulatory standards and tools aimed at defining mitigation and compensation measures for managing potential impacts.

The previously mentioned elements are correlated within the co-axial matrix to assess, by filling in the sections with a color-coded scale, whether the strategy under evaluation has a positive, moderately positive, neutral (i.e., present but without significant effects in either a positive or negative sense), moderately negative, or negative impact on the environmental components analyzed.

4 Application

The methodological approach outlined above has been applied to a major urban center in northern Italy. In this paper, to provide a practical illustration of the analytical criteria used in the development of the analysis, we propose applying them to one of the areas under consideration.

4.1 SWOT-STEEP Analysis

The aim of the SWOT-STEEP analysis is to obtain and present a comprehensive overview of the study area and its context. The process was informed by a thorough examination of the local area, encompassing the aggregation of data on various infrastructural and socio-economic factors. The factors considered included the number of vacant properties, employment levels, and service availability. The data were collected using online portals and statistical sources.

The SWOT-STEEP matrix is a tool used to simplify territorial analysis by dividing the system into smaller, more manageable components. This approach entails the identification of the positive and negative aspects of the area, including the opportunities offered by infrastructure and critical issues such as depopulation and lack of services.

Subsequent to the delineation of the SWOT elements for each STEEP category, a systematic collection of data was conducted for the purpose of establishing a solid knowledge base and supporting the implementation and development of the proposed methodology.

In practice, the process entailed the analysis of information gathered from official statistical sources (*Agenzia Regionale per la Protezione Ambientale* - ARPA, *Istituto Superiore per la Protezione e la Ricerca Ambientale* - ISPRA, *Istituto Nazionale di Statistica* - ISTAT), scientific literature (universities and other research bodies) and spatial databases (Geo-topographic databases). This made it possible to identify a set of key factors categorized as strengths, weaknesses, opportunities and threats, depending on whether they were internal or external to the territorial system. The assessment of these factors was carried out according to three main criteria: relevance, source reliability and representativeness of territorial dynamics.

Subsequently, the identified components were organized according to the analytical categories of the STEEP framework [35], in order to identify the territory's values more clearly (Table 1).

For example, the presence of attractive hubs and good transport links were classified as strengths (economic and technological dimensions), whilst the lack of local amenities and the presence of derelict or underused sites (social and environmental dimensions) were classified as weaknesses. Similarly, the attractiveness to prestigious international brands (economic dimension) was interpreted as an opportunity, whilst the high site remediation costs (environmental dimension) were seen as threats.

In this context, this functional integration enables a cross-referenced analysis of the nature of the phenomenon and its strategic significance.

The cartographic representation of the SWOT-STEEP analysis, an innovative element of the research, makes it possible to highlight the geographical distribution of the

Table 1. Description of STEEP components

	Description	Subtopics
SOCIAL	Analysis of the main sociodemographic variables, with a particular focus on factors influencing well-being and quality of life	Culture; Demographics factors; Housing; Services
TECHNOLOGICAL	Identification of current technological and infrastructure systems, based on their contribution to the local economy and market dynamics	Infrastructure; Mobility; Digitalization; Buildings
ENVIRONMENT	Assessment of the area's state of health, with reference to the general environmental factors that contribute to the sustainability and livability of the area	Air and climate; Green and blue infrastructure; Landscape; Sustainability; Soil and waste
ECONOMIC	Survey of relevant economic sectors, aimed at understanding their impact on the local context and on the dynamics of regional attractiveness	Economic activity; Investment; Property market; Income and employment
POLITICAL	Determination of the existence of plans, resources and programs designed to improve quality of life	Urban planning; Procedures; Public and/or private projects

identified elements, as well as their interactions and relationships with environmental and anthropogenic components.

The analysis of the maps shows that strengths (Fig. 1) are concentrated near significant environmental systems and complexes of recognized historical and artistic value, as well as along strategic transport routes and motorway links, and in areas characterized by emerging economic trends. Weaknesses (Fig. 2) mainly concern the lack of social welfare and sports facilities, the absence of sustainable transport solutions, the condition of the building stock, and the high volume of traffic along the main highways.

Opportunities (Fig. 3) are related to urban regeneration processes and the economic revaluation of the built environment following the conversion of abandoned industrial sites, while threats (Fig. 4) concern economic and administrative constraints and environmental problems related to soil sealing and hydraulic inertia.

Overall, the analysis provides a picture of an area in transition, where local potentialities and structural challenges coexist and mutually influence each other. These conditions are due to the area's peripheral location relative to the city center, which simultaneously functions as a gateway to the city, with important implications.

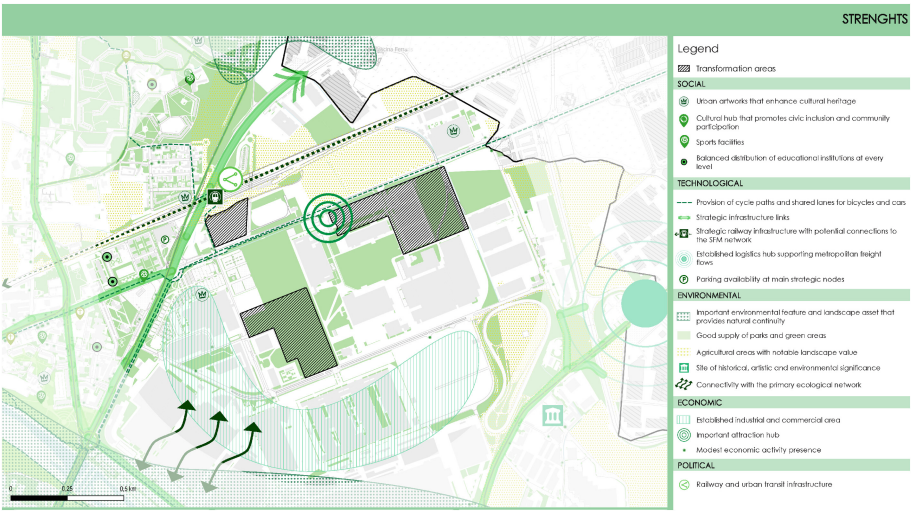

Fig. 1. A visual representation of the strengths identified by the SWOT-STEEP analysis for the area of study.

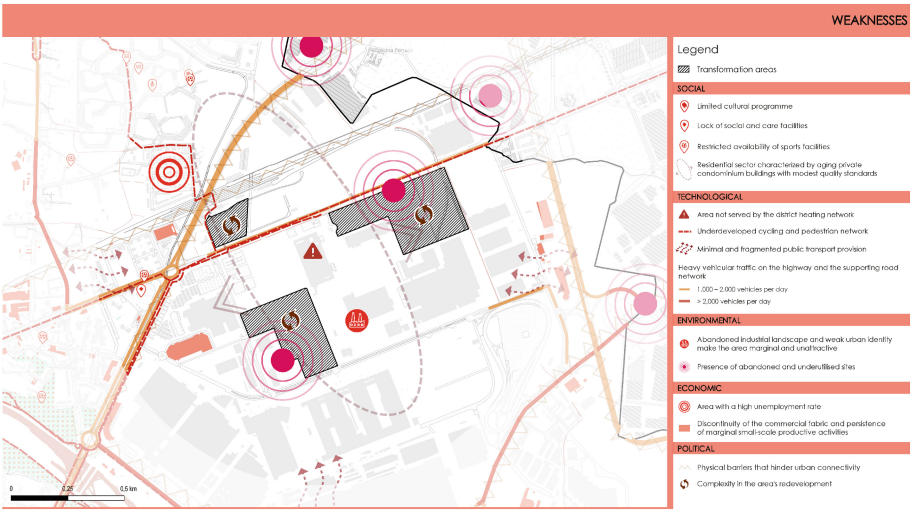

Fig. 2. A visual representation of the weaknesses identified by the SWOT-STEEP analysis for the area of study.

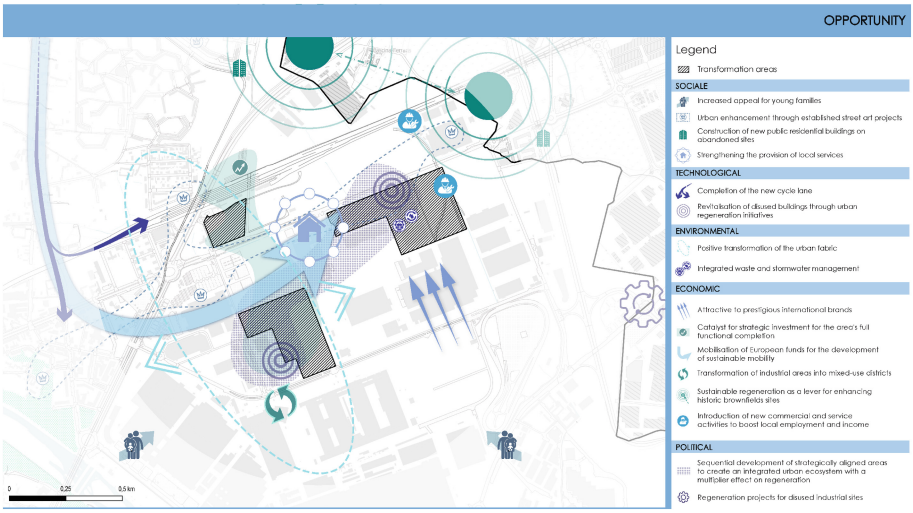

Fig. 3. A visual representation of the opportunity identified by the SWOT-STEEP analysis for the area of study.

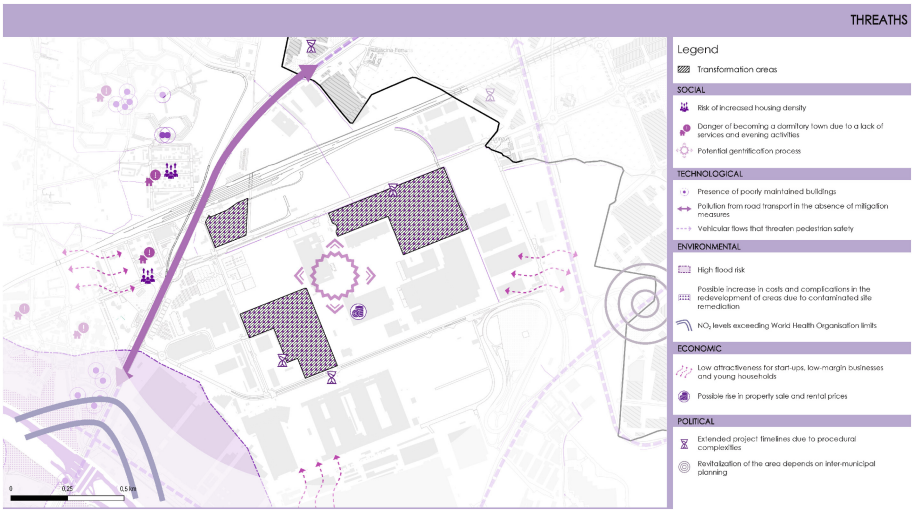

Fig. 4. A visual representation of the threats identified by the SWOT-STEEP analysis for the area of study.

4.2 Coaxial Matrix

Comparative analysis of the different scenarios using coaxial matrices highlights the systemic implications of the different components analyzed and supports the development of integrated spatial strategies, while also providing an operational tool to guide planning decisions.

The coaxial matrices were developed by translating the elements of the SWOT-STEEP analysis into causal relationships based on the DPSIR model, with the aim of clarifying cause-and-effect dynamics, making system interdependencies explicit, and sequentially identifying causal links and crucial points for intervention. In this process, the identified factors (strengths, weaknesses, opportunities and threats) were associated with drivers and pressures, with the observable effects were attributed to the state and impact components, and finally to possible planning response. For example, the increase in traffic flows (mobility system) is linked to higher emissions of atmospheric pollutants, the deterioration of air quality (state) and negative impacts on human health and well-being, and the quality of the urban environment; responses such as environmental mitigation are associated with these effects.

In order to evaluate all possible strategies and alternatives, three reference scenarios were considered: The first type is Inertial, which corresponds to maintaining the status quo and the absence of significant changes. The second type is Tendential, which considers the implementation of current planning requirements. The third type is Strategic, which is built on the opportunities identified by the SWOT analysis. A coaxial reference matrix was compiled for each of the above scenarios to assess the environmental impact of each one.

The coaxial matrix provides a systemic understanding of the entire DPSIR framework, showing the propagation of the effects of urban and infrastructural transformation and how pressures translate into cumulative impacts across multiple environmental components. Its main value lies in going beyond the limitations of a sectoral assessment, as it enables the identification of critical points and cross-cutting relationships, as well as the evaluation of the effectiveness of planned response. The different scenarios are directly integrated into the matrix, modifying driving forces and pressures and generating distinct configurations of the impact chain, thereby allowing the environmental effects associated with each alternative to be compared.

Figure 5 exemplifies the application of the co-axial matrix for the Strategic scenario and it shows consistency between certain planning projections and the development trajectories identified through the SWOT-STEEP analysis, with a stronger emphasis on sustainability, resilience and urban quality.

The interpretation of the coaxial matrix is based on the legend, which guides the reading of relationships along the DPSIR framework by distinguishing between the type and intensity of impacts. The cells indicate the presence, absence, or neutrality of effects, whilst the color scale specifies their nature (positive, negative, or neutral) and relative intensity. In order to facilitate the interpretation of the results Fig. 5, the distinction between the categories ‘no impact’ and ‘no effect’ is clarified: in the first instance, it can be stated that there is no interaction of any kind between the elements identified in the table; in the second case, however, the interactions between elements are tangible, but the result of these forces does not suggest any impact, neither positive or negative. This configuration enables the direction and magnitude of interactions to be immediately understood, thereby making the transformation dynamics associated with the various scenarios clearly legible and facilitating comparison between their configurations.

In particular, only the Strategic scenario results in a reduction of pressures and an overall improvement in urban quality, the analysis highlights how development outcomes are highly sensitive to the implementation of integrated policies on mobility, the environment and urban regeneration, although some residual issues remain regarding traffic volumes, noise and environmental pollution. The findings of the co-axial matrix analysis indicate the presence of potential environmental pressures, primarily associated with consumption, soil sealing, water resource exploitation, and increased atmospheric emissions. The aforementioned issues have the potential to affect ecosystem balance and the quality of the urban environment; however, they can generally be mitigated through the implementation of appropriate measures, such as environmental compensation. In this context, the implementation of permeable paving and rainwater harvesting systems has been identified as a potential strategy for mitigating pressure on soil and the water network. Additionally, the promotion of natural regeneration and urban reforestation initiatives has been proposed as a means of compensating for environmental damage. The implementation of these actions would result in the enhancement of environmental conditions and the ecological quality of urban spaces.

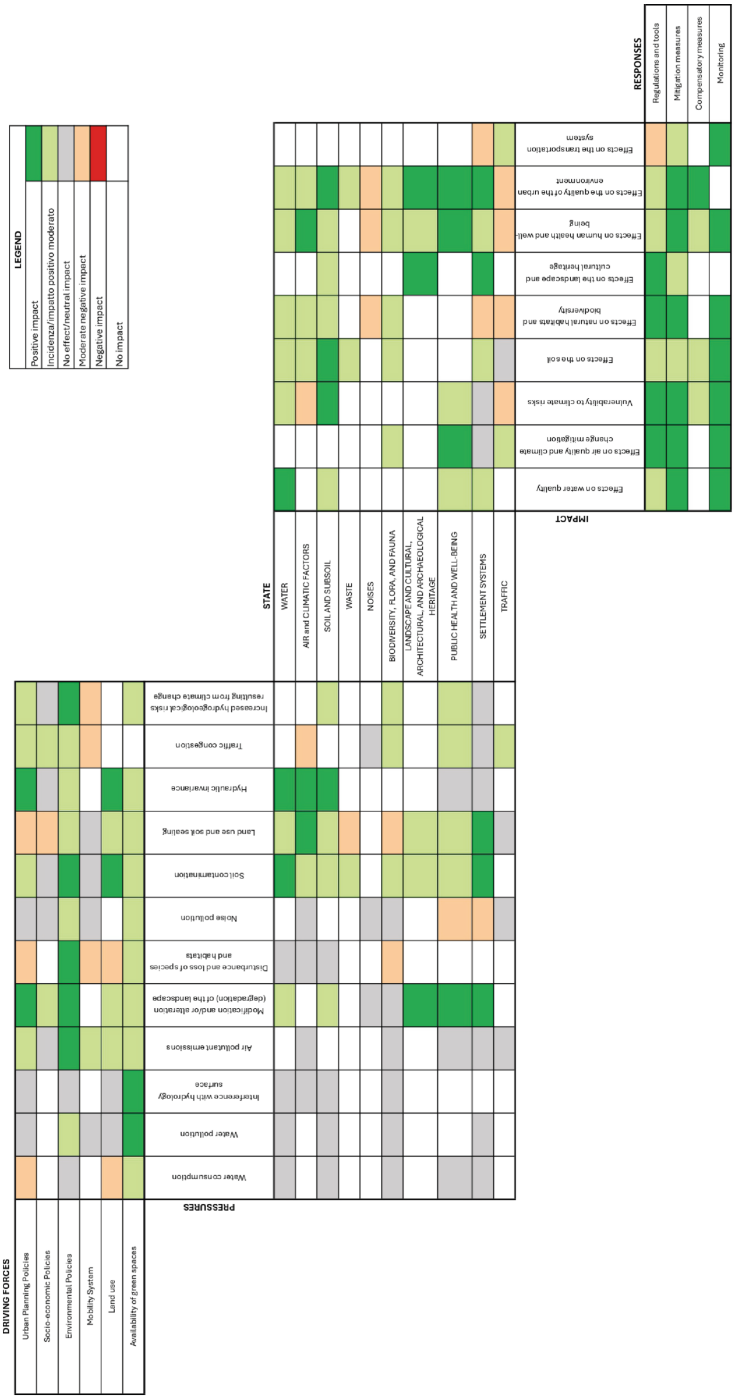

Fig. 5. Example of co-axial matrix of environmental impacts related to the Strategic scenario

5 Conclusions

This study proposes a work methodology to support the SEA process for the assessment of areas under transformation. The approach integrates the various components and dimensions of the territorial system. This integration facilitates the interpretation of preliminary analyses and results by visualizing key characteristics and ensuring that the work is comprehensible not only to experts but also to all stakeholders involved in the process.

The analysis conducted enabled a comprehensive and integrated assessment of the areas, highlighting the unique characteristics and shortcomings of the territory through an objective approach. This facilitated the SEA by conducting territorial analyses designed to examine individual aspects of the local context from the perspective of environmental sustainability. The objective of this approach was to ensure the proper development of the decision-making process.

The operational process followed a linear approach, starting from the current state of the areas to analyze it in detail. This analysis took into account not only the physical characteristics of the territory but also other dimensions, such as social, technological, economic, environmental, and political factors. Furthermore, consideration was given not only to ongoing or implemented actions, plans, or programs, but also to those that are foreseeable, thereby shifting the focus toward the area's potential. This methodological approach enabled the assessment of the potential benefits arising from the transformations, as well as any threats posed by current or future dynamics. In this manner, development scenarios and hypotheses were formulated that are congruent with the context and aimed at the regeneration of the area.

The workflow was enhanced by the development of coaxial matrices, which are widely used in SEA to quantify the potential effects of actions outlined in plans or programs. These matrices enabled the assessment of environmental impacts, thereby facilitating the identification of changes or alterations to this system. Additionally, they permitted the evaluation of the potential consequences of such transformations. A thorough analysis of these matrices revealed that the development of design scenarios based on a comprehensive study of the area, even if in some respects differing from current regulations, promotes their implementation in a more sustainable manner, from both an environmental perspective and in terms of public health and the restoration of communal and social spaces to cities.

The principal strength of this approach is its flexibility and replicability. It can be applied to study different contexts and case studies, ranging from an in-depth analysis of each territorial dimension to the development of coherent and well-informed strategies. Furthermore, integration with spatial analysis methods allows for the visualization of the spatial distribution of the identified elements, facilitating a deeper understanding of the dynamics at play and the identification of potential critical and strategic points for strategy development. This approach is further enhanced using coaxial matrices, which facilitate the visualization and assessment of potential environmental impacts.

Conversely, there appears to be a absence of participatory process involving the public in identifying the elements of both the SWOT analysis and the compilation of the co-axial matrices. Such a process could lead to a more comprehensive analysis that considers a variety of perspectives, including that of residents.

In the future, to refine the model, one preliminary step could be to consider the adoption of participatory methods, such as surveys and questionnaires. The implementation of these methodologies would facilitate the incorporation of supplementary viewpoints into the evaluation process, thereby ensuring the achievement of more comprehensive and accurate outcomes. Furthermore, the methodology could be executed through the utilization of quantitative factors and numerical indices. This approach is especially pertinent in the compilation of the coaxial matrix, where the application of value judgments expressed in numerical terms facilitates the derivation of a final index.

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Sustainable Mobility and Urban Development Models: An Integrated Scenario-Building Approach

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Abstract. The radical transition towards sustainable and resilient approaches to urban development has become increasingly urgent under the interrelated pressures of both environmental aspects and the evolution of the regulatory framework at European, national, and local levels. In the context of sustainable mobility, some steps forward are possible due to the increasing diffusion of digital solutions that support the implementation of real sustainable strategies in urban contexts. Starting from a theoretical-methodological investigation of the potential of eco-district models and the analysis of experiences at an international level, this work uses the case study of the San Salvario district in Turin as a laboratory for analyzing mobility strategies and sustainable actions. Through the adoption of an integrated approach of scenario building that combines SWOT analysis and Stakeholder analysis, the work proposes a reflection on different hypothetical scenarios for the neighborhood within the challenges of sustainable mobility and its solutions provided by digital tools. More specifically, the scenarios focus on some key elements of sustainable mobility such as the increase of awareness and social responsibility, the creation of synergies between institutions, urban policies and individual needs, the integration of new infrastructures within the existing system and a set of networking hubs for supporting multimodal transit, as well as the promotion and support of investment solutions. The implications of the proposed scenarios are discussed in terms of reconfiguring urban public transport services, adopting a policy- and decision-making-oriented approach.

Keywords: Sustainable neighborhood · Mixed method · Scenario design · Mobility · Strategic assessment

1 Introduction

In recent decades, many directives and programs have been adopted and supported by the European Union to promote sustainable development, especially in urban areas [1]. These areas present a particular challenge due to the interrelated and balancing population needs, environmental concerns and economic pressures. The United Nations Sustainable Development Goals (SDGs) have placed a significant emphasis on sustainable communities. For instance, SDG 11 (sustainable communities and cities) has

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 500–515, 2026.
https://doi.org/10.1007/978-3-032-30524-4_31

contributed to a notable increase in research on sustainable neighborhood planning and development [2–4].

The analysis has required to be shifted from considering and implementing individual buildings to broader scales, such as neighborhoods or entire cities. Smart cities, eco-districts, sustainable neighborhoods, Net Zero-Energy Districts (NZEDs), and post-carbon cities are some of the experiments, both theoretical-methodological and applied, to support sustainable development in urban contexts [1, 5, 6]. These approaches focus on the variety of aspects at stake and aim to explore and possibly compose viable and effective solutions, which must be considered by decision-makers in defining strategies for the transformation and development of the city.

The neighborhood, in particular, has been recognized as the most appropriate level for sustainable urban development, as it represents an "intermediate" level of analysis and action between the city and the building, where various social and institutional networks are directly active, offering greater opportunities for participation in collective decisions [7, 8]. Additionally, the neighborhood scale is precisely the ideal location for the fulfilment of daily requirements, social interaction, and creation of sense of community [9, 10]. Despite the fact that neighborhood planning has a relatively long history, it was not until the beginning years of the 21st century that researchers, policymakers, architects and urban planners began to experience the design and development of the neighborhood scale from a sustainable perspective [11, 12].

Policies and strategies at this scale can facilitate access to essential services by foot or bicycle, whilst also creating new open spaces for leisure and socializing. It is therefore evident that sustainable mobility is of crucial importance in ensuring the facilitation of straightforward connections to all services, the establishment of a safe environment, and the promotion of social interaction. Within this context, models like the Paris en Commun of the "15-min city" (or more generally x-minutes city) and Barcelona's "Superblocks" become significant experiences to be adopted and adapted to other contexts [13]. In fact, the possibility of reaching workplaces and essential services on foot or by bicycle, according to the French model, or the attempt by Superblocks to provide new open spaces for pedestrians, cyclists, and children, moving between bike paths, pedestrian paths, trees, street furniture, and equipment for recreation and play [13], becomes extremely strategic and relevant. Both proposals would give more space to slow mobility, becoming decisive bets to encourage public transport over private transport.

Within this context, this work aims to explore the concept and the potential of designing a sustainable neighborhood in a real-world case study, giving particular emphasis to the proposal of sustainable mobility. In particular, the case study of the San Salvario district in Turin (Italy) is used as a laboratory to analyze sustainable mobility strategies and actions from an eco-neighborhood perspective. This district has become a multicultural, vibrant, and constantly evolving place, showing its potential for innovation and growth and is a place worth investing in for transformation. In particular, starting from some theoretical and methodological considerations on the potential of the eco-neighborhood model and the analysis of international experiences, the San Salvario case study uses a scenario building approach that integrates SWOT analysis and Stakeholder Analysis(SA). The integrated approach proposes a reflection on the construction of different hypothetical scenarios for the neighborhood within the scope of opportunities defined

by the challenges of sustainable mobility and the solutions enabled by digital tools. The work will emphasize several pivotal elements, including an escalation in awareness and social responsibility, the cultivation of synergy between institutions and urban policies and local requirements, the establishment of novel support infrastructure within the prevailing system and a network of multimodal transit hubs, in addition to initiatives to encourage and facilitate investment. The work therefore assumes and discusses implications from a policy- and decision-making-oriented approach.

After this introduction, the remaining paper is structured as follows. Section 2 contains the background of research, which explores the literature regarding eco-districts and sustainable neighborhoods, with particular reference to the role of mobility. Section 3 presents the methodological proposal, that combines SA and SWOT+STEEP in a scenario-building approach. Section 4 contains the application of the methodological proposal to the specific case study. Section 5 illustrates the results of the application, including some remarks focused on a policy-oriented perspective. Finally, Sect. 6 contains the concluding remarks and future steps of the work.

2 Research Background

In the debate on sustainable transition, various development models and paradigms have been proposed, including those of so-called eco-districts and sustainable neighborhoods. The two terms are often used interchangeably to describe episodes of change and innovation within cities and, in particular, at a specific urban level, that of the neighborhood. Research conducted by Holden et al. (2015) classifies 420 projects as eco-district experiments around the world [14]. Despite the growing number of these experiments, the characteristics and strategies adopted are far from uniform and develop according to their own specific path. This is often also the result of the intrinsic variability in the meaning of sustainability and neighborhood, as well as in the role it plays within the urban areas, the policy framework and planning practices. The term district/neighborhood, in particular, does not correspond to any specific and codified characteristic in terms of type, number of people it hosts, size, or civic function [15].

At the same time, it seems limiting to consider the neighborhood simply as a subdivision of the city; the relationships and interactions that are established within and with neighboring areas play a fundamental role both in functional and intangible terms, such as the sense of belonging or recognition of a place. Similarly, the relationships between a part and the whole, i.e., between a specific district or neighborhood and the urban area in which it is located, deserve attention, as only through their analysis is it possible to reflect on the current impact of the interventions adopted and their potential in terms of the transferability of strategies or dissemination on a larger scale [16].

Another element of great variability among the various eco-district experiments around the world is related to the possibility of designing them in an existing context or in expanding areas. It is easy to imagine how the solutions and strategies adopted are enormously different and, consequently, so are the results obtained. In one case, it will be necessary to engage with an already established context in terms of both urban design and resident population; in the other case, despite having greater flexibility and freedom of action at the local level, it will be more of an isolated example than an experiment that could potentially be spread across the entire city.

Various authors have attempted to define the paradigm of eco-district/sustainable neighborhood in a clear and unambiguous manner. Luederitz et al. (2013) [17], for example, identify nine integrated principles for their development: (i) creation of a harmoniously coordinated human-environment system, (ii) urban metabolism, (iii) design of environmentally friendly buildings using local and sustainable materials, (iv) livable and vibrant neighborhood, (v) compact development and integrated sustainable mobility, (vi) resilient neighborhood, (vii) democratic governance and empowerment of neighborhood residents, (viii) satisfaction of human needs, (ix) consideration of the neighborhood's impact on the environment. This perspective, however, is more of a guide to implementation than a representation of how this paradigm is applied.

Bottero et al. (2019) show a lack of uniformity among the different experiences explored in Europe. The study identifies clusters of strategies adopted in different cities, which can be categorized as follows: energy/environmental aspects, socio-economic aspects, mobility, and urban design. The energy/environmental cluster mostly pushes attention to the energetic component (e.g., renewable energy sources, building materials). Limited attention is given to the environmental aspects: some examples mentioned about the increase of biodiversity or actions to promote flood protection. Regarding the socio-economic aspects, the strategies are mostly based on residents' engagement, stakeholders' cooperation and the realization of a community center, as well as the investigation of the types of investors and governance approach. Considering urban design, both private and public spaces are considered, especially trying to provide a mix of uses. According to the mobility – focus of this contribution – the European experiences (especially in [17] and [1]) highlight as one of the primary objectives to discourage the use of private cars by implementing public mobility services (in particular, new tram lines, but also railway and underground connections or new and extended bus lines). Furthermore, the disincentive to use private cars is encouraged by the growing spread of car-free areas, in which the number of parking spaces is significantly reduced, confining them to the edges of the district. In many cases, these actions are combined with the spread of mixed-use roads shared between pedestrians, cyclists, and recreational areas. In other cases, cars are allowed to pass, but only if they are electric or combined with carpooling and car sharing initiatives.

It is important to underline that mobility is worldwide considered one of the most important pillar for a sustainable neighborhood development and similar mobility strategies are also proposed outside Europe. For instance, Holden et al. (2015) [14] explored worldwide eco-urban neighborhoods experiences: they described these models as having higher densities, being located on brownfield sites and featuring mixed-use and social diversity [14]. They also involved more active discouragement of private car use and more encouragement of active and public transport [14]. In China, Qi et al. (2025) [18] highlight the increasing role of mobility modes combined with agglomeration and location for the development of sustainable neighborhoods, as testified by the literature review conducted and the analysis on the neighborhood sustainability assessments tools and China's regulations. In North America, Tiznado-Aitken et al. (2025) [19] identify as main policy in Toronto for Net Zero strategy the expansion of public transport services, providing more bus and rapid transit infrastructure or evaluating free transit in order

to reduce car use. However, Tiznado-Aitken et al. (2025) [19] clarify that these strategies should be in-depth examined according to people's lifestyles and neighborhood aspirations: in some contexts, people may prefer walkable and human-scale neighborhoods, others transit-oriented communities, while others may continue to favor car-based mobility places. These reflections underscore the necessity to transition from theoretical models to empirical case studies, incorporating meticulous analyses of citizens' awareness, acceptance, and preferences, as well as their local governance.

3 Methodology Proposal

Several assessment models are available to support the evaluation of policies, plans, and projects in the context of urban transformations. To increase the efficiency and effectiveness of these models, there has recently been growing interest in experimenting with integrated approaches that take into account the multiple actors and stakeholders involved, as well as the different values and perspectives at stake, such as socio-economic, technical, political, and environmental aspects [20, 21]. This contribution, in particular, integrates a Stakeholder Analysis (SA) and a SWOT+STEEP analysis, for developing a scenario building approach to support the definition of alternative mobility scenarios for the San Salvario neighborhood, taking into account the main elements characterizing the decision-making problem and the area of investigation, as well as the key actors involved in the process.

Scenario building is a tool that supports strategic planning [22–24] exploring "what-if" futures and preparing for multiple plausible realities. Scenario building is increasingly used in urban planning, which is characterized by high levels of uncertainty and complexity. It allows for the development of strategic thinking capable of giving rise to alternative courses of action through a sequence of coherent and sequential reasoning. Generally, in planning projects, at least three scenarios are considered: the inertial scenario which represents the state of art, the inertial scenario which refers to the preserving or transforming provisions contained in local and/or regional plans, and the strategic scenario(s) which can be more than one and refers to explorative visions based on strategic and competitive purposes. Building scenarios, particularly the strategic scenarios, requires following a step-by-step process: (1) clarifying the objectives, partners and time horizon of the project, (2) identifying internal and external elements of the project, (3) ranking the elements, (4) building the scenarios according to the ranking. In all steps, some frameworks and methods can be used to support the scenario generation.

SA can be useful in the first step to analyzing the possible partners and identifying the main goals and objectives. SA is a fundamental tool to identify and map all the actors and stakeholders involved and interested in a decision-making process. In the context of urban transformation and planning, and also at the neighborhood scale, it allows, on the one hand, to identify the roles, needs, degree of interest, and power of each actor and anticipate their impact; and, on the other hand, to support the definition of strategies shared among all the often conflicting demands of the various stakeholders [25]. Following Dente approach [25], once all the stakeholders are identified, it is possible to distinguish them according to their level of intervention (whether national, regional, or local), the category to which they belong (politicians, bureaucrats, experts, or those

with general or special interests) and the resources they have (political, economic, legal, and/or cognitive), as well as their roles and expectations. Among the various approaches to developing a stakeholder analysis, this research uses a power-interest matrix [26, 27]. Stakeholders are located in a 4-quadrants matrix according to their level of interest on the project and the power to stop it. The location of each stakeholder makes possible to understand the way in which they must be involved during the decision-making process: when both power and interest is low, it is sufficient to monitor if their views change over time (i.e. if their level of power and/or interest change); when interest is high but power is low, the stakeholder must be informed to avoid conflicts and oppositions; when power is high and interest is low, it is necessary to satisfy the stakeholders, because they have the resources to stop the process; when both power and interest are high, the decision-making process must be conducted actively involving those stakeholders.

In the second step, the STEEP or PESTEL framework makes it possible to organize the main drivers of a project according to Social, Technological, Environmental, Economic, Political and Legal components, while SWOT Analysis to analyze these drivers based on strengths, weaknesses, opportunities and threats. SWOT analysis is a technique widely used in strategic planning to analyze the strengths (S), weaknesses (W), opportunities (O), and threats (T) of a complex decision-making problem [28]. SWOT analysis supports the interpretation of the state of the art and the identification of strategies that can enhance strengths and opportunities and minimize weaknesses and threats. Despite the validity of the results obtained through SWOT, this contribution proposes integrating the SWOT model with the STEEP model in order to improve the efficiency and effectiveness of the analysis and visualization of the strategic factors to be implemented in action and transformation scenarios [29]. The STEEP analysis considers the following components: 1) Society (S), i.e., characteristics relating to the citizens living in the context under investigation; 2) Technology (T) refers to the presence or absence of devices and infrastructure; 3) the environmental component (E) provides an analysis of Environmental characteristics with the aim of monitoring the health of the context; 4) the Economic component (E) refers to the state of the sectors that contribute to GDP and make the context economically vibrant and attractive; 5) Politics (P) refers to the presence or absence of plans and programs, funds, or projects related to the topic under analysis [30].

In the third step, different types of ranking methods (from less to more structured systems) can be used to rank the driving forces. An example of method is the Building Wilson scenario matrix, scoring the drivers according to the level of impact and uncertainty. In this work, we avoid ranking drivers but we simply select among a long list of drivers, the most important ones from the SWOT+STEEP, considering the ones with the highest impact and less uncertainty.

In the fourth step, from the most important drivers or from the ranking is possible to identify the strategies used for the creation of the scenarios. In our case, the main drivers are combined with stakeholders' need to build three alternative strategic scenarios.

4 Application

4.1 Case Study

San Salvario is one of the 34 districts of the city of Turin, recognized by the municipality for administrative purposes. Its boundaries clearly separate the district from other parts of the city: to the west the main railway station, to the south the biggest city healthcare center, to the east the river, and to the north the city center. With an area of approximately 2.2 km^2, this district is mainly residential, characterized by a multi-ethnic population, partly due to its proximity to the railway station. It also has many shops and bars, mainly for evening entertainment, as well as some prestigious historic buildings, such as the Valentino Castle, the medieval village, and the Church of Saints Peter and Paul. Although the population residing in the neighborhood has declined since 1995, the number remains fairly stable, both due to the high number of students from different regions of Italy who decide to live here because of the presence of many universities in the immediate vicinity and the leisure opportunities offered by the neighborhood, and due to the high number of foreigners who increasingly reside in San Salvario [31]. The multi-ethnic and multicultural aspect is now one of the main characteristics of San Salvario. In fact, the Islamic cultural center, the Waldensian Church, and the Synagogue are located here.

In terms of transport and connections, San Salvario benefits from numerous bus lines and four metro stops (excluding Porta Nuova), which provide easy access to other areas of the city (Fig. 1). In addition, there are also several car and bike sharing stations. In terms of increasing slow mobility, the municipality has recently increased the number of bike lanes in and around the neighborhood and created some slow roads and free-car areas. In addition, the neighborhood of San Salvario has been selected to take part to the Torino Mobility Lab initiative to facilitate walking and cycling between home, and school and work[1].

[1] https://www.comune.torino.it/schede-informative/torino-mobility-lab.



Fig. 1. San Salvario district and its mobility elements

4.2 The Methodological Approach Applied to the Case Study

The methodological approach integrates in a scenario building framework a combination of SA and SWOT + STEEP to support the definition of alternative mobility scenarios for the San Salvario neighborhood. The combination of the these approaches makes it possible to combine the specific characteristic of the mobility system of San Salvario, with the socio-economic characteristics of the neighborhood and all the relationships with its surroundings. These relationships are not limited to spatial connections with the other parts of the city, but also in terms of stakeholders involved and satisfaction.

Figure 2 illustrates the main stakeholders involved in the sustainable mobility process of San Salvario, organized according to the power-interest methodology. In Fig. 3, instead, the components of the STEEP analysis have been integrated into the SWOT analysis, using specific codes, to analyze the complex dynamics of the study context. In particular, the list of elements contained in Fig. 3 only represents the most important aspects identified: a more detailed analysis was conducted for each component of the STEEP between 4 to 8 subcategories (such as demographic characteristics, traffic system, walkability and safety of the streets, local businesses, bureaucratic issues).

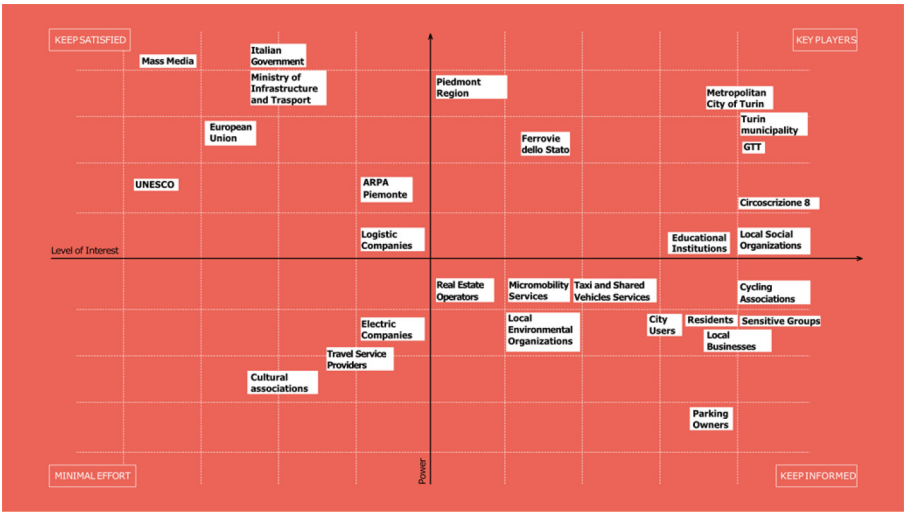

Fig. 2. Power-interest matrix applied to the case study



Fig. 3. SWOT+STEEP Analysis applied to the case study

From Fig. 2, it is possible to appreciate that the most important key players are the city of Turin, the public transport authorities (i.e. GTT for bus, tram and local train networks and Ferrovie dello Stato (RFI) for metropolitan-regional and national railway connections), as well as residents, thanks to the active involvement of district associations. Some synergies also emerged from the synthetic SWOT+STEEP (Fig. 3) aim at reducing potential conflicts between stakeholders. In particular, the opportunity of European funds, combined with local ones (e.g. FESR Piemonte 2021–2027 – priority III and

local incentives from PNRR), can boost the financing of sustainable mobility projects. Additionally, the presence of the widespread micro-mobility services (car and bike sharing, electric scooters, etc.) in the area can serve as the final link in the network provided by local public transport and railway connections, provided by GTT and RFI. San Salvario can benefit in this transition due to the presence of various local organizations and associations that can guide change, especially in terms of project acceptance at the level of local citizen action. Also, it benefits from a great number of young inhabitants and students that are generally more inclined to utilize alternative modes of transportation. It is worldwide recognized that the transition from private car usage to alternative transport modes is perceived as a high-cost behavior change (e.g., [32]), in terms of independence, flexibility, and comfort losing [33]. The city of Turin is currently experiencing a period of significant transformation, for the engagement in the process of formulating its new urban regulatory plan. One of the fundamental elements of the proposal is precisely the issue of mobility, which serves as the structural element of the entire urban development. Considering that this city is one of the most polluted in Italy and Europe in terms of air quality, and San Salvario is one of the districts with high traffic and congestion in different hours of the days, new mobility systems can improve the quality of life in the area by reducing congestion, pollution, and noise.

From digitalization, the district (but in general the whole city) requires some steps forward. In this context, the implementation of apps can assist residents, especially young people, in efficiently changing their mobility choices.

Based on the elements identified in the SWOT+STEEP analysis and the synergies with SA, it was possible to identify a series of strategies for mobility in San Salvario (Fig. 4). These range, for example, from improving pedestrian routes to implementing ICT technologies, from structuring a multimodal transport system to increasing shared mobility systems. Based on these strategies, three alternative scenarios were created (Fig. 5), exploiting the synergies between the actions. Scenario 1 organizes the blocks into macro-blocks, which promote pedestrian and bicycle mobility by limiting car traffic to the outer boundaries only, in the style of Barcelona's Superblocks. Scenario 2 creates a network of multimodal transit hubs throughout the neighborhood that allows access to and from the neighborhood through an integrated app-based service. Finally, Scenario 3 involves the development of various ICT tools to help citizens actively collaborate on mobility and share goods and services offered by the city.

Strategies	SCENARIO 01	SCENARIO 02	SCENARIO 03
1. Improve walkability	X	X	X
2. Create new public spaces	X		X
3. Increase the security on the roads	X		X
4. Implementation of ICT			X
5. Introducing electric public means of transport		X	X
6. Improve multi modality of transport system		X	
7. Increase the number of clients for night life activities	X	X	
8. Increase number of pedestrians in commercial activities' streets, easing the access			X
9. Improve Shared Services		X	
10. Partnership with local public and private institutions	X		X
11. Attempt of local political institutions to reach higher institutions	X		X
12. Reduce air pollution	X		X
13. Reduce noise pollution	X		X
14. Enhance and improve green areas and The Po river	X		

Fig. 4. Alternative strategies for the case study development

5 Results and Discussion

All three scenarios have, albeit in different ways, a significant social and environmental impact on life in the neighborhood.

Scenario 1, in particular, following the model of Barcelona's Superblocks, would reduce the overall flow of traffic within the neighborhood, with benefits in terms of the environment and social interaction among residents. However, the project could face considerable resistance from citizens due to the profound changes in habits that it would entail. Nevertheless, examples of Superblocks experiments have shown general acceptance by citizens due to the significant improvement in quality of life and enhanced social interaction. This experiment in San Salvario, thanks in part to the numerous associations in the area, could become a model of civic life that could be exported on a larger scale.

Scenario 2, on the other hand, represents a less invasive project in terms of changing residents' habits, but with significant benefits in terms of alternative mobility options offered to the inhabitants of San Salvario. In fact, it would complement and add new mobility solutions, particularly around the Porta Nuova station, potentially becoming a pilot example to be tested in other areas of the city.

Scenario 3 is the least invasive design solution from an urban and morphological point of view, although it requires considerable effort in terms of technological implementation costs. The app and its initial features could be developed fairly easily and quickly, but overall, the system and its adoption should be considered a long-term project, particularly in terms of acceptance and uptake among residents.

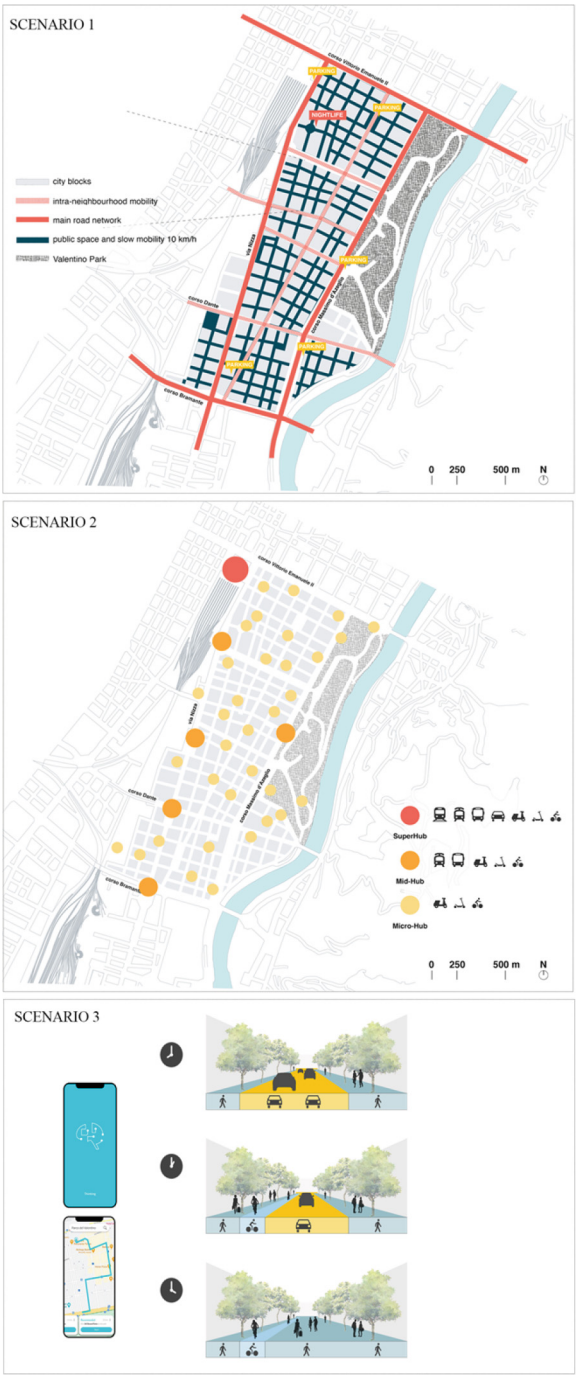

Fig. 5. The three mobility scenarios proposed for the case study

The city of Turin is at a particularly suitable moment for experimenting with new solutions for sustainable and resilient development, as it is in the midst of revising its Municipal Plan. The San Salvario neighborhood appears to be fertile ground for implementing technological and sustainable strategies, becoming a pilot test for future transformations on a larger scale. Other initiatives are also underway in the neighborhood to encourage the use and spread of soft mobility and, for example, in the area of separate waste collection and monitoring. These experiments could represent opportunities to to develop broader guidelines and guide cities toward sustainable development.

However, it is important to highlight that all scenarios could have some community or public resistance. For example, the super-block proposed in Scenario 1 should be developed with some mitigation strategies or participatory governance models in mind, to reduce resistance during actual implementation. Promoting a multimodal approach in Scenario 2 could also represent a radical paradigm shift affecting long-standing habits and economic interests. Scenario 3 relies on ICT tools which may face practical obstacles: for example, elderly residents may be excluded due to unfamiliarity with new software. Designing an interface, providing offline assistance or offering community training would make the proposal more effective for the entire community. Therefore, in all cases, the strategy must shift from a 'top-down' to a 'bottom-up' approach, gradually proposing these more sustainable and convenient alternatives.

6 Conclusions and Future Perspectives

The present study explored some theoretical urban development models (especially sustainable neighborhoods or eco-districts) to understand the possible strategies for real-world case applications. In particular, the work focuses on the mobility aspects proposed by such models, to identify some possible alternatives of development in a specific district of the city of Turin (Italy), i.e. the San Salvario district. The proposal considers this place as a suitable test bed for experimenting with sustainable mobility tactics and initiatives. To do that, the integrated use of SA and SWOT+STEEP Analysis in a scenario building approach made it possible to identify alternative solutions considering at the same time the specific characteristics of the district, its relationship with the overall city and its strategies, as well as all possible stakeholders involved in the process. In this way, the alternatives proposed should be coherent with the multiple aspects in play but also with the multiple perspectives of the different stakeholders involved.

The application to a single case study is certainly a limit of the present work. However, the methodology proposed for scenario building can be easily replicated and adapted to other contexts, analyzing the specific characteristics of the area under investigation through the SWOT+STEEP analysis and the stakeholders involved in the process.

Future prospects for this research will certainly involve the development of a quantitative or quali-quantitative analysis. In particular, it could be useful to introduce some quantitative KPIs to compare the alternatives (e.g. CO2 emission reductions, increased pedestrian zones, changes in transportation modes) or quali-quantitative methods, such as a multi-criteria analysis (MCA) in order to evaluate the best alternative with respect to the various elements at stake [34], from a social, environmental and economic perspective. In particular, MCA will show the best-performing alternative in relation to the

initial objective, but it will also provide an insight into the most suitable strategies to implement and, possibly, help to construct new scenarios.

Another important element of the research will concern the direct involvement of citizens through the administration of a questionnaire in order to identify their real needs and habits and define potential guidelines for transformation. In addition, monitoring the behavior of San Salvario residents could be useful in understanding the most relevant assets to implement, at least in the short term. In this perspective, further prospects could concern the application of participatory agent-based models in order to thoroughly evaluate the scenarios under consideration, taking into account the opinions and perspectives of residents and the various stakeholders involved in the process [35, 36].

The analysis conducted and the construction of the proposed scenarios can also contribute to a broader vision of urban development: building people-friendly cities that balance essential daily services with climate and disaster resilience. In this context, open and collective spaces serve a dual purpose, acting as strategic hubs for emergency response and fostering cohesive communities capable of synergetic action. The opportunities provided by models such as Superblocks or the x-minute city fit perfectly into the transformation prospects of contemporary cities that have to deal not only with economic problems, but also social, cultural, healthy, and environmental-climate. However, to minimize resistance and ensure alignment with local needs, all proposals must be developed through a bottom-up approach that prioritizes active community engagement.

Acknowledgments. Part of this work was carried out as part of the 2020 Summer School of the ASP – Alta Scuola Politecnica (Politecnico di Torino and Politecnico di Milano) entitled "Decision making for changing cities" (coordinator: Prof. Marta Bottero). The authors would like to thank the Summer School students for the data used in the research.

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Questionnaire Evolution as a Mirror and Device of Interaction in Socio-Technical Workshops

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Abstract. The paper examines how questionnaires evolved across a series of socio-technical decision workshops supported by Problem Structuring Methods (PSMs) and the MuVAM software. Rather than treating questionnaires as neutral tools for measuring workshop outcomes, the study analyses them as evaluative artefacts that both reflect and shape interaction. Questionnaires are considered part of the intervention architecture because they define relevant dimensions of experience, organise reflection, and influence how participants reconstruct the workshop. The research investigated twelve workshops' questionnaires, in different technological conditions, including sessions involving generative AI. The findings show that questionnaires changed in response to shifts in the workshops themselves: from reflective and value-oriented reports to short surveys focused on group dynamics, and later to more structured instruments addressing AI-supported interaction. Accordingly, the study contributes to the PSMs literature by showing that questionnaire evolution can be used as empirical material for analysing changing interaction regimes in socio-technical workshops, pointing to a form of evaluative performativity in how workshops are assessed.

Keywords: Problem Structuring Methods · questionnaires · socio-technical workshops · evaluative performativity

1 Introduction

Problem Structuring Methods (PSMs) were developed for situations in which neither the problem nor the relevant criteria are fully given in advance, and where action depends on the capacity of stakeholders to articulate concerns, negotiate meanings, and progressively stabilise a workable framing of the situation [1, 2]. In this tradition, facilitated workshops are not impartial venues in which pre-existing preferences are revealed. They are socio-technical settings in which participants, models, facilitation practices, and representational devices jointly shape what the issue is understood to be and how it can be acted upon [3].

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 516–532, 2026.
https://doi.org/10.1007/978-3-032-30524-4_32

From this perspective, evaluation is not a secondary matter. If PSMs' interventions are organised around interaction, then what counts as evidence of their effects depends on how interaction is rendered visible. Much of the literature has assessed interventions through workshop outcomes such as common understanding, commitment, or actionable options, often using interviews, observations, reflective discussions, and questionnaires [4]. Yet questionnaires have seldom been treated as an analytical object in their own right. More commonly, they appear as neutral instruments for registering workshop effects. This is problematic because questionnaires actively shape how workshop experience is articulated and reconstructed. Therefore, rather than treating questionnaires as neutral instruments, this paper conceptualises them as evaluative artefacts that define relevant dimensions of experience and shape how participants reconstruct the workshop.

Recent research makes this issue more pressing. Studies comparing PSMs-supported and non-PSMs workshops have highlighted both the importance and the difficulty of evaluating the usefulness of interventions and of linking process, outcomes, and context in a systematic way [5]. Other work has moved closer to the micro-dynamics of workshops, showing that soft OR interventions matter not only because they produce models, but because they shape how participants negotiate perspectives and values in real time, create knowledge, and agree on solutions [6]. A further extension has shown that representational and aesthetic features of workshop artefacts contribute to knowledge construction, group negotiation, and the formation of a collective orientation to action [7]. Taken together, these studies suggest that workshop artefacts are part of the interactional machinery through which problem structuring unfolds.

This issue becomes even more salient in contemporary socio-technical workshops. Recent work has shown that decision processes increasingly unfold through hybrid arrangements in which digital artefacts, software environments, analytics, and visual supports mediate how stakeholders compare options, stabilise judgements, and negotiate disagreement [8, 9]. In such settings, it is no longer sufficient to ask whether an intervention produced a useful outcome. It becomes necessary to examine how the devices mobilised within the intervention configure interaction itself. A questionnaire is one such device: its design helps organise how the workshop is later understood.

This paper takes questionnaire evolution as an analytical entry point into changing group interaction across a series of socio-technical decision workshops. Rather than focusing primarily on participants' answers, it examines the successive redesigns of the questionnaires themselves: what they ask, when they are administered, how they classify experience, and what forms of interaction they presuppose. Accordingly, the paper does not aim to provide a full case-by-case analysis of workshops, nor a detailed coding of participants' responses and workshop effects, which are addressed in [10]. Instead, it complements that work by examining the questionnaire itself as an evolving object of analysis, focusing on how its redesign progressively reframed participation, classification, and interaction across the workshop series.

Across the workshop series, the questionnaires move from broad reflective prompts oriented to values and overall process appraisal, to shorter *in-situ* surveys focused on involvement and group dynamics, and then to more structured instruments that explicitly track conflict, process phases, and the role of digital and AI-mediated support. These

shifts indicate that questionnaire evolution reflects changing assumptions about what counts as relevant interaction.

The following research question guides the paper: How does questionnaire evolution mirror and configure changing group interaction in socio-technical decision-making workshops? Framed in this way, the contribution is twofold. Substantively, the paper adds to current work on the socio-technical character of PSMs interventions by bringing the evaluative apparatus into view. Methodologically, questionnaire evolution is proposed as empirical material for studying changing interaction regimes, thereby extending calls for more process-sensitive and context-aware analyses of intervention practice.

2 Theoretical Background

The point of departure is the established view that PSMs are model-based, facilitated, participative, and iterative approaches intended to help groups deal with complexity, uncertainty, and conflict. Their distinctiveness lies not only in philosophical orientation but also in the use of transparent, visual, and requisite models that support exchange among multiple stakeholders and help them to look beneath the surface of an issue by sharing and interrogating different frames [11]. This makes interaction central. What matters is not just the model as a technical representation, but the intervention as an organised process in which representations, participants, and facilitation co-evolve. [12], therefore, argues that PSMs interventions should be studied as complex events whose efficacy cannot be grasped through traditional approaches alone. The analytical focus needs to shift towards narratives, networks, and the situated dynamics through which interventions are enacted over time.

A related line of work has emphasised the importance of understanding behaviour and socio-material mediation within PSMs interventions. [3] argue that OR interventions are exemplary settings in which people, artefacts, instruments, and practices interact, and they explicitly note the lack of strong theoretical and empirical studies capable of accounting for these interactions *in situ.* Their discussion of models as mediating artefacts is especially relevant here: models do not simply represent a problem but also help create the conditions for collective behaviour and social learning. Similarly, [13] treat facilitated modelling as a learning mechanism, and [14] recasts models as boundary objects whose cognitive affordances shape the micro-dynamics of collective interventions. This literature suggests that workshop artefacts should not be treated as passive carriers of information. They help structure attention, delimit interpretive possibilities, and support or constrain what can become a shared issue.

This argument resonates with broader socio-technical perspectives. [15] proposes that the use of PSMs can be viewed as a design science concerned not only with models and representations but also with how interventions are embedded in wider processes of action. He explicitly calls for more process knowledge about practice, especially the uncodified elements through which expertise is exercised *in situ.* [8] argue that actionable insight emerges in hybrid arrangements where human judgement, expertise, and data-driven systems are entangled rather than separable. [10], in turn, show that decision-support software creates affordances for shared visualisation, traceability, staged transitions, consensus building, and dissent management in workshop practice.

Together, these contributions reinforce the idea that socio-technical decision support is not reducible to a tool set; it is an interactional accomplishment produced through the alignment of people, representations, and digital artefacts.

For the present study, the most useful extension of this perspective comes from recent work on visual artefacts and performativity. Visual artefacts should be understood as active and performative agents in decision-making processes, capable of guiding negotiation, coordinating actors, and resolving conflicts at key moments. In linking Actor-Network Theory and PSMs, artefacts can be approached as boundary objects that do not merely document decisions but help produce them [9].

This is directly relevant to questionnaires. Although more modest than design drawings or shared digital models, questionnaires are also artefacts that intervene in decision processes. They define categories, prescribe moments of reflection, and shape how participants retrospectively reconstruct what happened. From this standpoint, a questionnaire is both a mirror and a device: a mirror because its evolution reveals what facilitators and researchers increasingly regard as salient in workshop interaction; a device because it helps configure that salience by selecting dimensions, scales, and terms through which interaction is rendered reportable.

This framing also addresses a longstanding problem in the evaluation of PSMs. The assessment of participative and systemic problem structuring methods is complicated by the fact that methods are always used in context, and that what counts as success depends on purposes, values, and local conditions [4]. If evaluations are themselves context-dependent and method-mediated, then their instruments should be examined as part of the intervention ecology rather than as neutral add-ons. The present paper therefore positions questionnaire evolution as empirical material for studying changing interaction regimes. While the paper is grounded in PSMs and socio-technical perspectives, the argument also resonates with broader work in evaluation theory that treats measurement instruments as constitutive rather than neutral. In particular, research on the performativity of metrics and evaluation devices has shown that indicators, categories, and measurement frameworks do not simply capture underlying phenomena but actively shape them by defining what is visible, comparable, and actionable [16, 17]. From this perspective, evaluation involves processes of commensuration through which heterogeneous experiences are translated into standardised forms, thereby reorganising attention, judgement, and action. Applied to PSMs workshops, questionnaires can be understood as commensurative devices that transform situated interaction into reportable categories, while simultaneously structuring how participants interpret their own experience. This extends existing accounts of evaluation in PSMs, which have tended to focus on outcomes and perceived usefulness [4], by showing that evaluative instruments participate directly in the production of the phenomena they are intended to assess. In doing so, it extends existing socio-technical and performative accounts of PSMs' practice to an evaluative artefact that has often remained in the background.

3 Research Design and Data Collection

3.1 Research Design

The study adopts a qualitative, longitudinal, comparative design in which the primary unit of analysis is the questionnaire as an evolving evaluative artefact. Rather than analysing only the substantive content of participants' responses, the study examines how questionnaire formats, prompts, scales, and timings change across successive workshops, and how these changes correspond to shifting workshop configurations and shifting assumptions about what counts as relevant interaction.

In this respect, the design is close in spirit to the participant-centred logic adopted by [10], while addressing a different empirical object. Whereas their analysis focuses on the affordances of decision-support software as perceived by workshop participants, including the qualitative coding of participants' responses and the evolution of observable group dynamics related to the changing decision-support setting, the present study focuses on the evaluative devices attached to those workshops. It therefore does not seek to replicate their case-by-case analysis of workshop outcomes or participant-level effects. Instead, it asks how the evolution of reports and surveys mirrors and configures the changing socio-technical ecology of facilitated decision-making.

The comparative logic is essential. Looking across multiple workshop settings makes it possible to distinguish one-off adaptations from more systematic shifts in the observational regime. The longitudinal logic is equally important, since it allows the reconstruction of a trajectory from delayed reflective reporting to immediate short-form surveying, to AI-oriented questionnaires, and finally to structured pre/post designs. The analytical aim is therefore not to identify a single best instrument, but to understand how different instruments enact different ways of seeing the workshop.

The corpus comprises twelve workshops (Table 1) conducted over several iterations of a decision support software-based teaching and research activity in France, Italy, Slovakia, Albania, spanning Bachelor's, Master's, PhD, and executive-learning settings. Specifically, the workshops were carried out using MuVAM, designed to tackle complex issues through collaborative discussion, the joint development of solutions, and deliberation within a user-friendly interface [10, 18]. The corpus deliberately combines in-place, remote, and hybrid sessions, as well as workshops without AI (WS/01–WS/08) and workshops in which generative AI was explicitly introduced as part of the socio-technical setting (WS/09–WS/14). This diversity is analytically useful because it makes it possible to compare not only different participant cohorts, but also different evaluative needs generated by different intervention formats.

Table 1. Research setting and workshop corpus.

ID	Institution	Programme	Participants	Mode	AI	Output
WS/01	Université Gustave Eiffel, Paris (FR)	Master 2, Sustainable Urban Development	15	In-place	No	Report

(*continued*)

Table 1. (*continued*)

ID	Institution	Programme	Participants	Mode	AI	Output
WS/02	Politecnico di Torino (IT)	Ph.D. Urban and Regional Development	13	In-place + remote	No	Report
WS/03	Politecnico di Torino (IT)	2nd Level Master's Degree in Governance of Resilient Territories	13	Remote	No	Survey
WS/04	Slovak University of Technology, Bratislava (SK)	Erasmus + Project "Blended Intensive Programme", Bachelor's degree	30	In-place + remote	No	Survey
WS/05	Polis University, Tirana (AL)	Horizon Europe Project "GreenFORCE", Bachelor's degree	9	In-place	No	Survey
WS/06	International Training Centre of the ILO, Turin (IT)	Master's Degree in Technology and Public Policy	15	In-place	No	Survey
WS/07	Université Gustave Eiffel, Paris (FR)	Master 2, Sustainable Urban Development	13	In-place	No	Report
WS/08	Politecnico di Torino (IT)	Ph.D. Urban and Regional Development	9	In-place	No	Report
WS/09	Politecnico di Torino (IT)	Master's Degree in Architecture, Construction and City	42	In-place	Yes	Report
WS/10	UGE 2024	Master 2, Sustainable Urban Development	18	In-place	Yes	Report
WS/11	Politecnico di Torino (IT)	Ph.D. Urban and Regional Development	11	In-place	Yes	Report + Survey
WS/12	UGE 2025	Master 2, Sustainable Urban Development	14	In-place	Yes	Report

(*continued*)

Table 1. (*continued*)

ID	Institution	Programme	Participants	Mode	AI	Output
WS/13	University of Parma (IT)	Master's Degree in Architecture for Sustainable Cities	32	In-place	Yes	Survey
WS/14	University of Parma (IT)	Master's Degree in Architecture for Sustainable Cities	59	In-place	Yes	Survey

3.2 Data Collection

Data collection followed an iteratively layered logic and combined delayed reports with immediate surveys. The heart of the dataset is the questionnaire material itself. Rather than privileging just one instrument type, the study reconstructs how different questionnaire forms were attached to different workshop settings and how their prompts evolved as the observed phenomenon changed.

For WS/01–WS/08, data collection relied on two main formats. In workshops where participants had the time to revisit the session after the event, teams were asked to prepare a structured feedback report within approximately three to four weeks. The report template evolved iteratively over time yet retained three almost invariant areas: group dynamics and collective interaction, values guiding collective and individual choices, and collective understanding of the problem. Across successive versions, questions were added, refined, or removed, but the report remained the preferred instrument whenever the aim was to elicit reflective, comparatively rich, and contextually grounded accounts of the workshop process.

Where course schedules or workshop formats did not allow for delayed written reflection, a short survey was administered immediately at the end of the session. These surveys mirrored the core areas of the reports while capturing an in-situ snapshot of the experience. In line with the rationale adopted by [10], the short survey was not treated as a substitute for the report in terms of depth, but as a complementary instrument capable of preserving immediacy, especially on questions related to collective understanding, felt involvement and group dynamics.

A second wave of data collection emerged with the AI-oriented workshops. For WS/09-WS/13, the report architecture was reworked to make the AI contribution directly observable. The prompts asked participants to reflect on the contribution of AI across the different phases of MuVAM, on its influence on group dynamics (including consensus building, dissent management, and the speeding up or slowing down of specific steps) and on the extent to which outcomes corresponded to their own position. In the AI-supported conditions, participants were also asked to document the actual interaction with AI by providing the full sequence of prompts and responses, supported by screenshots. In the workshop without AI, the questionnaire was adapted counterfactually and asked respondents to imagine what AI might have contributed. This redesign is

methodologically significant because it shows that once AI becomes part of the workshop ecology, evaluation can no longer focus only on generic workshop effects; it must explicitly capture hybrid agency and phase-specific mediation.

A third wave is represented by WS/14, where the questionnaire design became more explicitly structured and closer to a pre/post logic. The corpus includes an English pre-survey/post-survey pair. These instruments move beyond broad reflective prompts and decompose the experience into prior familiarity with AI, expectations about its role in decision-making, phase-specific uses during the workshop, types of tasks delegated to AI, and perceived effects on speed, option clarification, trade-off clarification, participation, and control. This phase is especially important for the argument of the paper because it makes clear that questionnaires do not merely follow workshop change; they actively configure what counts as evidence of that change.

Taken together, the dataset is not a single questionnaire administered repeatedly, but a corpus of evolving evaluative devices (Table 2). The analytical value of this corpus lies precisely in the coexistence of stable cores and progressive redesign. The reports preserve a reflective narrative mode. The short surveys preserve immediacy and comparability. The AI-specific instruments add phase-sensitive and socio-technical dimensions. The later pre/post surveys introduce baseline expectations and perceived change. This combination makes it possible to analyse questionnaire evolution not as noise in the dataset, but as part of the phenomenon under study.

Table 2. Data collection waves and dominant questionnaire logic.

Workshop	Main instrument	Dominant evaluative focus	Analytical role
WS/01–WS/02, WS/07–WS/08	Structured feedback reports	Reflective assessment of group dynamics, values, and outcomes	Primary source for delayed, interpretive, and comparatively rich accounts
WS/03–WS/06	Immediate end-of-workshop Google surveys	Collective understanding, involvement, group dynamics, workshop rhythm	*In-situ* complement to the reports; captures immediacy and supports triangulation
WS/09–WS/13	AI-oriented reports and report + survey combination	AI contribution by phase, influence on group dynamics, outcome evaluation, interaction traces	Transitional source showing the shift from human-only to hybrid workshop evaluation
WS/14	Structured AI surveys, including pre/post design	Prior familiarity, expectations, phase-specific AI use, perceived effects on decision-making	Most explicit evidence of questionnaire redesign as a device for observing hybrid interaction

Two brief illustrations help clarify why the questionnaire should be understood here as a practical tool rather than as a neutral recording device. In WS/01, conducted with Master's students in Sustainable Urban Development at Université Gustave Eiffel in Paris, the post-workshop report explicitly asked participants to reflect on the influence of the methodology and software on collective interaction. This prompt elicited a concrete reconstruction of how the shaping and designing phases redistributed voice around the urban-transformation issues under discussion. As reported in the companion analysis by [10], participants noted that "the group's words were much more important than individual words" and that the shared workspace helped ensure that no one was left out of the discussion. In this case, the questionnaire did not merely collect a general judgement of satisfaction: it made visible how the procedure supported compromise formation, equal participation, and the legitimisation of the collectively endorsed problem focus.

A different function emerges in WS/02, held with Ph.D. participants at Politecnico di Torino. Here the questionnaire architecture linked the collective phases more explicitly to the subsequent individual comparison and analysis stages. The answers therefore made it possible to identify the point at which deliberation was translated into a ranked choice. In the related workshop evidence discussed by [10], the analysis phase was described as the moment that allowed participants to "integrate each member's opinion in a standard and systematic way" and to compare individual responses with the final group result; another respondent observed that the methodology led the group "in a direction that we wouldn't necessarily have taken intuitively". The questionnaire thus operated diagnostically: it did not simply register whether agreement had emerged, but clarified where, and through which interactional mechanism, the final decision became collectively stabilised.

4 Findings

The first finding is that the questionnaires do not evolve according to a simple logic of progressive refinement (Fig. 1). They are repeatedly re-specified because the object to be observed changes. In the earliest instruments, the principal concern is to reconstruct how participants experienced the workshop as a whole. The questionnaire functions primarily as a reflective device: it asks respondents to narrate how the methodology affected collective work, which values guided the choices made during the process, and whether the outcome corresponds to their own view of the case. At this stage, the instrument is oriented less toward isolating variables than toward eliciting a second-order account of the intervention.

That orientation changes in the later instruments. Once the workshops begin to incorporate a more explicit concern with group process, and later with AI-supported decision making, the questionnaire no longer asks only what participants thought of the workshop overall. It asks, instead, how understanding was produced, whether people felt involved, how phases affected rhythm, whether all participants were able to contribute, and eventually how AI entered specific stages of the process. The underlying shift is therefore from a holistic reconstruction of the workshop toward a more selective observation of interactional properties.

In this sense, questionnaire evolution mirrors a deeper transformation in the intervention setting. The observed object moves from collective sensemaking around values and

alternatives, to immediate experience of participation and rhythm, then to complexity and conflict management, and finally to hybrid human-AI interaction. The questionnaires change because the workshop changes.

According to this logic, in Fig. 1, each question and related topic is assigned a colour, which is retained even when the wording changes slightly. When a question remains essentially the same, it is connected to the next node by a solid line. When the question changes but stays within the same theme, informing the following one, it is connected by a dashed line, with the thematic addition and/or modification explained in words. The same logic also applies across reports and surveys, showing a process of progressive evolution.

4.1 A Reflective and Value-Oriented Regime

The earliest regime may be described as reflective and value-oriented. In the first report-based instruments, the questionnaire is designed to elicit interpretation rather than measurement. Respondents are asked to reflect on how the different stages of the methodology influenced group dynamics, which values guided the collective and individual phases, and whether the results appear satisfactory. Such prompts assume that the relevant evidence lies in participants' retrospective interpretation of the experience, not yet in the measurement of discrete process variables.

Two implications follow. First, the workshop is primarily observed as an exercise in collective sensemaking. What matters is whether the process helps participants articulate and organise values in relation to a problematic situation. Second, the instrument leaves substantial interpretive space to respondents. It does not impose a strong vocabulary of standardised constructs. Participants are not yet asked to rate agreement, influence, or participation on a scale; they are asked to narrate how the process unfolded and how they situate themselves in relation to its outcomes.

The questionnaire therefore acts less as an external measuring tool than as an extension of the intervention itself. It prolongs the reflective work of the workshop by inviting participants to stabilise, after the event, a particular version of what the collective exercise was about. In this early regime, the questionnaire is already active, but its action is documentary and interpretive rather than decompositional.

4.2 A Short, Immediate, and Interaction-Focused Regime

A second regime emerges when the longer reports are replaced, in several workshops, by very short surveys administered at the end of the session. This transition is consequential because it alters both the temporal position and the analytical grain of the instrument. The questionnaire now seeks to capture immediate experience rather than retrospective interpretation. Its recurring concerns are no longer primarily values and post-hoc evaluation, but collective understanding, involvement, group dynamics, and rhythm.

This shortening is not merely a practical concession to workshop and teaching constraints. It also changes what becomes visible. By privileging questions that can be answered quickly at the end of the session, the instrument foregrounds aspects of interaction that are felt in the moment: whether participants understood the problem better, whether they felt involved, and how the phases affected the pace and quality of the

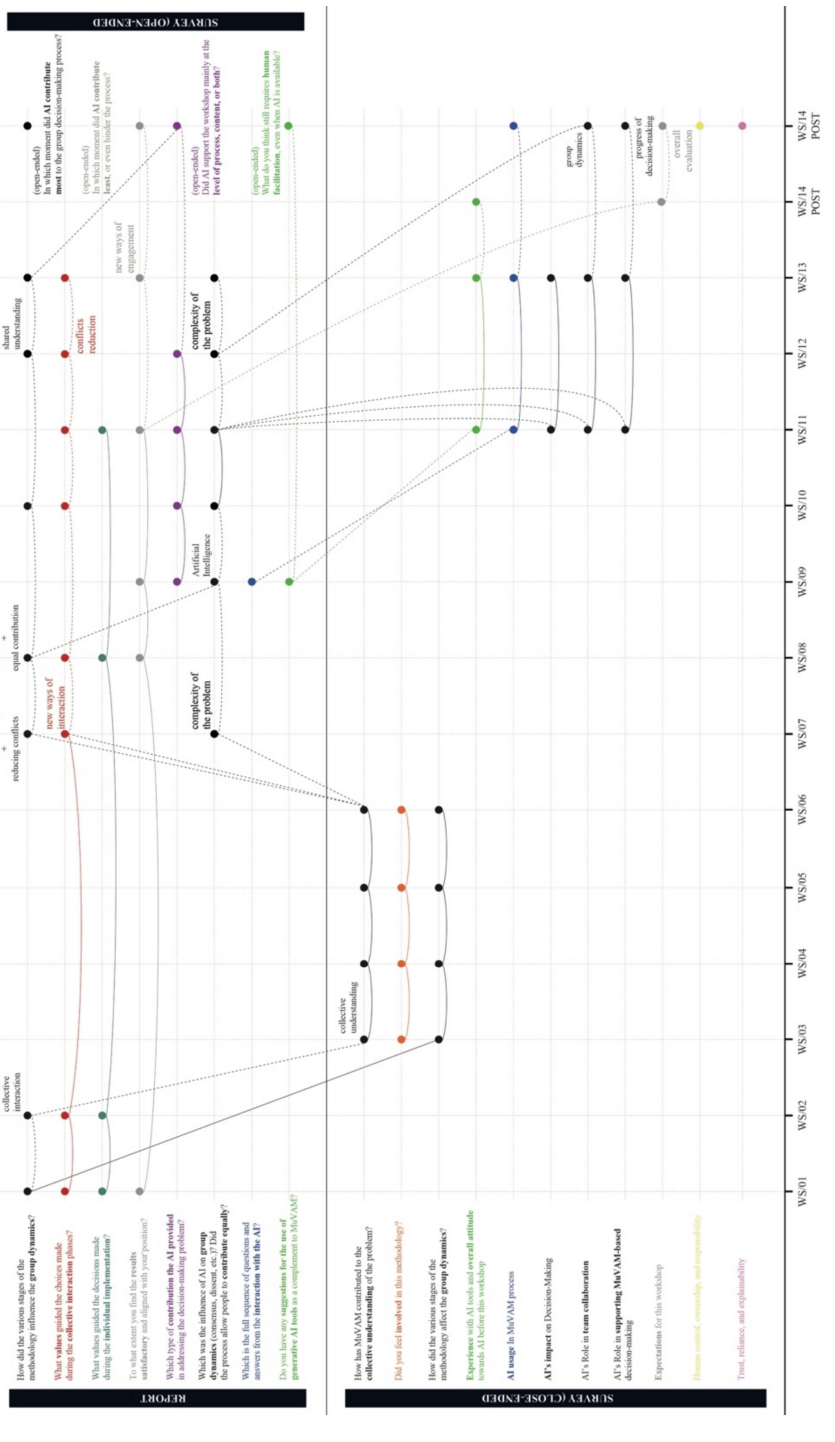

Fig. 1. The evolving structure of the questionnaires.

collective process. The workshop is thus re-specified as an interactional setting whose inclusiveness and temporal rhythm become salient objects of observation. The questionnaire, at this point, begins to produce a taxonomy of categories for group process. Understanding, involvement, and rhythm are not neutral descriptors; they are categories through which respondents are prompted to re-read what just happened. The instrument is therefore already doing more than recording impressions. It is helping to define which dimensions of experience count as relevant.

4.3 From Generic Group Dynamics to Complexity and Conflict in Participation

A further finding is that the questionnaire does not simply become shorter or more structured; it also becomes more selective about which dimensions of interaction deserve explicit attention. In the transitional instruments, generic references to group dynamics begin to give way to sharper concerns with perceived complexity, conflict reduction, equality of contribution, and new modes of engagement in problem solving. This is an important analytical shift because it indicates that the workshop is no longer being observed only as a setting in which participants share values or impressions. It is being observed as a process that may redistribute voice, alter perceptions of problem complexity, and transform the way disagreement is handled.

The introduction of conflict and complexity is especially significant. Earlier instruments tend to imply that the goal of the process is collective clarification and movement toward a satisfactory outcome. The later formulations recognise, more explicitly, that disagreement and uncertainty are constitutive dimensions of these workshops. Conflict becomes something to be managed, reduced, or made productive; complexity becomes something whose perception may itself be transformed through collective work and visualisation. Participation, similarly, is no longer treated only as a feeling of involvement but as a question of whether contributions were distributed more equally across the group.

The consequence is that the questionnaire begins to act as a finer-grained analytical device. It no longer asks simply whether the process was useful; it asks how the process reorganised cognition, disagreement, and voice. This marks a decisive step away from general workshop appraisal toward the observation of interactional mechanisms.

4.4 Explicit Comparison and Hybrid Agency Tracking with AI

The most substantial transformation in the corpus occurs when AI enters the workshop design. At this point, the questionnaire is reorganised around a different problem: not only how the group interacted, but how interaction was reconfigured once an additional sociotechnical actor entered the process. The AI-related instruments ask about the contribution of AI across different stages of the methodology, its influence on group dynamics, the quality of the outputs produced, and the way participants interacted with software, prompts, and externally generated responses. A concrete example can be seen in WS/11, where the Google survey begins by asking respondents to state their group, disciplinary background and nationality, previous experience with AI tools (from no prior experience to expert level), and their initial attitude towards AI in decision-making (from skeptical to highly positive). This design choice does not merely collect descriptive information:

it establishes a baseline of familiarity and trust against which the later use of AI in MuVAM can be interpreted, making hybrid agency empirically observable rather than only theoretically asserted.

This is a major change in the implied ontology of the workshop. Earlier questionnaires treated the intervention largely as human interaction mediated by a methodology and a facilitation environment. The AI-specific questionnaires treat the workshop as a hybrid assemblage in which agency is distributed across people, prompts, interfaces, generated responses, and procedural sequences. The instrument therefore has to change because the phenomenon being observed has changed. Questions about AI contribution, centrality, support, influence, and control are not add-ons to the earlier framework; they indicate that the group process is now being understood as a different configuration of action.

The request, in some cases, to document the exchange with AI through prompts, answers, and screenshots further reinforces this transformation. The questionnaire becomes partly archival. It no longer collects only perceptions of the workshop; it gathers traces of the interactional chain through which the workshop unfolded, particularly through pre/post evaluation in WS/14. In methodological terms, this is a significant move from reflective reporting to process tracing within a socio-technical setting.

4.5 A Variable-Based Decomposition of the Process with AI

Another finding is that the AI-related phase brings with it a stronger decomposition of the workshop into phases, functions, and variables. Earlier instruments asked respondents to reflect on the process as a whole or on broad workshop phases. The later pre/post and post-workshop questionnaires break the process down more systematically: prior familiarity with AI, prior expectations, phase-specific use of AI, types of requests addressed to AI, perceived usefulness, degree of influence on the final decision, and agreement with statements about speed, clarification of options, clarification of trade-offs, and related process effects. The WS/11 Google survey is especially indicative in this respect: by separating prior AI experience from prior normative attitudes towards AI, it already decomposes the socio-technical setting into distinct variables before the workshop begins. In practical terms, this makes it possible to read subsequent differences in reported speed, clarification, or influence not as generic reactions to AI, but as effects filtered through different initial positions of competence, confidence, and critical distance.

This decomposition does not merely increase analytical precision. It changes the mode of observability. The questionnaire is no longer satisfied with asking whether the workshop was useful or whether AI mattered. It defines, in advance, a set of dimensions through which AI's role is to be recognised and judged. This is especially evident in the pre/post architecture of WS/14, which establishes a baseline before the workshop and then channels post-workshop reflection through a structured grammar of hybrid decision making. The instrument thus pre-configures what will count as evidence of change.

Seen in this light, the questionnaire does not stand outside the intervention. It participates in the production of a particular reflective order. Respondents are encouraged to think in terms of centrality, contribution, speed, trade-offs, and human control because the instrument has already declared these to be relevant categories. The questionnaire

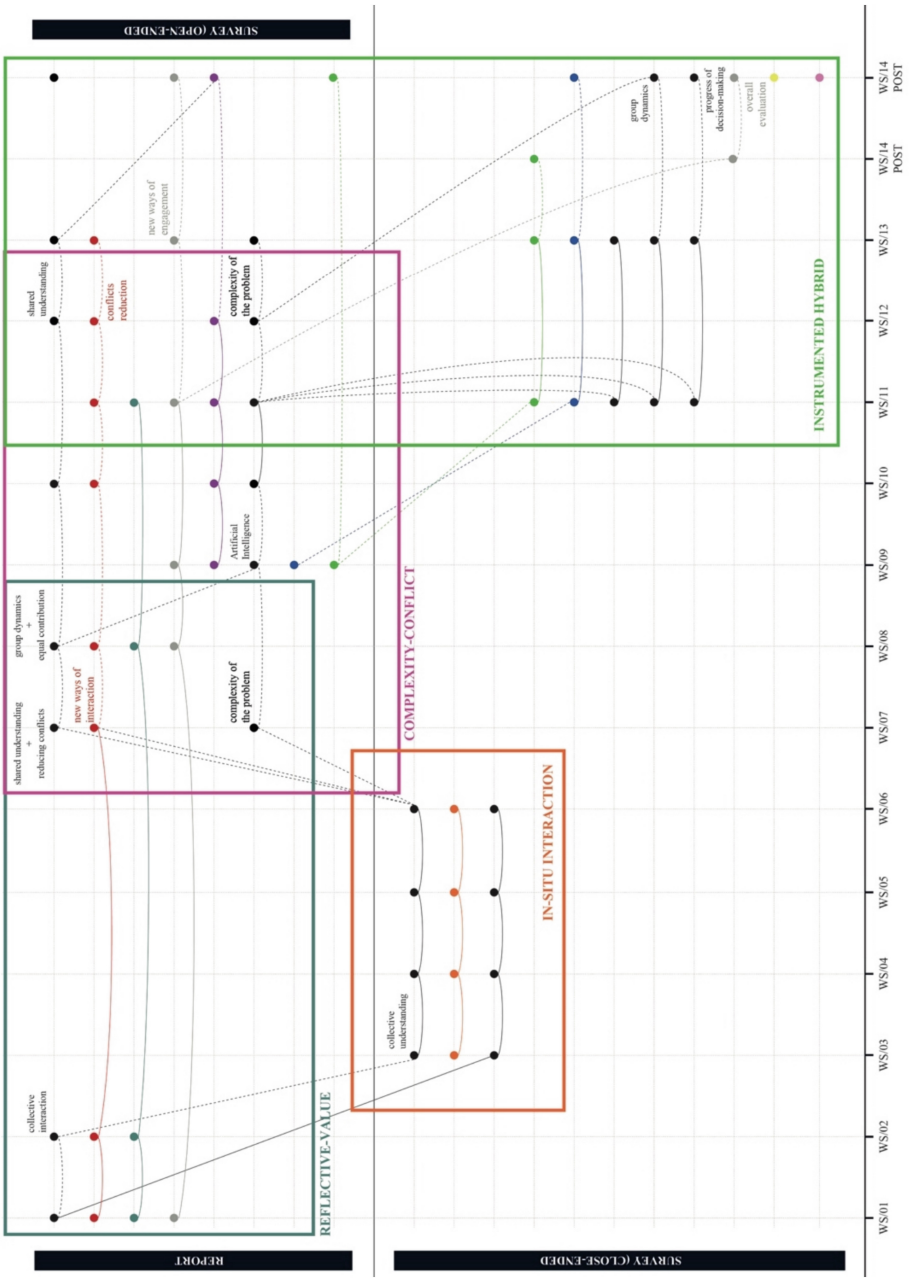

Fig. 2. Four regimes of observation in questionnaire evolution.

therefore acts not only as a mirror of interaction but also as a device that helps make that interaction legible in a specific way.

4.6 Evaluative Performativity

Across the questionnaire corpus, four overlapping regimes of observation can be identified (Fig. 2). The first is a reflective-value regime, centred on participants' values, collective and individual choice, and overall outcomes. The second is an *in-situ* interaction regime, focused on immediate perceptions of understanding, involvement, and group dynamics. The third is a complexity-conflict regime, which foregrounds management of the disagreement, and distribution of participation. The fourth is an instrumented hybrid regime in which the role of digital tools and the contribution of AI emerge within human machine interaction. While elements of these regimes coexist, their relative emphasis shifts over time, reflecting changes in both workshop design and evaluative priorities. The analytical significance of these regimes lies in demonstrating that questionnaires evolution is not simply a matter of refinement or improved measurement. These regimes may be understood as a form of evaluative performativity.

Each regime enacts a different way of rendering interaction observable, moving from holistic, interpretive accounts towards increasingly structured and decomposed representations of process. In this sense, questionnaires do not merely track changes in workshops; they participate in redefining what counts as relevant interaction and how it can be known. The transition across regimes therefore reflects a broader shift from viewing workshops as sites of collective sensemaking to understanding them as socio-technical systems in which interaction is progressively formalised, instrumented, and, in the case of AI-supported settings, distributed across human and technological actors.

5 Conclusions

This paper shows that questionnaires in socio-technical workshops are not neutral instruments for capturing outcomes but active elements of the intervention itself. By examining their evolution across multiple workshops, the analysis demonstrates that questionnaires participate in shaping how interaction is rendered visible, structured, and interpreted. Rather than simply recording participant experience, they define categories, organise reflection, and stabilise particular accounts of what the workshop was and what it achieved. In doing so, questionnaire design becomes part of the process through which collective sensemaking, participation, and, in more recent settings, human–AI interaction is constituted and understood.

This insight matters for both theory and practice. Theoretically, it extends work in PSMs and socio-technical systems by bringing the evaluative apparatus into view as a performative component of intervention, aligning with broader perspectives in evaluation theory that treat measurement as constitutive of the phenomena it assesses. It therefore reframes evaluation not as a downstream activity but as an integral part of how interaction unfolds and is stabilised. This suggests that facilitators and researchers need to treat questionnaire design as a strategic intervention choice rather than a technical afterthought. Different questionnaires privilege different aspects of interaction, such as

values, participation, conflict, or distributed agency, and therefore shape what becomes visible, discussable, and actionable within and beyond the workshop.

An important limitation concerns the paper's strong empirical anchoring in a single decision-support environment, MuVAM, and in workshop settings that were mainly educational and comparatively low-stakes, which means that the identified patterns should be interpreted as analytically suggestive rather than automatically generalisable to other tools, facilitation designs, or higher-conflict decision arenas. Future research should extend this analysis by linking questionnaire design more directly to observed interactional dynamics and outcomes, combining the study of evaluative instruments with *in-situ* observation and response analysis. Comparative work across different PSMs traditions and decision-support settings would help clarify how alternative evaluative designs privilege different forms of knowledge and participation. In addition, the increasing integration of AI into decision processes raises new questions about how evaluation can capture distributed agency, evolving roles, and the balance between human judgement and machine support. Exploring these issues would deepen understanding of how evaluative practices co-evolve with the socio-technical systems they are intended to assess.

Acknowledgments. The authors gratefully acknowledge Zhaowen Liu for her contribution to the drafting of the AI-related questionnaires used in the workshops. During the preparation of this work the authors used Deepl Translate in order to check the translation of the manuscript and ChatGPT 5.0 in order to improve grammar, spelling and readability. After using this service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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

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Evaluating the Socio-economic Impact of Citizen Science: Lessons from 54 European Environmental Initiatives for Urban and Regional Policy

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Abstract. Citizen science (CS) initiatives are increasingly recognised as valuable contributors to environmental monitoring, urban governance, and regional planning. Yet their potential to inform public decision-making is undermined by a persistent evaluation deficit: most projects lack standardised frameworks for assessing their socio-economic impact. This paper presents an empirical analysis of 54 European CS projects drawn from the European Commission's Joint Research Centre inventory of citizen science activities for environmental policies. We examine the extent to which these initiatives adopt socio-economic evaluation methodologies, their documented policy uptake, and their survival beyond initial funding periods. Our findings reveal that half of the analysed projects reported no impact assessment whatsoever, and among those that did, methodological fragmentation (spanning survey-based evaluations, indicator frameworks, and cost-benefit analyses) prevents meaningful cross-project comparison. Despite 65% of projects declaring policy relevance, actual documented policy uptake remains limited. Notably, projects that conducted impact assessments were more likely to continue operating after their initial funding period. These findings have direct implications for urban and regional planning, where the integration of citizen-generated data into decision support systems requires evaluable and comparable evidence. We situate our analysis within recent developments in CS-policy integration and propose directions for standardised evaluation approaches tailored to urban and regional contexts.

Keywords: Citizen science · Impact assessment · Cost-benefit analysis · Urban planning · Environmental policy · Socio-economic evaluation

1 Introduction

Citizen science (CS), the active involvement of non-professional scientists in research activities, has grown substantially over the past two decades, particu-

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 533–549, 2026.
https://doi.org/10.1007/978-3-032-30524-4_33

larly in the environmental domain. European initiatives have engaged citizens in monitoring air quality, tracking biodiversity, and assessing flood risk, among other activities, generating datasets that complement and sometimes provide a greater coverage than those produced by institutional monitoring networks. This growth has been accompanied by rising expectations that CS projects will inform public decision-making at urban and regional levels, contributing to sustainable development goals and evidence-based governance [2,18].

Recent evidence confirms that demand for citizen-generated data in policy contexts is increasing. Callaghan et al. [6] analysed over 1,300 environmental impact statements produced under the US National Environmental Policy Act, finding that 40% incorporated CS data in 2022, compared with just 3% in 2012. At the European level, CS data now contributes to approximately 68% of Global Urban Monitoring Framework indicators [17]. In spatial planning specifically, CS has been shown to instigate behavioural change, cultivate trust towards scientific evidence and policies, and enhance the democratic legitimacy of planning decisions [9].

Yet this growing demand encounters a significant supply-side bottleneck. Despite the proliferation of CS initiatives, the majority do not adopt standardised frameworks for evaluating their socio-economic impact. The absence of such evaluation hinders their capacity to continue their operations and attract funding for the production of comparable evidence [24]. For urban and regional planners seeking to integrate CS into decision support systems, this evaluation deficit represents a fundamental obstacle: without reliable, standardised impact assessments, CS projects cannot be meaningfully compared, aggregated, or incorporated into evidence-based planning processes.

This paper addresses this gap through a qualitative analysis of 54 European CS projects selected from the European Commission's Joint Research Centre (JRC) inventory of citizen science activities for environmental policies [15]. We examine: (1) the extent to which these projects adopt socio-economic evaluation methodologies; (2) the nature and comparability of the evaluation approaches employed; (3) the degree of policy uptake achieved; and (4) the relationship between impact assessment practices and project sustainability beyond initial funding. Our analysis contributes to the understanding of how evaluation practices in CS projects relate to their capacity to provide reliable inputs for urban and regional policy-making.

The remainder of this paper is organised as follows. Section 2 reviews the literature on economic evaluation of CS and its relevance to urban and regional planning. Section 3 describes our data and methods. Section 4 presents the findings across four dimensions: project characterisation, evaluation practices, policy uptake, and post-funding survival. Section 5 discusses the implications and Sect. 6 concludes.

2 Theoretical Background

This section reviews the conceptual and methodological literature that frames the analysis, focusing on definitions of citizen science, approaches to socio-

economic evaluation, and the relevance of these debates to urban and regional policy.

2.1 Citizen Science: Definitions and Impact Dimensions

While no single definition of CS has achieved universal acceptance (Haklay et al. [13] identify over thirty in the academic and policy literature), common features include the participation of non-professional scientists in research activities conducted under the direction of trained researchers, typically involving data collection, analysis, or interpretation. Importantly, not all definitions agree on the voluntary nature of participation, a point with direct consequences for the economic assessment of such projects.

The impacts of CS projects span multiple dimensions. Following Wehn et al. [24], these can be organised into five categories: *environmental* (effects on natural systems), *social* (community building, individual empowerment), *scientific* (knowledge production, data generation), *economic* (financial sustainability, value creation), and *political/governance* (policy influence, civic participation). This multi-dimensionality hinders evaluation, as different impact types require different assessment methodologies and data.

2.2 Economic Evaluation Methodologies

The economic evaluation of CS projects can draw on several established methodologies, each with distinct strengths and limitations [19,21]. *Cost-effectiveness analysis* (CEA) computes the cost per unit of a non-monetary outcome (e.g., cost per data observation), offering comparability within projects using the same indicator but not across projects employing different ones. *Cost-benefit analysis* (CBA), grounded in welfare economics, monetises all costs and benefits, enabling cross-project comparison but requiring extensive data and often contentious monetisation of non-market goods such as health improvements or environmental quality [10]. *Multicriteria analysis* (MCA) accommodates qualitative alongside quantitative dimensions, but produces context-dependent results that resist aggregation [20]. *Return on investment* (ROI), while computationally simple, is limited to projects with identifiable financial returns and lacks time-adjustment [3].

The European Union's CBA guidelines for investment projects [10] provide a standardised framework for cost and benefit identification, discounting, and sensitivity analysis. However, CS projects present specific challenges for CBA: the prevalence of non-market benefits (e.g., increased environmental sensitivity, community cohesion), the difficulty of attributing outcomes causally to project activities rather than confounding factors [12], and the limited availability of data for monetisation. The cost dimension is arguably more tractable, with Alfonso et al. [1] estimating CS data collection costs between €37 and €300 per observation; it is the benefit side that remains largely ad hoc.

The literature proposes several techniques for benefit quantification, including influence in scientific literature [23], environmental attitude measurement [7,16], community monitoring frameworks [8], and data complementarity assessment [1]. Yet these remain fragmented, with researchers often developing bespoke metrics rather than building on existing instruments [22]. The OECD's recent assessment confirms that standardised evaluation guidelines for CS remain absent at the policy level, though six key success factors (funding, legal frameworks, institutional culture, capacity building, infrastructure, and societal dialogue) have been identified as prerequisites for effective integration of CS into research and governance systems [18].

2.3 Citizen Science and Urban/Regional Policy Integration

The relevance of CS to urban and regional planning has been the subject of growing scholarly attention. Beck and Mitkiewicz [2], in a systematic review of 94 studies, identify CS as a tool for fostering sustainable cities and data-driven decision-making, although its integration with policy processes remains an underdeveloped research area. Similarly, Bonhoure et al. [5] highlight the potential of CS to address the complexity of sustainable urban development, while emphasising gaps in the inclusion of underserved communities and in policy integration. Goosse et al. [9], analysing 22 Belgian and Dutch cases, find that CS can strengthen the social relevance and democratic legitimacy of spatial planning decisions, but only when evaluation mechanisms are in place to demonstrate outcomes to decision-makers.

The role of CS in policy can be conceptualised along four dimensions [14]: as a source of information for policymaking, as an object of research policy, as a policy instrument, and as a form of sociotechnical governance. For urban and regional planning, the first dimension is most immediately relevant: CS projects that produce evaluable, comparable evidence can serve as decision support systems for sustainable development, environmental monitoring, and participatory governance. However, the absence of standardised evaluation frameworks fundamentally constrains this potential.

3 Methodology

This section describes the empirical basis of the study and the analytical choices used to examine the selected projects, including the data source, selection criteria, and variables of interest.

3.1 Data Source and Selection Criteria

The empirical basis for this analysis is the European Commission Joint Research Centre's dataset "An inventory of citizen science activities for environmental policies" [15]. The dataset originates from a study developed by Bio Innovation Service (FR) in collaboration with Fundación Ibercivis (ES) and The Natural

Table 1. Variables used for project screening and analysis. Source: authors' elaboration based on the JRC inventory [15].

Variable	Description	Source
Geographical extent	Projects classified as at least "macro-regional".	JRC inventory
Start year	Projects starting in 2007 or later.	JRC inventory
Documentation availability	Excluded inactive, undocumented, or non-English cases.	Authors' screening
Project objectives/thematic focus	Used to define the substantive scope of each initiative.	Project documentation
Stakeholder involvement	Main actor groups engaged in project activities.	Project documentation
Policy uptake/involvement of public actors	Evidence of public authority participation, policy outputs, or documented uptake.	Project documentation
Post-funding survival	Continuation, partial continuation, or no evidence/not ascertainable.	Websites and follow-up traces
Impact assessment methodology	None, survey-based, indicator-based, cost-benefit analysis, or mixed.	Deliverables, reports, and articles

History Museum (UK), and documents 503 CS projects of relevance to environmental policy and the United Nations Sustainable Development Goals, providing descriptive information on project topics, dates, geographical extent, countries of implementation, policy aims, and SDG contributions.

To select projects comparable in scale and scope, we applied two screening criteria. First, geographical extent was restricted to at least "macro-regional", ensuring sufficient scale for policy relevance. Second, a start year of 2007 was set as a baseline to ensure comparability of technological solutions. These criteria reduced the sample to 126 projects. A further restriction based on the availability of relevant documentation (excluding projects with inactive websites, unavailable deliverables, or non-English documentation) yielded a final sample of 54 projects. The substantial attrition from 126 to 54 is itself a noteworthy finding, suggesting either poor survival rates or limited attention to documenting impact.

3.2 Variables of Interest and Analytical Approach

For each selected project, a documentary analysis of public deliverables, scientific articles, and project websites was conducted to identify the variables reported in Table 1.

These variables were chosen to capture multiple dimensions of CS project impact relevant to urban and regional policy: the objective defines the scope for evaluation; stakeholder involvement indicates the breadth of engagement;

policy uptake signals relevance to governance; post-funding survival indicates long-term viability; and evaluation methodology reflects the project's capacity to produce comparable evidence. The analysis is limited by its reliance on publicly available documentation; projects may have conducted evaluations that were not published or accessible.

4 Results

This section presents the findings of the analysis, moving from the overall characterisation of the selected projects to their evaluation practices, policy uptake, and post-funding sustainability.

4.1 Characterisation of Selected Projects

The 54 selected projects display heterogeneity across several dimensions. Table 2 presents the full list of analysed projects, reporting duration, whether a publicly available impact assessment was identified (IA), the continuation status after the initial funding period (Cont.), and thematic domain. Projects marked with an asterisk are the illustrative cases discussed more explicitly in the text and were selected through a maximum variation sampling strategy [25] to ensure representation across three key dimensions: (i) impact assessment status (projects with and without documented evaluation), (ii) post-funding continuation outcomes (full continuation, partial continuation, and cessation), and (iii) thematic domains (spanning water management, air quality, biodiversity, road sustainability, humanitarian mapping, and others).

Regarding policy relevance, out of the 54 projects, 43% held relevance in the field of policy monitoring or implementation, 33% in problem definition, 15% in early warning, and 9% in policy evaluation. This distribution suggests that CS projects predominantly serve as input providers to existing or emerging policies, rather than contributing to the formulation of new ones, a finding with direct implications for their role in urban and regional planning cycles, where the demand is precisely for evidence that can support monitoring, assessment, and iterative adjustment of planning decisions.

The temporal distribution reveals a pronounced spike in 2016, with 20 of the 54 projects starting that year, likely linked to the implementation of the Horizon 2020 programme and its dedicated actions on societal challenges, green development, and citizen engagement. The publication of the Green Paper Citizen Science Strategy 2020 for Germany in the same year further illustrates the growing institutional recognition of CS during this period. The most common type of project initiator is academia (52%), followed by consortia of both public and private entities (22%), governmental organisations (13%), non-governmental organisations (7%), and private organisations (6%). The dominance of academic initiators is relevant to the evaluation question: academic-led projects might be expected to have greater potential for rigorous assessment, yet even within this group, evaluation practices were inconsistent.

Table 2. Complete list of 54 CS projects analysed. Projects marked with an asterisk are the illustrative cases discussed more explicitly in the text. IA = Impact Assessment (Y/P/N); Cont. = Continuation (Y/P/N/A). Source: authors' elaboration based on JRC inventory [15].

Project	Duration	IA	Cont.	Domain
AirSensEUR	2016–19	N	P	Air quality
∗ BEWATER	2014–17	Y	Y	Water
∗ BigPicnic	2017–	Y	P	Food security/RRI
BioVill	2016–	Y	P	Sustainable consumption
∗ BlueSCities	2017–	N	P	Water/waste integration
CAPSELLA	2016–	Y	P	Biodiversity
CAPTOR	2016–	Y	P	Air quality
CASI	2014–17	P	P	Climate
∗ CITCLOPS	2014–	Y	P	Coastal monitoring
∗ CITI-SENSE	2012–	Y	P	Environmental sensing
∗ Cities at Night	2014–	N	Y	Light pollution mapping
∗ COBWEB	2012–	Y	Y	Crowdsourcing platform
COST Action Citizen Sensor	2012–	N	P	Land monitoring
∗ Crowd4Roads	2016–	Y	Y	Road sustainability
D-NOSES	2018–	N	P	Air quality
Decarbonet	2013–16	Y	P	Sustainable consumption
ENABLE.EU	2016–	Y	P	Sustainable consumption
EU BON	2012–	N	P	Biodiversity
EuroBirdPortal	2016–	Y	P	Biodiversity
FoodSmartphone	2017–	N	P	Resource efficiency
∗ GAP2	2011–15	Y	P	Fisheries governance
Greenmapper	2016–	N	P	Land monitoring
Ground Truth 2.0	2016–	Y	P	Biodiversity
∗ GROW	2016–	N	Y	Soil/water monitoring
∗ hackAIR	2015–	Y	Y	Air quality platform
Hercules Landscapes	2013–	N	P	Biodiversity
∗ Humanitarian OSM	2010–	N	Y	Humanitarian mapping
I-REACT	2016–	Y	P	Cross-cutting
ICARUS	2016–	N	P	Air quality
InSPIRES	2017–	Y	P	Environmental health
INTAROS	2017–	N	P	Sustainable consumption
∗ INTERACT	2010–16	N	Y	Arctic monitoring
ISABEL	2015–	N	P	Resource efficiency
iSCAPE	2016–	Y	P	Air quality

(*continued*)

Table 2. (*continued*)

Project	Duration	IA	Cont.	Domain
∗ iSpot	2008–	N	Y	Biodiversity observation
Landsense	2016–	N	P	Land monitoring
LIFE AskREACH	2017–	N	N/A	Environmental health
LIFE EUROLARGECARNIVORES	2017–	Y	N/A	Biodiversity
NETLAKE	2012–16	N	P	Water
∗ Noise Tube	2008–	Y	Y	Noise monitoring
Omniscientis	2012–14	N	P	Air quality
PERARES	2010–14	Y	P	Cross-cutting
PERSEUS	2011–	P	P	Sustainable consumption
∗ POWER	2015–	Y	Y	Water awareness
PROSO	2016–18	N	P	Sustainable consumption
SAF21	2015–	N	P	Sustainable consumption
Scent	2016–	N	P	Land monitoring
SeaChange	2015–	Y	P	Biodiversity
∗ STARS4ALL	2016–	N	Y	Dark sky preservation
Vespa Velutina	2016–	Y	Y	Biodiversity
Waste4Think	2016–	Y	P	Waste management
Water Shrew Survey	2017–	N	Y	Biodiversity
∗ WeObserve	2017–	Y	Y	CS mainstreaming
Women for Water Partnership	2016–	Y	Y	Sustainable consumption

4.2 Impact Assessment Practices

The most striking finding is that half of the analysed projects did not report any impact assessment or, if conducted, did not publicly share results. This finding is consistent with the barriers identified in the literature, including the mismatch between project durations and the longer-term nature of impact materialisation, limited resources for evaluation, and the absence of standardised methodologies [24]. For urban and regional planning, this means that roughly half of the potential CS evidence base is entirely invisible to decision-making processes.

Among the remaining 27 projects, three main evaluation approaches were identified, along with one mixed methodology case. The distribution of these approaches (expressed below as percentages of the total 54 projects to convey the scale of each category relative to the full sample) is itself revealing of the methodological fragmentation that characterises the field.

Survey-Based Evaluation. Approximately 19% of the sampled projects (10 initiatives) relied on questionnaires administered to end users, project partners, or external experts. These surveys typically assessed progress towards project

objectives, strengths and weaknesses of developed solutions, and user acceptance. Evaluation forms were dispensed on various occasions, including thematic events and workshops, and were sometimes complemented by structured and semi-structured interviews.

Two distinct orientations were observed. First, evaluation forms have been administered to project partners, advisory board members, or external experts, aimed at assessing progress towards objectives, sometimes at different implementation stages, yielding recommendations and good practices. Second, forms have been administered to end users, aimed at evaluating the acceptance of solutions developed during pilot implementation, including feedback on perceived environmental, social, and economic impacts.

Survey-based evaluation yields project-specific results that are difficult to compare across projects. In anonymised project #1, CS was combined with collaborative learning and environmental grassroots activism through a generic questionnaire tailored to each pilot's specific needs. The resulting data captured perceptions of CO_2 reduction, awareness of cultivation methodologies, and economic impacts such as agricultural income and job creation, but the format remained unique to that project.

Impact Indicator Evaluation. Another 19% of the sample (10 projects) employed quantitative and qualitative indicators to assess multi-dimensional impact. Two sub-approaches were observed within this category.

Projects in the first sub-category defined ad hoc key performance indicators (KPIs) aligned with their specific objectives. This tailor-made approach produces indicators highly specific to the project's activities but lacking in comparability and replicability. Examples include the availability of project deliverables, the number of conferences organised, and the capacity of citizens to influence policies on project-specific topics.

Projects in the second sub-category drew on established frameworks, most notably the Impact Assessment for Social Innovation (IA4SI) methodology [4], developed within the Collective Awareness Platforms for Sustainability (CAPS) domain. Three of the ten projects in this category adopted the IA4SI framework, selecting from its vertical indices those that aligned with their foreseen impact areas. Table 3 presents a representative set of indicators from one anonymised project, illustrating the range of measurable dimensions across social, environmental, economic, and political areas.

The anonymised project #2, focused on air quality awareness and forest fire probability, combined IA4SI-derived indices with project-specific indicators and behavioural change experiments. The most prominent behavioural impacts were recorded in terms of citizen empowerment in local policy definition, perceived and actual knowledge of air pollution, and soft mobility behaviour. While this approach offers greater structure than pure survey-based evaluation, the selective adoption of framework elements still limits full comparability across projects.

Cost-Benefit Analysis. Only six projects (approximately 11%) adopted formal CBA frameworks. This low uptake is significant given that CBA is the methodology most suited to inform allocation decisions and enable cross-project comparison of socio-economic returns, precisely the evidence that urban and regional planners require.

The projects that did employ CBA shared a common feature: clear-cut definitions of expected impact areas and identifiable benefits, including health improvements from better environmental conditions and avoided costs from reduced disaster risk. Project implementation costs were generally tractable through accounting records and internal investigations with partners, covering both investment costs (capital expenditure for solution development) and estimated running costs (maintenance, based on partner expectations).

Benefit estimation, by contrast, required substantially greater methodological effort. Benefits were typically framed either as positive gains (e.g., health improvements from better air quality) or as avoided costs (e.g., reduced life risks, averted infrastructure damage from flooding). The anonymised project #3, focused on emergency management and flood risk, defined a CBA case at the national level of one pilot country, collecting information through interviews, working sessions, and stakeholder consultations to define costs (CapEx, OpEx, disaster damages) and benefits (social benefits, avoided costs from system adoption).

The difficulty of monetising non-market benefits (such as increased environmental sensitivity, community cohesion, or civic participation) remains the principal barrier to wider CBA adoption in CS [11]. This challenge is compounded by the externality problem: many CS benefits operate outside market mechanisms, requiring estimation techniques (stated-preference surveys, revealed-preference methods, value transfer) that add complexity and cost to the evaluation process [10].

Mixed Methodology. One project adopted a distinctive approach, combining multiple evaluation strands tailored to different solution types. For passive environmental control systems and behavioural change interventions, economic methods from the literature (hedonic pricing, meta-analysis) were deployed to estimate health-related benefits from air quality improvements. For policy-related interventions, living labs, and CS activities, MCA-based indicators were used to capture predominantly social impacts on quality of life. This modular approach, while sophisticated, further illustrates the field's tendency towards bespoke solutions that resist standardisation.

4.3 Policy Uptake

Thirty-five of the 54 projects either mention policy aims in their documentation, issue recommendations or policy briefs, or involve public authorities in project activities. While a third of the initiatives reported not having a declared policy aim, all projects were nonetheless classified as having some form of policy

relevance in the JRC inventory, distributed as noted in Sect. 4.1. This seems to ascribe to CS projects a role limited to providing inputs to already existing or emerging policies, rather than contributing to the formulation of new ones.

However, the actual documented uptake of results by local or regional authorities is very limited, despite these stated ambitions. Three principal barriers were identified from the project documentation:

First, *limited trust in citizen-provided data* on the part of public authorities. Several projects reported resistance from decision-makers who perceived citizen-generated data as less reliable than data from established institutional monitoring networks. This trust deficit is particularly relevant for urban planning contexts, where data quality requirements for regulatory decisions are stringent.

Table 3. Representative impact indicators from an anonymised project, based on the IA4SI framework [4].

Impact Area	Dimension	Indicator Examples
Social	Community building	Number of platform users (start vs. end); degree of communication
	Information access	Perceived improvement in information access; influence on information asymmetries
	Behavioural change	Number of engagement participants; change in opinion and awareness
Environmental	Environmental behaviour	Compensation activities since engagement
	Sensitivity	Capacity to increase users' sensitivity towards pollution
Economic	Empowerment	Impact on entrepreneurship and access to finance
Political	Civic participation	Increase in grassroots organisations; participation in campaigns

Second, *institutional reticence to depart from traditional paradigms*. Public authorities were recorded as reluctant to adopt systems perceived as less mature and "experimental", preferring established data collection methods even when CS alternatives offered broader spatial or temporal coverage.

Third, *insufficient project duration* to document actual policy influence. The timeline of most projects (typically two to four years) does not align with the longer cycles of urban and regional policy development, making it difficult to trace the pathway from project outputs to policy adoption.

The most notable exception involved a project that successfully influenced new legislation and licensing activities, directly attributable to the systematic involvement of local authorities in all phases of its demonstrators. While collaboration with public authorities is beneficial, as it shapes project activities to align

with public needs, this does not automatically imply policy translation. The lesson for urban and regional planning is that CS-policy integration requires deliberate institutional design, embedding public authorities as co-creators rather than passive recipients of project outputs.

It is also worth noting the role that CS projects can play in the policy cycle beyond direct adoption. Following the typology proposed by Haklay [14], CS may function as a source of information for policymaking, as a policy instrument, or as a form of sociotechnical governance. Our data suggest that most projects in the sample operate in the first mode, generating data and knowledge, but few succeed in transitioning to the second or third modes, where CS actively shapes or constitutes governance processes.

4.4 Post-funding Sustainability

Out of 54 projects, 16 (30%) reported some form of continuation beyond the initial funding period, through mechanisms such as the creation of foundations, the persistence of user communities, or the generation of successor projects. Conversely, nearly half (24 projects) either lacked an active website or showed no evidence of recent updates. The remainder had developed business plans or commercialisation strategies without documented evidence of actual continuation.

A particularly noteworthy finding is that more than half (9 of 16) of the projects that reported continuation had also conducted an impact assessment, a proportion modestly above the sample-wide base rate of 50% (27 of 54). While this correlation does not establish causality, it suggests that the practice of evaluating socio-economic impact may be associated with the development of evidence that supports funding decisions and institutional support for project continuation, a dynamic directly relevant to the long-term integration of CS into urban governance structures.

5 Discussion

Our analysis reveals four interconnected findings with implications for the integration of CS into urban and regional planning.

A Systematic Evaluation Deficit. Half of the analysed CS projects reported no impact assessment. This is not merely an academic gap; it represents a fundamental barrier to the use of CS outputs in evidence-based urban and regional planning. Decision support systems require evaluable inputs; without standardised assessment, CS projects produce data that may be scientifically valuable but remains invisible to planning processes that demand quantified, comparable evidence of costs and benefits.

Methodological Fragmentation. Among the projects that did conduct evaluations, the diversity of approaches (from ad hoc surveys to IA4SI indicators to

formal CBA) prevents meaningful cross-project comparison. This fragmentation echoes the broader finding that CS impact assessment lacks standardised guidelines [18,24]. For urban and regional planners, this means that even when evaluation evidence exists, it cannot be aggregated across projects to inform portfolio-level decisions about CS investment.

A Disconnect Between Policy Ambition and Policy Uptake. While 65% of projects declared policy relevance, actual documented uptake was limited. The barriers identified (institutional distrust, perceived immaturity, short project durations) align with the broader literature on CS-policy integration challenges [2,5]. The contrast with Callaghan et al.'s [6] finding of rapidly growing CS incorporation in environmental impact statements suggests that the bottleneck lies primarily on the supply side: projects are not producing the evaluable evidence that policy processes demand.

Evaluation and Sustainability. The correlation between impact assessment and post-funding survival, while not causally established, suggests that evaluation practices may contribute to project sustainability. Projects that quantify their impact are better positioned to justify continued funding, attract institutional support, and demonstrate value to urban and regional authorities. This is consistent with the OECD's [18] identification of funding and institutional culture as key success factors for CS.

These patterns are not distributed uniformly across project contexts. Projects operating at broader territorial scales and led by academic or multi-actor consortia more often produce formal documentation and declare policy relevance, but this does not automatically translate into documented uptake by public authorities. By contrast, the few cases showing clearer policy influence appear to be those with stronger institutional anchoring and more direct involvement of public actors in project activities. Likewise, post-funding continuation seems more plausible where project outputs remain embedded in an identifiable organisational or territorial setting, rather than depending solely on the lifespan of the original grant.

These findings suggest that the development of standardised, yet flexible, evaluation frameworks for CS, tailored to the specific needs of urban and regional planning contexts, would address multiple gaps simultaneously. We propose that such frameworks should satisfy five requirements:

Multi-dimensionality. The framework must accommodate the environmental, social, scientific, economic, and political dimensions of CS impact, as these are rarely reducible to a single metric. The IA4SI framework [4] offers a useful starting point, but requires extension to incorporate the cost-benefit dimension that European guidelines [10] require and that planning practitioners need to justify resource allocation decisions.

Comparability. Outputs should be structured to enable meaningful comparison across projects, regions, and temporal periods. This requires a core set of

common indicators, complemented by domain-specific modules that capture the particularities of different CS applications (e.g., air quality monitoring versus biodiversity mapping).

Resource Efficiency. Given the inherent funding and staffing constraints of CS projects, evaluation methods must be deployable without disproportionate cost. The finding that CBA (while most informative) was adopted by only 11% of projects reflects the heavy data requirements that deter its use. Simplified CBA approaches or cost-effectiveness proxies may offer more practical alternatives for routine evaluation.

Accessibility. Evaluation tools should be usable by non-specialists, reflecting the diverse composition of CS project teams that include academics, community organisations, and citizen volunteers [22]. Template-based approaches, with built-in guidance on data collection and analysis, could lower the entry barrier.

Policy Legibility. Outputs must be formatted and communicated in ways that are interpretable by urban and regional planners, municipal decision-makers, and funding bodies. This means translating multi-dimensional assessments into summaries that can inform portfolio-level decisions about CS investment, for example through composite indices or standardised reporting templates aligned with established planning frameworks such as the Global Urban Monitoring Framework [17].

A further consideration concerns the timing of evaluation. Our analysis reveals that most projects that conduct assessments do so ex post, typically at or near the end of the funding period. Yet the European CBA guidelines [10] emphasise the value of ex ante evaluation for allocation decisions. An integrated approach, combining ex ante assessment at the planning stage with ex post evaluation for accountability and learning, would better serve the needs of urban and regional governance, where both prospective planning and retrospective accountability are required.

6 Conclusions

This paper has presented an empirical analysis of socio-economic evaluation practices across 54 European citizen science initiatives in the environmental domain. Our findings reveal a persistent evaluation deficit that constrains the integration of CS into urban and regional policy-making: half of the projects lacked any reported impact assessment; those that did conduct evaluations employed heterogeneous and non-comparable methodologies, and the gap between declared policy ambitions and documented policy uptake remains substantial.

The contribution of this work is threefold. First, it provides systematic empirical evidence on the state of evaluation practices across a substantial sample of European CS projects, confirming and extending findings from the recent literature [2,24]. Second, it identifies the correlation between impact assessment

and post-funding sustainability, offering a pragmatic argument for evaluation investment. Third, it frames the evaluation deficit specifically in terms of its consequences for urban and regional planning, where the demand for citizen-generated data is growing [6,17] but the supply of evaluable evidence remains inadequate.

A further result is that the implications of citizen science are not uniform across territorial and institutional contexts. Projects operating at broader scales or within structured multi-actor consortia more often produce formal documentation and declare policy relevance, whereas clearer examples of policy uptake tend to emerge in place-based initiatives where public authorities are involved more directly in project activities. Likewise, post-funding continuation appears more plausible when project outputs remain embedded in a specific organisational or territorial setting. This contextual variation helps explain why the same evaluation deficit generates uneven consequences across urban and regional governance contexts.

Our study is subject to limitations. The analysis relies on publicly available documentation and English-language sources, potentially underestimating the evaluation efforts of projects that publish in other languages or do not make their assessments publicly available. The JRC inventory, while comprehensive, reflects a particular point in time (2018) and the CS landscape continues to evolve. The anonymisation of detailed case studies, while necessary, limits the specificity of the methodological examples.

Future work should develop standardised evaluation toolkits for CS projects operating in urban and regional contexts. These toolkits could build on frameworks such as IA4SI [4] while incorporating the cost-benefit dimension called for by the OECD [18] and European guidelines [10]. A further extension of this research would be an exploratory cluster analysis based on variables such as territorial scale, policy relevance, evaluation methodology, stakeholder configuration, and post-funding continuity, in order to identify recurring profiles of citizen science initiatives across different governance contexts. Longitudinal studies tracking the evolution of CS-policy integration, particularly in the context of smart city initiatives and participatory urban governance, would further illuminate the pathways through which citizen-generated evidence enters planning processes.

Acknowledgments. This work was supported by the SOCIO-BEE project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 101037648. The authors wish to thank the project consortium partners for their contributions to the data collection and analysis.

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

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Integrating ESG+ Metrics into Urban Green Infrastructure: A Comprehensive Sustainability Rating Framework

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Abstract. Urban Green Infrastructure (UGI) plays a crucial role in improving environmental performance, resilience, and quality of life in cities. However, existing sustainability assessment frameworks remain insufficient for urban-scale evaluation. Environmental, social, economic, and governance (ESG+) dimensions are not fully integrated at the urban scale. This gap motivated the development and application of the Green Infrastructure Sustainability Performance Assessment Model (GISPAM), a structured framework for evaluating the sustainability performance of UGI projects. The model has twelve criteria in four sustainability dimensions and applies a normalization, weighting, and aggregation process using the Rank Order Centroid (ROC) method and Multi Attribute Value Theory (MAVT). The framework contains three international case studies which are The High Line (USA), Cheonggyecheon Stream Restoration (South Korea), and Madrid Río (Spain). The results highlight the importance of multidimensional assessment and explain the practical applicability of GISPAM. GISPAM can be used as a transparent and comparable decision-support tool for UGI planning and management.

Keywords: Sustainability Assessment · Urban Green Infrastructure · Multi-Criteria Decision Aiding (MCDA)

1 Introduction

In recent decades, sustainability has become a major concern in urban planning and infrastructure development in cities. In this context, the Urban Green Infrastructures (UGIs) play a crucial and fundamental role in improving environmental performance and resilience. This is also reflected in the United Nations New Urban Agenda [1], which highlights the role of sustainable and resilient urban infrastructure in supporting inclusive and environmentally responsible urban development. However, less attention has been paid to decision-making processes for UGI, particularly regarding long-term management and performance evaluation. Since the 1990s, sustainability assessment in

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2026
O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 550–562, 2026.
https://doi.org/10.1007/978-3-032-30524-4_34

the built environment has developed and evolved from focused approaches to more integrated frameworks. Recent sustainability assessment models adopt a multidimensional perspective, integrating environmental, social and economic dimensions. In this context, several sustainability assessment frameworks, such as LEED, BREEAM and Envision, have been developed to provide structured assessment schemes [2]. Although these systems have expanded beyond the building scale to include urban communities [3], they still lack comprehensive and specialized integration of ESG (environmental, social, and governance) principles in general, but more specifically for green infrastructure. Furthermore, they often prioritize environmental metrics without fully incorporating governance efficiency as an integrated and equally important pillar. In addition, urban green infrastructure projects often involve multiple stakeholders, long-term management responsibilities, and trade-offs between ecological, social, economic, and governance objectives. For this reason, their assessment requires decision-support tools capable of integrating heterogeneous criteria and making sustainability priorities explicit. This is particularly relevant when comparing projects developed in different urban, institutional, and geographic contexts.

To bridge this gap, this study implements a framework based on multi-criteria decision analysis (MCDA), specifically with the application of multi-attribute value theory (MAVT) [4] to support decision-making in the context of UGIs [5]. In particular, the framework named Green Infrastructure Sustainability Performance Assessment Model (GISPAM) aims to integrate the concept of ESG+ rating to simultaneously assess environmental, social, economic and governance performance and to enable stakeholder involvement in the weighting and prioritization of criteria, ensuring that the assessment reflects the different priorities of decision makers (DMs).

This chapter is organized as follows: Sect. 2 reviews the existing literature on sustainability rating systems and ESG dimensions. Section 3 describes the methodology, focusing on the MAVT approach and stakeholder engagement. Section 4 presents the GISPAM model and its hierarchical structure, while Sect. 5 discusses the application of the model to case studies. Finally, Sect. 6 concludes and suggests future research directions.

2 Methodology

The research framework is based on MAVT to structure the sustainability assessment of urban green infrastructure. The process began with the conceptualization of an ESG+ framework, where twelve key criteria were identified across environmental, social, economic, and governance dimensions. To ensure that the model aligns with practical urban planning priorities, a panel of experts with academic and professional expertise in urban sustainability was consulted to define the value functions for each indicator and establish the relative importance of the criteria. To address the inherent subjectivity of the weighting process, the SMARTER method (Simple Multi-Attribute Rating Technique Exploiting Ranks) [11] was employed to translate expert rankings into surrogate weights through the Rank Order Centroid (ROC) method. All qualitative and quantitative indicators were then normalized to a dimensionless value scale ranging from 0 to 1 based on the identified value functions. Finally, sustainability performance was aggregated

using the MAVT additive model to calculate a synthetic index. This decision support framework enables a transparent assessment of trade-offs, supporting policy makers in evidence-based infrastructure management.

2.1 ESG-Based Criteria Selection

The selection of metrics started with the identification of the most recurring indicators in the environmental, social, economic, and governance dimensions of the built environment. This initial set was then refined to eliminate methodological redundancies and conceptual overlaps, ensuring that each criterion represented a distinct aspect of sustainability. This filtering process was essential to prevent double counting during the aggregation phase.

The criteria were selected based on two fundamental requirements: direct applicability to urban green infrastructure projects and the availability of real, accessible data. At the end of this process, twelve key criteria were identified, which form the backbone of the GISPAM.

For instance, in the renewable energy integration indicator, a value of 0 Wp/m^2 corresponds to a normalized score of 0.0, while a value of 10 Wp/m^2 corresponds to a score of 1.0. Values between these thresholds are calculated proportionally using a linear normalization function (Table 1).

Table 1. Criteria and Indicator Tables

Dimension Name	Criteria Name	Indicator
1. Environment	1.1 RES Integration	0.0–0 Wp/m^2; 0.5–2 Wp/m^2; 1.0–10 Wp/m^2
	1.2 Potable Water Reduction for Irrigation	0% - Fully potable water; 50% - Half potable half alternative water; 100% - Fully alternative water
	1.3 - Climate Adaptation and Resilience	0–5 °C temperature reduction (ΔT)
2. Social	2.1 - Universal Accessibility	0.0–30% accessible pathway network; 0.5–65% accessible pathway network; 1.0–100% accessible pathway network
	2.2 - Noise Reduction	0.0 - No major evidence for noise reduction; 0.5 - Indirect evidence for noise reduction; 1.0 - Strong Evidence for noise reduction
	2.3 - Visitor Intensity	0.0 – <1 million visitors/year; 0.5–10 million visitors/year; 1.0 – >10 million visitors/year
3. Economic	3.1 - Life Cycle Cost Efficiency	€/m^2 over the project life cycle

(*continued*)

Table 1. (*continued*)

Dimension Name	Criteria Name	Indicator
	3.2 - Operational Cost Reduction Evidence	1.0 - Quantified operational cost reduction or direct financial evidence; 0.5 - Design-based or qualitative operational efficiency evidence; 0.0 - No evidence reported
	3.3 - Property Value Increase	1.0 – Quantified property value increase reported; 0.5 – Qualitative economic regeneration evidence; 0.0 – No evidence reported
4. Governance	4.1 - Stakeholder Engagement and Public Involvement during design	0 – No stakeholder participation; 0.5 – Limited consultation or information sharing; 1 – Extensive participatory planning and co-design
	4.2 - Governance and Management Systems	0 (V = 0.0) – No maintenance plan. 1 (V = 0.3) – Ad-hoc or basic maintenance plan; 2 (V = 0.7) – Certified Environmental Management System (e.g., ISO 14001) or scheduled KPI monitoring; 3 (V = 1.0) – Fully integrated into municipal masterplans with guaranteed long-term funding
	4.3 - Transparency and Reporting	1.0 - Comprehensive official documentation publicly available; 0.5 - partial documentation available; 0.0 - no documentation

2.2 Data Normalization and Value Function Definition

Since the selected indicators use different units and scales, direct comparison was not possible. Therefore, a normalization process was applied. This step ensured comparability and measurability between the indicators, transforming raw data into dimensionless scales ranging from 0 to 1, where 0 represents the minimum or worst value while 1 represents maximum or best value. Intermediate values between 0 and 1 represent proportional performance between these thresholds. The reference thresholds were defined as a combination of international standards, academic literature, and best practice benchmarks in urban green infrastructure [6–10]. It includes guidelines related to energy performance, water management, and urban environmental quality.

This approach allows different indicators to be combined into a single performance score while maintaining consistency across multiple case studies.

2.3 Weighting Method

To determine the importance of each indicator, a structured weighting process was conducted through expert validation. A panel of six experts with academic and professional expertise who worked in urban sustainability, infrastructure planning, and decision-making processes were asked to rank the criteria and dimensions. The experts ranked the criteria and dimensions according to their own experiences. The panel included both researchers and practitioners with international academic and professional experience across Europe, the Middle East, and Asia. This ensured a balanced perspective between theoretical and practical considerations.

The final weights were calculated using the SMARTER approach, based on the ROC method [11]. This method provides a simple and transparent way to define weights based on preferences sorted by importance. At the same time, this method reduces subjectivity compared to direct weighting techniques. First, experts were asked to rate the relative importance of each sustainability dimension, i.e., ESG+, as well as the criteria within each dimension. Each expert ranked the criteria from most to least important using a Likert scale. For example, in a set of criteria, the first-ranked criterion receives a higher weight, say 0.61, the next criterion receives 0.28, and the third criterion has 0.11. The experts' ratings of the dimensions and criteria are presented in Table 2 and Table 3.

Table 2. ROC Weighted Dimension Table

Dimension Name	Rank	Average Score	ROC Weight
1 Environmental	1	4.67	0.520
2 Social	3	3.84	0.145
3 Economic	2	4.00	0.256
4 Governance	4	3.34	0.040

Table 3. ROC Weighted Criteria Table

Criteria Name	Rank	Average Score	ROC Weight
1.1 RES Integration	1	4.34	0.611
1.2 Potable Water Reduction for Irrigation	3	5.67	0.111
1.3 - Climate Adaptation and Resilience	2	5.33	0.277
2.1 - Universal Accessibility	2	5.33	0.277
2.2 - Noise Reduction	1	5.83	0.611
2.3 - Visitor Intensity	3	5.17	0.111
3.1- Life Cycle Cost Efficiency	2	5.50	0.277
3.2 - Operational Cost Reduction Evidence	1	5.67	0.611
3.3 - Property Value Increase	3	4.84	0.111

(*continued*)

Table 3. (*continued*)

Criteria Name	Rank	Average Score	ROC Weight
4.1 -Stakeholder Engagement and Public Involvement during design	1	5.50	0.611
4.2 - Governance and Management Systems	2	4.50	0.277
4.3 - Transparency and Reporting	3	3.84	0.111

2.4 Aggregation Method

The final sustainability performance score is calculated by aggregating the normalized criteria values and their respective weights using the MAVT additive model. In this phase, each normalized value is multiplied by its corresponding weight, determined through the SMARTER process. The overall sustainability score (V) is obtained by the sum of these weighted values, as shown in the following equation:

$$V = \sum_{i=1}^{n} w_i \cdot v_i \tag{1}$$

where n represents the number of criteria (12), w_i is the weight of the -th criterion, and v_i is its normalized performance value. The resulting GISPAM score is expressed on a scale from 0 to 1, where values approaching 1 indicate a higher sustainability performance. If the values closer to 1 means that project has higher sustainability performance score.

3 Empirical Application

3.1 Case Studies Selection

The GISPAM framework was tested on three international UGIs: The High Line (New York), Cheonggyecheon Stream Restoration (Seoul), and Madrid Río (Madrid). These cases were selected based on specific methodological criteria to ensure a comprehensive validation of the model.

First, the projects represent diverse UGI typologies, ranging from the adaptive reuse of an elevated industrial railway to the daylighting of a buried stream and the ecological conversion of a highway corridor. This variety is essential to test the flexibility of the GISPAM model across different physical and functional contexts.

Second, the scale diversity of these benchmarks allows for global validation. The cases vary from a local linear park to a large-scale regional riverfront, providing a broad testing ground for the model's scalability.

Third, the geographic dispersion and scale diversity of these benchmarks allow for global validation. By selecting cases from North America, East Asia, and Europe, the study tests the model against different regulatory frameworks, climatic conditions, and urban planning traditions.

Finally, the availability of high-quality data and official documentation for these international "best practices" ensures a rigorous quantitative application of the twelve indicators. By selecting these complexes, multi-billion-dollar interventions, the study demonstrates that the GISPAM model can capture the sustainability trade-offs of large-scale projects, making it applicable to a wide range of urban regeneration scenarios.

3.1.1 The High Line (USA)

The High Line is an elevated linear park and urban revitalization project located in New York City, United States. Developed on a former rail line built in the 1930s, the project repurposes the infrastructure into a multifunctional public space. Since its opening in 2009, The High Line has become a widely recognized tourist attraction point. The High Line combines different aspects of their design. These are ecological restoration, art, leisure, and pedestrian connectivity within an intense urban context. It has become an internationally recognized example of adaptive reuse, landscape urbanism, and public-private cooperation in city-making.

The project reduces environmental impacts through the reuse of existing steel infrastructure and the implementation of nature-based solutions, including extensive native planting and permeable surfaces. Furthermore, the park operates under a public-private partnership (PPP) governance model. The city of New York owns the infrastructure while the non-profit organization Friends of High Line manages daily operations and maintenance. The project also has attracted substantial private investment to surrounding neighborhoods. It contributes to local economic development while raising discussions to property value increase and potential green gentrification effects [12].

3.1.2 Cheonggyecheon Stream Restoration (South Korea)

Located in central Seoul, South Korea, the Cheonggyecheon Stream Redevelopment Project is a major urban regeneration project and linear ecological corridor. The project's primary goal was to rediscover and restore the historic Cheonggyecheon Stream by demolishing a highway. The project began in the early 2000s and was led by the Seoul Metropolitan Government in collaboration with various public and private stakeholders, including urban planners, environmentalists, and citizen groups.

The reconversion of the polluted industrial corridor into a public space generated a flow of tens of thousands of daily visitors, with direct benefits for public health and environmental quality. However, ecological success was mediated by complex governance: implementation required lengthy negotiations and the relocation of numerous street vendors, confirming how critical stakeholder coordination is in large urban regeneration projects [13].

3.1.3 Madrid Río (Spain)

Madrid Río project is a large-scale urban park and riverfront regeneration project developed along the Manzanares River in Madrid. By transforming former highway infrastructure into green public space, pedestrian routes, and recreational areas, the project became one of the most prominent examples of comprehensive urban regeneration integrating landscape design, mobility, and urban sustainability.

It also represents a major public infrastructure initiative that reconnected historically separated districts, enhancing accessibility, social cohesion, and urban livability [14].

3.2 Application of the GISPAM

To validate the GISPAM framework, three landmark UGIs projects were selected. These cases represent diverse geographic contexts, urban morphologies, and intervention scales, ranging from linear parks to large-scale riverfront restorations. The GISPAM framework was applied to the selected case studies to evaluate their sustainability performance. Data for the selected case studies were collected from official reports, academic publications and publicly available documentation. The selected criteria were measured using available evidence related to environmental, social, economic, and governance (ESG+) performance.

Criteria values were normalized using predefined threshold values and transformed to 0–1 scale. Then the normalized values were weighted using the Rank Order Centroid (ROC) method. The final sustainability performance score was then calculated using MAVT.

The value that comes from the calculation represents the overall GISPAM score for each project which enables direct comparison of sustainability performance between different urban green infrastructure projects.

4 Results

4.1 GISPAM Performances

The GISPAM model was systematically applied to the three selected case studies to assess their sustainability performance across the environmental, social, economic, and governance dimensions. The final sustainability scores were derived through the MAVT additive aggregation process, combining normalized criteria values with ROC-derived weights. The computed scores, presented in Table 4, reveal a differentiated performance pattern among the projects. Cheonggyecheon Stream Restoration achieved the highest overall score (0.473), followed by Madrid Río (0.421), while The High Line recorded the lowest score (0.347). On a scale from 0 to 1, these figures indicate moderate sustainability performance overall. The difference between the highest and lowest scores suggests variability in how the selected projects address ESG+ criteria. The aggregate scores provide a structured basis for comparing sustainability outcomes, but a disaggregated analysis by dimension is required to fully understand these differences. The following Section 4.2 breaks down the contributions of each ESG+ dimension to the final scores, offering further insight into the specific strengths and weaknesses of each project.

Table 4. Final GISPAM scores across case studies

Project Name	Cheonggyecheon Stream Restoration	The High Line	Madrid Ríos
GISPAM Score	0.473	0.347	0.421

4.2 Dimension-Based Results

Dimension calculations show differences in sustainability performance in the selected case studies based on ROC weighted dimensions scores. Among the four dimensions, governance scores are relatively stable across the three projects, with Cheonggyecheon Stream Restoration and The High Line both scoring 0.040, and Madrid Río scoring slightly lower at 0.030. This suggests that the three projects show comparable levels of structured management, stakeholder engagement, and publicly available documentation, although with some differences in implementation.

The social dimension shows particularly strong performance in the Madrid Río project which reached the highest score (0.137). This indicates strong public accessibility, recreational use, and community engagement. Similarly, Cheonggyecheon Stream Restoration showed more balanced social performance which is 0.080. And The High Line demonstrated moderate social performance which is 0.093. Mainly associated with visitor activity and accessibility features.

Economic performance also varies across the case studies, Cheonggyecheon Stream Restoration achieved the highest score which is 0.220. It reflects strong evidence of operational efficiency and economic impact. In contrast, The High Line and Madrid Río reached similar results, which is 0.142. It indicates moderate but consistent financial and economic performance.

Environmental performance also differs across the three projects. Cheonggyecheon Stream Restoration and Madrid Río showing relatively higher scores which are 0.133 and 0.112. Mainly associated with climate adaptation and ecosystem restoration measures. The High Line achieved a lower environmental score which is 0.072. It reflects more limited performance in renewable energy integration and water management indicators.

Overall, dimension calculations highlight the multidimensional nature of sustainability performance and show the ability of GISPAM model to find variations in environmental, social, economic, and governance dimensions in urban green infrastructure projects (Table 5).

Table 5. Dimension-based sustainability performance scores across case studies

Project Name/Dimension Name	Cheonggyecheon Stream Restoration	The High Line	Madrid Río
Environment	0.133	0.072	0.112
Social	0.080	0.093	0.137
Economic	0.220	0.142	0.142

(*continued*)

Table 5. (*continued*)

Project Name/Dimension Name	Cheonggyecheon Stream Restoration	The High Line	Madrid Río
Governance	0.040	0.040	0.030

4.3 Comparative Results Across Case Studies

A general comparison of the overall GISPAM scores shows that Cheonggyecheon Stream Restoration project achieved the highest sustainability performance, which is 0.473 in the selected case studies. This result reflects that Cheonggyecheon Stream Restoration has strong economic performance and balanced governance and environmental management strategies. Madrid Río project has the second highest performance, which is 0.421, and it shows a well-balanced sustainability profile. Especially in the social dimension which recorded the highest score in the all three projects.

On the other hand, The High Line Project reached the lowest overall score, which is 0.347. Even though the project performed consistently in governance and social dimensions other two dimensions, which are environmental and economic performance, are relatively lower than the other case studies. These differences highlight how project scale, management structure, and environmental interventions affect sustainability outcomes in urban green infrastructure projects.

Overall, the comparative results of GISPAM show that distinguishing sustainability performance across the projects with different urban contexts, design strategies, and operational characteristics. The dimension-based sustainability performance scores are visualized in Fig. 1.

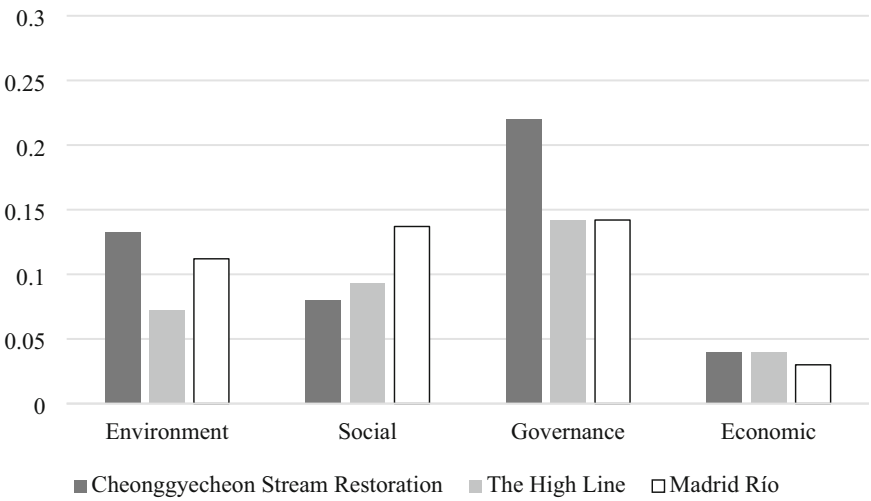

Fig. 1. Dimension-based sustainability performance scores across the three case studies.

5 Discussion

5.1 Interpretation of the Results

The results show that sustainability performance varies depending on the project scale, design strategy, and management structure. The Cheonggyecheon Stream Restoration project reached the highest overall GISPAM score. This reflects the strong economic performance and structured governance framework of Cheonggyecheon Stream Restoration. The project also benefits from large scale ecological restoration measures that contribute to environmental resilience.

Madrid Río shows a balanced performance across the sustainability dimensions, especially in the social dimension. This reflects the project's contribution to public accessibility, recreational use, and urban livability. The project represents a comprehensive urban regeneration initiative integrating landscape design, mobility, and public space development.

On the other hand, The High Line project has the lowest overall score in all three case studies. Although it performs well in the social and governance dimensions, its environmental and economic performance is relatively lower due to limited renewable energy integration and moderate long term cost efficiency. Notably, although Cheonggyecheon achieves the highest overall score, no single project dominates across all four ESG+ dimensions. This suggests that sustainability performance in UGI projects is not determined by excellence in any one dimension, but rather by the balance achieved among environmental, social, economic, and governance outcomes. These findings highlight how different project priorities and operational contexts affect sustainability outcomes, confirming that a multidimensional assessment is essential to capture the complexity of UGIs performance.

5.2 Implications of the GISPAM

The application of the GISPAM shows the value of using an integrated ESG based framework for evaluating urban green infrastructure projects. Combining environmental, social, governance, and economic dimensions into a single assessment structure, the model provides a comprehensive understanding of sustainability performance at urban scale.

The results show that sustainability cannot be evaluated using a single criterion or dimension. It needs a multidimensional approach to capture complex interactions between environmental performance, social benefits, economic efficiency and governance capacity. In this context, The GISPAM provides a practical tool for policymakers, planners and DMs to support evidence-based planning and long-term sustainability management.

Furthermore, property value increase can be interpreted as an indicator of consumer preferences and project-area attractiveness. However, although this criterion captures relevant economic benefits, it may also signal green gentrification and potential social displacement [15]. For this reason, economic outcomes should be interpreted alongside social criteria such as accessibility, inclusiveness, and community engagement. The GISPAM framework therefore supports a balanced, multidimensional assessment where such trade-offs can be identified.

5.3 Limitations of the Study

This study has several limitations that should be considered when interpreting the results. First, the availability of data availability varies across case studies. In some cases, this required the use of indirect indicators or proxy data.

Since the GISPAM framework is based on MAVT, variations in criteria weights are expected to influence the final sustainability score. This sensitivity should not be considered a weakness of the model, but rather a feature of multi-criteria decision support, as it allows different stakeholders' priorities to be reflected in the assessment. In this study, the ROC method was adopted to provide a transparent and reproducible baseline weighting structure based on expert rankings. Future applications of GISPAM may test alternative weighting scenarios, such as equal weighting or stakeholder-specific weighting, to examine how different decision-making priorities affect the final scores.

Second, the reference thresholds used for normalization were based on literature and best-practice benchmarks, as well as local conditions and project-specific contexts. Future research could refine these thresholds using larger datasets and more standardized performance indicators.

Even though there are limitations, the results show that using GISPAM is a structured and transparent framework. With evaluating sustainability performance in urban green infrastructure projects.

6 Conclusion

GISPAM is an integrated framework designed to evaluate the sustainability performance of urban green infrastructure projects using environmental, social, governance and economic (ESG+) dimensions.

The model was applied to three international case studies. These three international case studies show that sustainability performance varies depending on project scale, management structure, and long-term operational strategies. The results showed that a multidimensional approach is crucial to capture the complexity of sustainability in urban environments.

These findings also show the importance of transparent evaluation methods. It supports evidence-based planning and decision-making in urban development. This structured and comparable assessment framework shows that GISPAM can assist planners and policy makers. To identify strengths and weaknesses in sustainability performance.

There are different options for future research. It may focus on refining thresholds, expanding the dataset to additional case studies and improving availability of standardized performance data for urban green infrastructure projects.

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Preliminary Insights on the Modelling of a Wine Region Landscape with Human Factor and Willingness to Pay

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Abstract. This contribution describes preliminary insights on a research work that extends a three-dimensional model formulated as a system of Ordinary Differential Equations (ODEs). The model includes the Willingness To Pay (WTP) as an economic parameter to explore the potential dynamics within an environmental system decomposed into landscape units (LUs) in which the human factor influences the environment. The case study is the UNESCO wine landscape in Piedmont, and the results here presented refer to two representative areas. The purpose of this ongoing work is to test the sensitivity of the mathematical model with the WTP parameter conceived as the payment of a certain monetary amount in view of supporting the preservation of the landscape. Therefore, the authors recognise this model as a potentially useful decision-aiding tool for UNESCO landscape planning and management.

Keywords: Mathematical modelling · Human-environment system · WTP

1 Introduction

Landscapes continuously evolve according to the relationships between ecological processes, cross-spatial levels and human behavior [1]. Landscape planning requires multidisciplinary analysis and assessment capable of taking into account the complexity of landscape value [2]. In the case of cultural landscapes, the above mentioned interlinkages are crucial to preserve and manage this complex value through human generations. Among the methods and tools commonly applied in landscape planning, three-dimensional mathematical models falling

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 563–579, 2026.
https://doi.org/10.1007/978-3-032-30524-4_35

into the family of Ordinary Differential Equations (ODEs) are carrying interesting insights to this research domain.

This paper describes a mathematical model for landscape ecology including economic and social features in the dynamics. This paper is the result of the experience and previous research works of the authors on mathematical modelling for landscape ecology and on landscape economics to support decision-aiding processes. Starting from the pioneer work in paper [3] until to the recent review in [4], this class of mathematical models shows a great potential in predicting the time evolution of landscape ecology characteristics in relation to social and/or human behavior. Particularly, this work provides a novel extension through the integration of an economic variable corresponding to the Willingness to Pay (WTP) expressed by society who live/visit a region. This direct integration represents a step forward at the interface between landscape ecology and landscape economics domains. Economic variables of pure public goods (e.g. cultural landscape), monetary and non-monetary, can be determined through decision-aiding evaluation techniques for the economic appraisal of project profitability [5,6], as well as for policy design [7]. From a methodological point of view, these tend to be employed individually or matched to the numerical simulations [8,9]. The authors searched on Scopus the following keywords to investigate whether these are directly integrated within the dynamical model: "ordinary differential equations", "willingness to pay" "mathematical model", "integration", "landscape" did not give back results in this resear. There are no valid results in this field, but rather in product development and epidemiology, so that they have been excluded [12,13]. Therefore it is possible to state that this work is carrying an original and novel contribution to the current state of academic literature.

The WTP represents the community's willing to support economically both landscape preservation and management solutions and it is obtained from a survey which belongs to a past study [10]. This is here normalised and integrated into the dynamical model together with ecological and social parameters to investigate the way of this economic attitude relates with ecological and human features in determining future states within a landscape. The dynamical model is applied to a wine region landscape in Southern Piedmont (Italy), namely "Vineyard Landscape of Langhe-Roero and Monferrato", which has been included in the UNESCO World Heritage List since 2014 [11]. This territorial context depicts an interesting case study to prove the reliability of the model, since the social dimension continues to shape the identity of this living cultural landscape over the centuries, whereas the wine-making process is the main driving force of the local economic development. The expected outcome of this research work is twofold. On the one hand, the paper extends a class of mathematical models for landscape ecology by directly incorporating an economic variable as one of the model's parameters. On the other hand, the results are finalised to support the definition of landscape preservation and management policies by enhancing the interdependencies between society and cultural identity, ecological state, and local economic development. After this introduction, the paper is organised in the following sections: Sect. 2 presents the model and describes the methodology

used to estimate the model's parameters based on ecological and economic data; Sect. 3 illustrates the application to the case study focused on two core zones of the UNESCO site; Sect. 4 presents the numerical solutions to explore how ecological conditions, social behaviour and the normalised WTP jointly influence the temporal evolution of the system; Sect. 5 closes with conclusions and future perspectives.

2 Methodology

This section presents the methodology used to develop the mathematical model and its ecological stability.

2.1 The Mathematical Model

We consider an environmental system consisting of N landscape units (LUs), representing distinct regions separated by natural or anthropogenic barriers, such as rivers, roads, motorways, railways, buildings, and industrial infrastructures.

Our framework builds upon the model introduced in [14], where human action is incorporated through the fraction of environmentalists within the population. This model is mathematically consistent and exhibits a rich dynamical behavior, in particular inducing periodic oscillations of environmental and human variables, associated with resilient territories.

In this work, we extend that model by incorporating an economic indicator representing the Willingness To Pay (WTP) of a community in a given region. This quantity captures the propensity of the population to allocate resources either to benefit from a natural asset or to support the restoration of green areas. Namely, we consider three state variables that describe the ecological state of each LU and the impact of the human behaviour on the ecological quality of the environment.

These indicators are represented by the normalized state variables $v(t)$, $b(t)$ and $x(t)$ at each time t, where v indicates the green area of the LU with high ecological quality, b measures the biological energy produced by the vegetation inside the LU, and x is the proportion of environmentalists that preserve and protect the green areas. The human-landscape model proposed in paper [14] to describe the ecological state of each LU is given by

$$\dot{v} = dv(1-v) - hUv - s(1-x)v, \tag{1a}$$

$$\dot{x} = \kappa x(1-x)[c - v + \delta(2x-1)], \tag{1b}$$

$$\dot{b} = ab(1-b) - l(1-v)b. \tag{1c}$$

Parameters d, h, U, a, and l describe structural and environmental characteristics of the LU, whereas s, κ, c, and δ govern the social dynamics. In particular, the parameter s links the social behaviour to the ecological dynamics. The specific meaning of the parameters is described as follows:

- d depends on solar exposure, relative humidity and ecotonal length, with this last quantity being the length of the borders among LUs; d is therefore an indicator of the ecological quality of the LU; it measures the intrinsic ecological quality and regenerative capacity of the LU;
- h is the ratio between the total perimeter of built-up sectors and the total perimeter of the LU; it captures fragmentation and edge effects generated by urbanization;
- $U \in (0, 1]$ is the ratio between the total built-up area and the total area of the LU, and it quantifies the level of urbanization within the LU;
- s is the human-caused environmental degradation rate, which measures the negative impact of the non-environmentalists on green areas and acts as a coupling parameter translating social behavior into ecological damage;
- κ represents the imitation speed, which determines how fast individuals modify their behavior through social interaction.
- c represents the perceived conservation value of green areas and the social benefit attributed to environmental quality and promotes pro-environmental behavior;
- δ measures the uniform pressure to remain in the same group due to injunctive social norms; it models conformity and social inertia and may reinforce majority behaviour;
- $a \in [0, 1[$ is the weighted average of the area of the LU exposed to SE-W-NE and measures the solar exposure of the LU;
- $l \in (0, 1]$ is the ratio between the surface area of the impermeable barriers included in the LU and the total area of the LU; it represents structural ecological constraints limiting vegetation growth.

In the present work, we introduce a variant of model (1) defined by incorporating an additional economic variable representing the Willingness To Pay (WTP) of a community in a given region. This quantity captures the propensity of the population to allocate resources in order to benefit from a natural asset. The new human-landscape model is described by

$$\dot{v} = dv(1 - v) - hUv - s(1 - x)v + w_1 v(1 - v), \tag{2a}$$

$$\dot{x} = \kappa x(1 - x)[c - v + \delta(2x - 1)], \tag{2b}$$

$$\dot{b} = ab(1 - b) - l(1 - v)b, \tag{2c}$$

where the parameter w_1 denotes normalized monetary quantities representing the WTP for the preservation of high-quality green areas within the region.

Remark 1. As in paper [14], we assume that the behavior of the non-environmentalists has a direct impact on the degradation of v, an effect captured by the loss term $-s(1-x)v$, with s denoting the rate of human-induced environmental degradation.

Remark 2. The new term $w_1 v(1 - v)$ in Eq. (2a) is a logistic type term representing the contribution of individuals willing to pay a maximum amount for the preservation of high quality green areas.

2.2 Equilibria and Stability

The temporal dynamics of model (2) can be studied in two steps, since Eq. (2c) decouples from the system (2a–2b), and therefore the dynamics of v and x are independent of that of b.

The analysis in this section will focus on the determination of equilibria of the reduced system (2a–2b), for the sake of brevity. Accordingly, we consider the reduced model

$$\dot{v} = dv(1-v) - hUv - s(1-x)v + w_1 v(1-v), \tag{3a}$$

$$\dot{x} = \kappa x(1-x)[c - v + \delta(2x-1)]. \tag{3b}$$

The above system retains the same mathematical structure as the one studied in [14]. Therefore, the analysis of the equilibria, including their existence and stability conditions, follows the same arguments as in [14].

The equilibrium states of model (3) are as follows

$$E_0 = (0,0), \quad E_1 = \left(1 - \frac{hU+s}{d+w_1}, 0\right), \quad E_2 = (0,1),$$

$$E_3 = \left(1 - \frac{hU}{d+w_1}, 1\right), \quad E_4 = \left(0, \frac{\delta - c}{2\delta}\right), \tag{4}$$

$$E_5 = \left(1 + \frac{s(-1+c+\delta) + 2hU\delta}{s - 2(d+w_1)\delta}, 1 + \frac{(d+w_1)(1+c-\delta) + hU}{s - 2(d+w_1)\delta}\right).$$

The conditions ensuring the existence of the equilibrium states (4), as well as their stability properties, are analogous to those obtained in [14] for the equilibria of the corresponding model, the details are therefore omitted.

3 Application

This section describes the case study and the estimation of the model's parameters, based on ecological and economic data, together with suitable assumptions for the social parameters.

3.1 Case Study: the Wine Region Landscape of Langhe-Roero and Monferrato

The case study falls in the UNESCO World Heritage Site "Vineyard landscape of Piedmont: Langhe-Roero and Monferrato" and consists of six core zones representing the Outstanding Universal Value (OUV) and two buffer zones aimed at preserving the serial site's value [11]. In this work, the term core zone is operationally labelled with the term landscape units (LUs), that is used in the literature on landscape ecology to refer to spatial portions composed of sets of

biotopes with a certain degree of homogeneity and all contribute to the configuration of a comprehensive ecomosaic of the Environment [15,16]. Indeed, the Landscape Regional Plan of Piedmont designated the perimeter of this UNESCO site following both the Landscape Ambits and Units, since they result in recognisable interactions between morphological, natural and cultural components.

This work focuses on two core zones of this UNESCO site as reference landscape units (Fig. 1). The core zone 1 "Langa del Barolo" corresponding here to the Landscape Unit 1 "Diano d'Alba', where Nebbiolo's vines form outstanding terraces and alternated by historical testimonies (e.g. castles, or boroughs, among others). The core zone 4 "Nizza Monferrato and the Barbera" is labelled here as "Landscape Unit 4" 'Nizza Monferrato' representing the beating core of Barbera's wine-making production of Monferrato.

The core zones were not chosen a priori by the authors, but were selected after performing numerical simulations of the mathematical model over all six core zones.

For each landscape unit, we investigated the system response under different degradation levels and in the presence or absence of the economic contribution, with the aim of assessing the combined role of ecological conditions, social behaviour, and Willingness To Pay mechanisms in shaping the system dynamics. The results revealed that these two landscape units, which have distinct configurations and dynamics, provide the most meaningful outputs.

3.2 Economic Parameter Estimation

The economic component of the model is based on the Willingness To Pay (WTP), estimated from the results of the paper [10] that developed a Multiple Regression Analysis based on a Choice Experiment (see Table 1) by surveying both residents and tourists, by asking their willingness to pay for three alternative scenarios of this landscape by varying its attributes (i.e.naturalness, vineyards extension, landscape quality, intangible heritage, cultural accessibility, and cost). That survey was conducted in those years immediately before the inclusion of this wine landscape into the UNESCO World Heritage List [10]. Those years were crucial in terms of social awareness on the value of these lands, as a result of a process begun in the early 2000s [11]. The choice of focusing on the results of a past study is motivated by the fact that the attention of the authors is currently on proving the reliability of this mathematical modelling extension and reflecting outputs' expectations. The Choice Experiment regressors are taken into account to estimate the individual WTP parameter (€) for both residents and tourists, and for each alternative scenario presented by that survey. Due to the limited number of pages, the authors decided to focus on the first alternative scenario of that study (Alternative 1) [10], which represented the state of the art, characterized by:

- Naturalness and protected species: medium/low
- Vineyards: medium-sized vineyard areas
- Landscape quality: excellent and high landscape quality

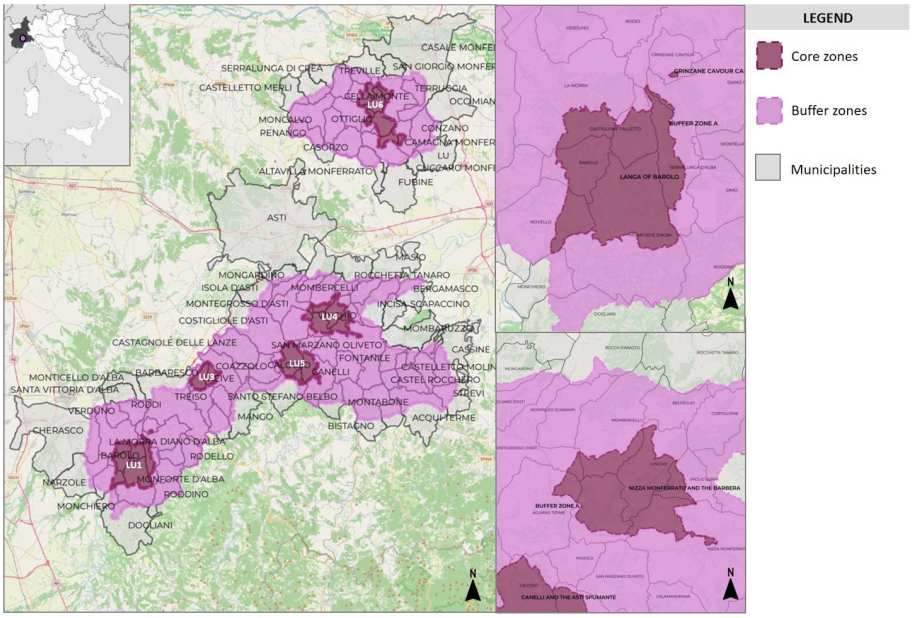

Fig. 1. Territorial localisation of Langhe-Roero Monferrato (left), selection of the core zones 1 (Diano d'Alba) and 2 (Nizza Monferrato) as landscape units for numerical simulations.

- Intangible heritage: high
- Cultural accessibility: extremely difficult
- Cost: 100 €

To estimate the WTP, we applied the conditional mean formula reported in paper [17]:

$$WTP = \frac{\ln(1 + e^a)}{-b}, \quad WTP \geq 0 \tag{5}$$

where e refers to the regressor value, the apex a is the weight of the regressor, and b is the regression coefficient related to the monetary attribute (Table 2).

At a certain point, the two individual WTP of the respondents (i.e. residents and tourists) are merged with an arithmetic mean for each LU

$$WTP_{\text{mean}} = \frac{WTP_{ri} + WTP_{ti}}{2} \tag{6}$$

where WTP_{ri} refers to the WTP of residents in the i-th LU, whereas WTP_{ti} concerns the WTP of tourists in the same LU.

The WTP parameter is firstly normalized on the maximum WTP value of the considered LUs. The highest WTP value equal to 1 does not represent really the general maximum WTP value may be expected, so that we retained useful to calculate a ratio between the WTP mean and the maximum value being expected

Table 1. Estimated coefficients of the Multiple Regression Analysis for the Choice Experiment, as reported in [10].

Attributes	Tourists		Residents	
	B	Sign.	B	Sign.
Vineyards surface	0.509	0.000	−0.297	0.043
Landscape quality	1.081	0.000	0.71	0.000
Intangible heritage	0.496	0.000	−0.281	0.075
Cultural accessibility	0.376	0.000	0.198	0.1
Price	−0.017	0.000	−0.036	0.000
Constant	−5.17	0.000	−0.999	0.329

Table 2. Individual WTP values for tourists and residents in Alternative 1.

Tourists		Residents		Alternative 1	
e^a	b	e^a	b	WTP_{it}^1	WTP_{ir}^1
2.599	−0.017	0.712	−0.036	75.33 €	14.94 €

(100 €). This numerical adaptation of the WTP parameter does not compromise its structural meaning but is an adaptation necessary to be included into the mathematical model together the other dimensionless parameters.

$$WTP_i^G = \frac{WTP_{\text{mean},i}}{WTP_i^{\max}} \tag{7}$$

The analysis focuses on two representative landscape units, namely Diano d'Alba (Core zone 1) and Nizza Monferrato (Core zone 4), denoted by LU1 and LU4, respectively. The corresponding economic values, expressed in terms of WTP mean and its normalized form, are reported in Table 3.

Table 3. Mean Willingness To Pay (WTP) and corresponding normalized values for the selected landscape units.

Landscape Units	mean WTP	mean WTP/100 €
LU1	65.22 €	0.652
LU4	33.74 €	0.337

3.3 Ecological Parameters

The ecological parameters used in this family of mathematical models are mainly based on european and regional spatial geodatabases (e.g. EU Project Copernicus, or Geoportale Piemonte). In the latest years, researches have benefitted from

the Copernicus Project that has enriched its mapping services and data elaboration. Since the results of that survey are referred to 2014, the closest spatial data useful to calculate the ecological parameters identified are: (i) Corine Land Cover Map 2012, and (ii) Digital Territorial Model (DTM, LoD = 10 meters) made available by Geoportale Piemonte geocatalogue. Both the vector and raster files were imported within the QGIS Software (version 3.4) and calculated surfaces and perimeters as basis for the calculation of the ecological parameters. To know the equation formulas, please see the paper [8] and publications therein. Table 4 below lists the ecological parameters for the selected LUs, namely (i) Diano d'Alba and (ii) Nizza Monferrato:

Table 4. Ecological parameters for each landscape unit LU1 and LU4.

Landscape Units	U_i	h_i	a_i	d_i	l_i
LU1 - Diano D'Alba	0.001	0.016	0.502	0.394	0.001
LU4 - Nizza Monferrato	0.008	0.052	0.598	0.423	0.008

3.4 Social Parameters

The selection of the social parameters is based on a previous work by some of the authors [14]. Their definition was guided by the available literature and, as discussed therein, was shown to be suitable for the study of the coupled social-ecological dynamics. As already mentioned before, the focus of this paper is to prove the reliability of the mathematical model, even if the authors recognise a research gap reflecting on the opportunity to calculate these indicators through a more sociological approach. Due to the lack of suitable information in the 2014 survey to estimate these social parameters, and in the absence of indirect data, we refer instead to plausible social behaviours at that time in relation to the potential evolution of the wine landscape as a UNESCO site. Thus, the values shown in the Table 5 below are the numerical translation.

Table 5. Social parameters for each landscape unit LU1 and LU4.

Landscape Units	s_i	k_i	c_i	δ_i
LU1 - Diano D'Alba	0.6	1	0.1	0.18
	0.9	1	0.1	0.18
LU4 - Nizza Monferrato	0.3	1	0.1	0.18
	0.7	1	0.1	0.18

4 Results

In this section, we present some numerical simulations aimed at illustrating the potential of the proposed model as a quantitative support tool for the analysis of coupled ecological and social dynamics in wine landscape areas. More precisely, the simulations are used to explore how ecological conditions, social behaviour, and the normalized Willingness To Pay jointly influence the temporal evolution of the system.

4.1 Initial Data and Input Data

The simulations are performed using model (2), with initial conditions given in Table 6. The corresponding ecological and social values are chosen consistently with the procedure and the assumptions explained in Subsects. 3.3 and 3.4 for parameters of the same nature.

Table 6. Initial conditions for the landscape units LU1 and LU4.

Landscape Units	v_0	x_0	b_0
LU1 - Diano D'Alba	0.073	0.50	0.328
LU4 - Nizza Monferrato	0.117	0.50	0.339

Moreover, the ecological parameters of system (2) are those from Table 4 and the social parameters are from Table 5. The monetary component is incorporated through the normalized WTP reported in Table 3.

The numerical results highlight the role of the economic contribution w_1 in shaping the evolution of the system. In the considered scenarios, we analyse baseline configurations corresponding to different values of the human-induced environmental degradation rate s, and compare them with configurations including the normalized WTP. This setting enables a direct assessment of the impact of the economic contribution on the system dynamics. Overall, the introduction of the WTP term leads to a more favourable evolution of the green area variable v in both landscape units. This behaviour is consistently observed across all the considered scenarios and provides clear evidence of the role of the economic component in supporting ecological preservation.

4.2 Results of LU1 - Diano D'Alba

Figure 2 illustrates the results for LU1 (Diano d'Alba). In the first row, we analyse the scenarios associated with $s = 0.6$, which represents a degradation rate comparable in magnitude to the WTP contribution w_1.

In the baseline case ($w_1 = 0$), on the left plot, the system is strongly affected by environmental degradation. Despite the initial presence of a community of

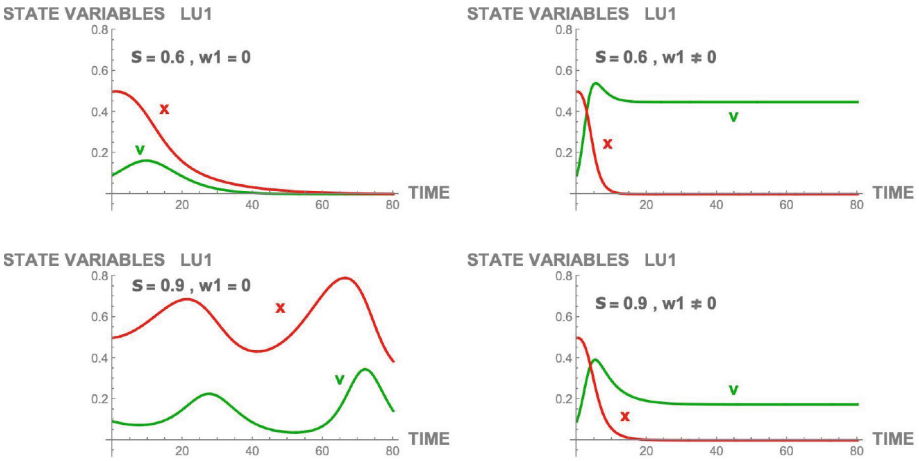

Fig. 2. LU1 – Diano d'Alba. Asymptotic behaviour of the green area v and the proportion of environmentalists x. The first row corresponds to $s = 0.6$, while the second row corresponds to $s = 0.9$. The first column shows the case without economic contribution ($w_1 = 0$), whereas the second column includes the normalized WTP ($w_1 = 0.652$). The comparison highlights the combined effect of social pressure and economic incentives on the evolution of the system.

environmentalists, the social response is not sufficient to counterbalance the degradation pressure. After a short transient phase, the green area of high ecological quality declines rapidly, eventually vanishing. At the same time, the proportion of environmentalists decreases towards zero, indicating a progressive loss of social engagement in environmental protection. The asymptotic trend clearly points to a fully degraded state, characterised by the disappearance of high-quality green areas and the absence of active environmentalists. This scenario highlights that, in the absence of effective mitigation measures, the long-term evolution of the system is dominated by degradation, raising critical concerns in terms of sustainability.

In contrast, on the right plot of the first row in Fig. 2, the corresponding scenario with economic contribution ($w_1 = 0.652$) shows a significant qualitative change in the system dynamics. The introduction of the willingness-to-pay term effectively counteracts the degradation process, leading to a stable configuration where the green area of high ecological quality is preserved at a significant level (approximately 50%). Interestingly, in this case, the proportion of environmentalists still tends to zero asymptotically. This behaviour can be interpreted as follows: once the ecological state of the system improves and stabilises at a sufficiently high level, the perceived need for active environmental engagement decreases. As a consequence, the social pressure sustaining environmentalist behaviour weakens, and the population gradually shifts towards a passive equilibrium in which preservation is maintained primarily by the economic contribution rather than by collective social action.

We now turn to a more extreme configuration, in the second row of Fig. 2, corresponding to $s = 0.9$, which can be interpreted as a limit scenario used to test the robustness of the system under high degradation pressure. In this case, the dynamics exhibit a pronounced oscillatory behaviour over a relatively long time interval. In particular, the proportion of environmentalists fluctuates approximately between 40% and 80%, inducing oscillations in the green area of high ecological quality, between 12% and 30%. This behaviour highlights a dynamic feedback between social response and environmental conditions. However, this regime is not sustainable in the long term. After this transient oscillatory phase, the system loses its resilience, the green area of high ecological quality eventually collapses, and the proportion of environmentalists simultaneously declines to zero. This behaviour indicates that, under strong degradation pressure, the region is not able to maintain a stable balance between ecological and social components, leading ultimately to a fully degraded state.

In the corresponding scenario with economic contribution, in the right plot, the introduction of the willingness-to-pay term modifies the long-term behaviour of the system. Although the proportion of environmentalists tends asymptotically to zero, the green area of high ecological quality does not collapse. Instead, it approaches a strictly positive steady state with approximately 25%, indicating the persistence of a non-trivial steady state sustained by the economic contribution.

4.3 Results of LU4 - Nizza Monferrato

A similar qualitative behaviour is observed in Fig. 3, corresponding to LU4 (Nizza Monferrato). In both scenarios considered in the simulations ($s = 0.3$ and $s = 0.7$), the introduction of the economic contribution w_1 consistently improves the long-term outcome of the system.

In particular, the presence of the WTP term enhances the persistence of the green area of high ecological quality, preventing its complete degradation and leading to higher asymptotic levels compared to the baseline cases. This confirms the stabilizing role of the economic component also in regions characterised by different ecological and social conditions.

4.4 Comparative Interpretation Between the LUs Results

The comparison between LU1 and LU4 is also informative. Since the normalized willingness to pay is higher in LU1 than in LU4, the positive effect of the economic term is more pronounced in LU1. This suggests that the response of the model is sensitive not only to the ecological and social parameters, but also, as expected, to the magnitude of the monetary support associated with each landscape unit.

A further insight emerging from this comparison is that the proportion of environmentalists x tends asymptotically to zero in all simulations of Fig. 3. This behaviour can be explained by the structure of the social dynamics: as the ecological state improves (i.e., higher values of v), the incentive for pro-environmental

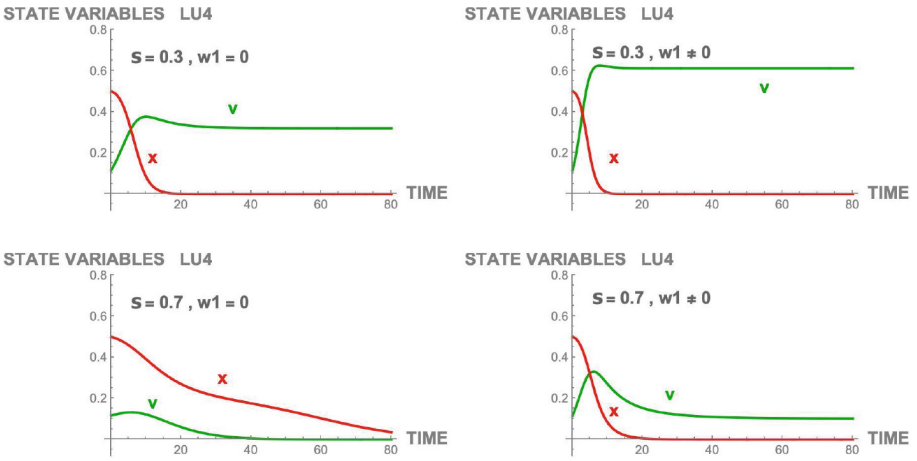

Fig. 3. LU4 - Nizza Monferrato. Asymptotic behaviour of the green area v and the proportion of environmentalists x. The first row corresponds to $s = 0.3$, while the second row corresponds to $s = 0.7$. The first column shows the case without economic contribution ($w_1 = 0$), whereas the second column includes the normalized WTP ($w_1 = 0.337$). The comparison highlights the combined effect of social pressure and economic incentives on the evolution of the system. (Color figure online)

behaviour decreases, leading to a gradual loss of active engagement. From a modelling viewpoint, this indicates that the system evolves towards a regime in which environmental preservation is no longer driven by social pressure, but is instead sustained by structural or economic mechanisms.

4.5 Transition Between Social and Economic Regimes

We now consider a representative hypothetical configuration designed to explore the combined effect of social perception and economic incentives. As a baseline configuration, we consider now a low degradation rate, $s = 0.3$, together with a significantly higher perceived conservation value, $c = 0.6$. This choice reflects a context in which social awareness and environmental sensitivity are strong. Moreover, the degradation pressure is lower than the economic contribution, in the sense that we have $s < w_1$, creating favourable conditions for ecological preservation.

We first analyse the baseline scenario in the left plot of Fig. 4, without economic contribution, $w_1 = 0$. In this case, the system evolves towards a stable configuration where both the green area of high ecological quality and the proportion of environmentalists remain positive. This reflects a socially-driven regime, sustained by the high perceived value of environmental quality.

When the economic contribution is introduced, $w_1 = 0.652$, a clear qualitative change in the system dynamics is observed, as shown in the right plot. This behaviour indicates a transition between two distinct regimes. The improvement

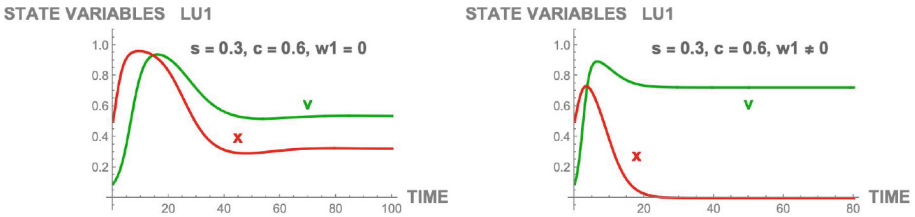

Fig. 4. LU1 – Diano d'Alba. Asymptotic behaviour of the green area v and the proportion of environmentalists x, for a small value of the degradation rate, $s = 0.3$, and a greater value of the perceived conservation value of green areas, $c = 0.6$, Left plot without economic contribution, $w_1 = 0$, and right plot with $w_1 = 0.652$.

of the ecological state, driven by the economic contribution, reduces the social incentive for active environmental engagement. As a consequence, the system transitions from a socially-driven regime, characterised by the coexistence of v and x, to an economically-supported equilibrium in which the preservation of the green area is maintained despite the disappearance of environmentalists.

Remark 3. Overall, these simulations provide a first quantitative indication that the inclusion of a willingness-to-pay component may improve the ecological outcome of the system, especially when combined with favourable social behaviour. From an applied perspective, this supports the interpretation of the model as a useful tool for exploring how ecological conditions, human behaviour, and economic incentives interact in the management of UNESCO wine landscapes, and for guiding planning and intervention strategies.

5 Conclusions and Perspectives

In this paper, a three-dimensional mathematical model for landscape ecology and economics was presented and applied to the Vineyard landscape of Piedmont. The results proved the sensitivity of the mathematical model thanks to the integration of the Willingness to Pay (WTP) as a variable on economic attitude of users together ecological dynamics and human behavior. It can be stated that this extension is a valuable advance for this class of mathematical models in addressing both the current research and policy demands in landscape planning [3,4]. The resulting model preserves the structure of the original framework while introducing an additional nonlinear (logistic) term to the ecological variable v, i.e. the green area with a high ecological quality, allowing for a direct coupling between economic behaviour and environmental dynamics.

The qualitative analysis shows that the inclusion of the WTP parameter w_1 does not alter the fundamental structure of the equilibria, whose existence and stability conditions remain analogous to those of the baseline model. However, w_1 modifies the effective growth term of v, contributing positively through a logistic-type component.

The numerical simulations performed for the selected landscape units indicate that positive values of w_1 can counterbalance the degradation term, leading to higher asymptotic levels of ecological quality. This effect is particularly evident in scenarios characterized by strong anthropogenic pressure (large values of the degradation rate s), where the economic contribution acts as a stabilizing mechanism.

Furthermore, although the WTP parameter does not enter explicitly into the social equation, its indirect influence on v feeds back into the dynamics of x, i.e. proportion of environmentalists, potentially promoting higher values of x itself. The ecological parameters, derived from spatial datasets, and the assumed social parameters provide a coherent, though preliminary, parametrization of the model. Several aspects remain open for further investigation. In particular, the calibration of social parameters based on empirical data would allow for an increase in the model robustness and thus reducing the gap on human behavioral indicators [18].

Other research lines will also address the analysis of an extended model including a rehabilitation term associated with areas with low ecological quality. In this case, to take into account these features, the model is further enriched by incorporating the WTP for the rehabilitation of areas with low ecological quality and for the restoration of green areas. Introducing a new parameter w_2 denoting the normalized monetary quantities representing the WTP for the rehabilitation of areas with low ecological quality, Eq. (2a) relative to the evolution of v, is formulated as:

$$\dot{v} = dv(1-v) - hUv - s(1-x)v + w_1 v(1-v) + w_2(1-v), \tag{8}$$

where the term $w_2(1-v)$ is proportional to the low-quality portion of the green area $1-v$, and represents the contribution of individuals or governmental institutions willing to pay for the rehabilitation of areas with low ecological quality.

Another research avenue is to investigate the full network of coupled landscape units, following the strategy of papers [3,8]. This would make it possible to investigate not only the internal dynamics of each landscape unit, but also the interactions among different units within a broader landscape system. Such developments are expected to provide deeper insight into the role of economic incentives in shaping the long-term behaviour of coupled social-ecological systems. Hence, the launching of a new survey to elicitate the WTP in the same case study is not excluded, after more than one decade from the UNESCO WHL inscription.

In this sense, the presented model can provide predictions of decision-aiding utility for policy design. Regarding its usability for plans of technical-economic affordability (i.e. *Piano di Fattibilità Tecnico-Economica*) of public policy measures, and/or in partnership with private actors, these could benefit from the application of this dynamical model and potentially in completion of other assessment techniques during the screening phase. For example, the model can help policy makers to distinguish between economic support for the conservation of existing high-quality areas and economic support for the restoration or

rehabilitation of degraded areas, even before activating a resource-intensive programming, such as in the case of the localisation of projects nature-based [6]. However, the operational usability of this mathematical model closely depends on data availability (i.e. ecological and economic ones), and currently on the calibration of social parameters that is expected to be more empirical for real policy-oriented applications. In conclusion, the model offers a useful basis for future applications in protected areas, cultural landscapes and UNESCO sites, where conservation, local development and community values are strongly interdependent in influencing the real estate values of properties. In this sense, a Geographically Weighted Regression (GWR) based on Hedonic Prices Mehod (HPM) will deepen these interdependencies [19].

Acknowledgments. A.J.S. thanks the support of the research Project FCT-CMAT-UM-UID/00013/2025 (https://doi.org/10.54499/UID/00013/2025).

Disclosure of Interests. No competing interests to declare.

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Computational Mechanics, Intelligence, and Data (MIND 2026)

Clustering-Based Automated Generation and Multiscale Analysis of Metamaterial Representative Volume Elements

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Abstract. Drawing on representative volume elements (RVEs), artificial intelligence (AI) approaches and computational methods, an automated methodology was integrated to generate and assess mechanical metamaterials. The method is aimed at directly converting image-based inputs into 3D geometries independently of manual CAD simulations to substantially accelerate preprocessing.

This study performed material region identification and complex geometry reconstruction through learning-based image segmentation and incorporated filtering into the method to establish a feasible structure and discard configurations with mechanical inconsistency and/or instability.

Emphasizing the dependence of key mechanical properties on geometric variables, lattice-based structures were evaluated to validate the proposed method. The equivalent modulus of elasticity was found to be smaller relative to the base material by up to two orders of magnitude, with the numerical results being in good agreement with experimental data. The computational cost was also found to be remarkably (≈95%) lower than conventional modeling.

This effective and efficient methodology with superb scalability can be employed in a range of applications, including additive manufacturing (AM), multiscale modeling, and structural engineering, where metamaterials are designed and analyzed in an automated manner.

Keywords: Metamaterials · Representative Volume Element · Image Segmentation · Artificial Intelligence · Homogenization · Finite Element Analysis

1 Introduction

To develop architected metamaterials, it is vital to carefully evaluate their mechanical behavior, as predicting elastic and plastic responses under vari-

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 583–598, 2026.
https://doi.org/10.1007/978-3-032-30524-4_36

ous loads is essential for engineering applications. However, the microstructural topology quite effects the prediction of homogenized elastic responses in lattice designs, particularly under stochastic and periodic loads. To address this challenge, researchers have developed inverse design approaches aimed at achieving specific stress-strain profiles or mechanical constants. For instance, Cao et al. [1] introduced a deep operator learning frame that utilizes a small microstructural dataset to identify the nonlinear mechanical behavior of disordered metamaterials. Additionally, Park et al. [2] employed a dynamic approach to decouple the geometric effects on stiffness and vibrational features in 3D chiral structures through generative modeling. Furthermore, in [3], ultra-elastic constitutive formulations were developed, incorporating incremental 3D finite element (FE) modeling to derive mean stress-strain trajectories.Several studies [4,5] have focused on assessing collapse loads under a uniform average stress to identify the stress threshold. In this context, 1D structural elements serve as an alternative approach to manage complex 3D hexahedral grids, utilizing the lower bound theorem to estimate the collapse limit directly. Although repeatedly algorithms have been proposed in the literature to couple finite element (FE) analysis with limit analysis [6,7], the method discussed here offers greater computational productivity and a more direct way to estimate the ultimate limit load. Researchers have expanded the literature beyond linear elasticity by examining post-yield behavior and plastic responses, especially in systems where high energy dissipation, cyclic load resilience, and long-term durability are critical. For instance, Song et al. [10] investigated the effects of geometric hierarchy on the localization of plastic strain and the complement of energy absorption in compressively loaded hierarchical structures. Experimental methodologies, especially when combined with fracture morphology analysis and high-fidelity strain field mapping, are essential for validating numerical modeling and evaluating such complex phenomena. Moreover, plasticity plays a crucial role in origami- and kirigami-inspired metamaterials, where localized folding zones represent important failure modes or are intentionally designed as deformable areas. The mechanical behavior of a deformable origami-based structure was analyzed under cyclic and high-strain loads, yielding encouraging results for the development of bioengineering scaffolds [13]. Additionally, Li et al. [14] investigated nonlinear elastic and plastic behavior in architected structures by combining physical and mechanical tests with resemblant numerical modelings and in situ observational data. Researchers have recently examined the assimilation of mechanical modeling with programmable or active components that can control or trigger plastic deformation as a functional mechanism. A study reported in [15] proposed an embedded actuator-driven reconfigurable mechanical system. Meanwhile, [16] provided a comprehensive review of the design principles underlying active structures. Key characteristics of such systems include dynamic stiffness flexibility and controlled shifts between varied deformation modes. This paper focuses on a systematic evaluation of both elastic and plastic performance to understand the micro-scale mechanical behavior of structured metamaterials. The primary goal is to propose an effective numerical methodology to assess the ultimate strength of these materials, referred

to as periodic micro-structured continua. These materials demonstrate periodic repetitions and perform as essential building blocks for complex frameworks, suggesting significant potential for developing performance-oriented structures through additive manufacturing (AM) [3,19–22]. The octet-truss lattice is analyzed within the elastic range using ANSYS to investigate its mechanical behavior under virtual loading. The resulting stiffness matrix is then utilized to assess material isotropy based on Zener's criterion, allowing for the identification of specific density configurations that demonstrate isotropy. To extend the analysis into the plastic regime, a pioneering finite element limit analysis technique developed by the authors (FELA) [4] is employed. This method is based on the lower bound theorem [23–26] and utilizes self-equilibrated stress fields characterized by discrete nodal parameters to define admissible stress states. The objective is to identify the maximum load that is in equilibrium with these admissible fields, representing the ultimate collapse threshold. The paper depicts the potential role of AI in the homogenization process within both the elastic and plastic ranges. By merging AI into the FELA procedure, it becomes possible to create clusters and sub-clusters for lattice representative volume elements (RVEs) that describe the composition of metamaterials.

2 Computational Characterization of RVEs: Homogenization and Limit Analysis

The elastic homogenization and the evaluation of isotropic characteristics are performed within specific, well-established configurations of structured metamaterial Representative Volume Elements (RVEs). In particular, the study examines a cubic topology: a truss-based architecture merging Body-Centered Cubic (BCC) and Pure Cubic (PC) geometries, which termed the isotropic truss; an equivalent star-system, and an octet truss, as represented in Figure 1.

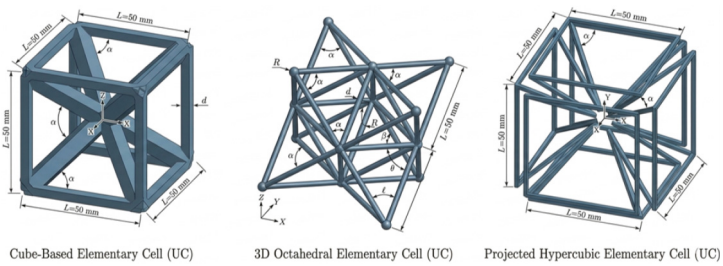

Fig. 1. case study representation

The objective of the research focuses on implementing the AI in a well-established limit analysis framework for these unit cells, aimed at improving the calculation performance on massive lattice RVEs. This section outlines a succinct overview of the methodology employed to assess the elastic properties of

the metamaterial architectures. The adopted approach is informed by the theoretical foundations established by Lakes [27], who derived estimates for elastically isotropic lattices characterized by stretching-dominated mechanisms at the mesoscopic scale. It is also based on the report in [28] regarding the topology optimization of isotropic truss structures. Drawing on earlier works, analytical criteria of lattice topologies are formulated so that microscopic elastic isotropy is obtained.

2.1 Constitutive Modeling of the Equivalent Elastic Continuum

FE modeling is implemented to capture the elastic behavior of such structures, in which uniform macroscopic strain fields are applied to representative unit cells. This study also uses periodic boundary conditions (PBCs) to ensure mechanical compatibility throughout the RVE. Unit cells are simulated in the form of a beam element frame with axial and flexural degrees of freedom (DOFs) in the nodes. It should be noted that the consistency of the mechanical response does not change upon the replacement of the beams with link elements serving as totally axial rods. This study employs 1D elements that address not only pure flexural (bending) behavior but also pure axial (extensional) behavior for the simulation of representative unit cells. The mean fields of continuum mechanics are used to characterize the homogenized medium, including the displacement vector field $\mathbf{u}(\mathbf{x}) = \{u_1, u_2, u_3\}$, the derived strain tensor field $\boldsymbol{\varepsilon}$, and the resultant stress tensor field $\boldsymbol{\sigma}$.

$$\begin{aligned} \boldsymbol{\varepsilon} &= \frac{1}{2}\left(\nabla^T \mathbf{u} + \nabla \mathbf{u}\right) \\ \boldsymbol{\sigma} &= \mathbf{C}\boldsymbol{\varepsilon} \end{aligned} \tag{1}$$

Where $\mathbf{C}$ is the fourth-order elastic tensor of the homogenized continuum. Voigt notation is used to reformulate the second- and fourth-order tensors for subsequent FE analysis. Index contraction transforms the elastic tensor into a symmetrical 6×6 second-order matrix. A predefined elementary strain (specifically a unit strain from the strain basis) is imposed on the framed structure to obtain the RVE stress using simultaneous nodal displacements applied throughout all faces of the cube (see Fig. 1). Then, the resulting mean strain is:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{u_i(x_j)}{\Delta x_j} + \frac{u_j(x_i)}{\Delta x_i}\right) \tag{2}$$

The nodal reaction forces are used to obtain the homogenized stress components:

$$\sigma_i = \frac{\sum_n F_i}{A_i} \tag{3}$$

where all nodes on face i of the cube with an area of A_i are incorporated into the summation. A unit strain vector is used for each fundamental case, with the corresponding columns of the elastic stiffness matrix comprising the resulting stress components. Translational DOFs constitute the predefined nodal displacements

to trigger a unit strain. This study neglects rotational DOFs due to their inconsistency with the standard 3D Cauchy continuum model. The anisotropy of the material is determined using the symmetry classification of the elasticity matrix **C**. Based on Lord Kelvin's theories, Cowin et al. [29–32] comprehensively classified anisotropy in the elastic tensor **C**. For the cubic RVE, the equivalent material's elastic tensor reduces to three independent constants. In Voigt notation [33], this cubic elastic matrix is expressed as:

$$\mathbf{C} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \tag{4}$$

This symmetry is characterized by the equalities $C_{11} = C_{22} = C_{33}$, $C_{12} = C_{13} = C_{23}$, and $C_{44} = C_{55} = C_{66}$.

In this study, a preliminary simplified analysis is performed to verify the isotropic properties of the homogenized medium. Isotropic materials are defined by a specific elastic matrix that depends on only two independent parameters: the Lamé constants, μ and λ:

$$\mathbb{C} = \begin{bmatrix} 2\mu+\lambda & \lambda & \lambda & 0 & 0 & 0 \\ \lambda & 2\mu+\lambda & \lambda & 0 & 0 & 0 \\ \lambda & \lambda & 2\mu+\lambda & 0 & 0 & 0 \\ & & & \mu & 0 & 0 \\ & Symm & & 0 & \mu & 0 \\ & & & 0 & 0 & \mu \end{bmatrix} \tag{5}$$

Given the structure of the isotropic matrix, the Zener ratio (z) is defined as:

$$z = \frac{C_{11} - C_{12}}{2C_{44}} \tag{6}$$

For isotropic materials, this ratio is unity, and any variance from this value serves as a numerical indicator of the material's anisotropy [34,35]. Computational analysis verifies that the stiffness matrix **C** comprises two 3×3 diagonal blocks, while the off-diagonal 3×3 blocks are zero. Furthermore, the lower-right submatrix simplifies to a strictly diagonal form.

As an example, the results obtained for an Isotropic truss configuration are reported below in the following Table 1.

Table 1. Parametric Analysis of the Isotropic Truss: Identifying the Unitary Zener Coefficient

d_{FCC} (mm)	d_{PC} (mm)	ρ	Zener Link Element	Zener Beam Element
0.10	0.40	4.00	6.07	6.04
0.15	0.40	2.67	2.74	2.72
0.22	0.40	1.82	1.29	1.27
0.23	0.40	1.74	1.19	1.16
0.24	0.40	1.67	1.08	1.07
0.25	**0.40**	**1.60**	**1.00**	**1.00**
0.30	0.40	1.34	0.71	0.69
0.40	0.40	1.00	0.42	0.39

2.2 Evaluation of Ultimate Strength via Limit Analysis

To determine the peak load-bearing capacity of the lattice RVE, a direct numerical strategy is employed based on the lower bound theorem [4]. This study calculates the collapse load multipliers and determines the macroscopic yield domain of the homogenized medium to incorporate constituent properties and structure using finite element limit analysis (FELA). The representative macrostresses, i.e., the nodal forces (Eq. (3)), are used in the lower bound technique to find the critical force magnitudes at collapse, and FELA considers the limit load to be the maximum sustainable threshold that meets the material yield and mechanical compatibility criteria.

This study reviews FELA concisely to elaborate on the fundamental principles. First, the manifold of admissible stress states is identified. Admissible stress fields in the structure are the superposition of the elastic response σ^e, which is obtained from the loads applied in an ideal elastic framework, and a self-equilibrating stress field σ_0^e. The multiplicity of balance equations governed by $E_{eq}(f)$ must be met by the self-equilibrated state:

$$\sigma \in E_{eq}(f) \iff \langle \sigma, \delta\epsilon \rangle = 0, \quad \forall \delta u, \delta\epsilon \tag{7}$$

RVE mechanical equilibrium is divided into a primary equation and an ideal elastic equation, with the former reflecting the real stress distribution and the latter incorporating the stress field induced inside a theoretical material under a linear elastic constitutive law.

$$\begin{cases} \langle \sigma, \delta\epsilon \rangle - \langle f, \delta u \rangle = 0 & \text{for the actual structure} \\ \langle \sigma^e, \delta\epsilon \rangle - \langle f, \delta u \rangle = 0 & \text{for the indefinitely elastic structure} \\ \langle \sigma^e + \sigma^{0e}, \delta\epsilon \rangle - \langle f, \delta u \rangle = 0 & \text{for the actual structure} \\ \langle \sigma^{0e}, \delta\epsilon \rangle = 0 \implies \sigma^{0e} \in \text{Null}(E_{eq}) & \text{Null space definition} \end{cases} \quad \forall \delta u, \delta\epsilon \tag{8}$$

An admissible stress state is a state remaining in the elastic domain (D^e) boundaries, which ensures that no increment occurs in the plastic strain rate ϵ^p:

$$\dot{\epsilon}^p = 0 \iff \sigma \in \text{int}(D^e) \tag{9}$$

Here, σ^{0e} is a crucial parameter, and the self-equilibrated stress manifold is to be analyzed comprehensively through a vector basis for the Null(E_{eq}) space, which is constructed in FELA based on nodal parameters and the shape functions used in the description of FE displacement fields.

Despite procedural versatility in several types of elements, Bernoulli beam elements are employed in the proposed RVE model. In this context, the local self-equilibrated stresses reduce to ordinary element forces, such as axial forces N, shear forces S_i, and bending moments M_i with $i \in \{1, 2\}$, defined along the axes of the element's cross-sectional plane. Although shear effects are often neglected in specific applications, the effective stress and generalized strain vectors are generally established as:

$$\begin{aligned} \sigma &= \{N, M_1, M_2\} \\ \epsilon &= \{\Delta u_3, \chi_1, \chi_2\} \end{aligned} \tag{10}$$

By analyzing the structural response under zero external loading, the self-equilibrating stress field can be defined as a linear mapping of the vector δ. This vector comprises nodal parameters that represent the permanent strains at the element level alongside the displacements of constrained nodes. As detailed in the direct formulation presented in [4], a linear operator V is established to link these parameters to the generalized self-equilibrated stress components:

$$\sigma^{0e} = V\delta \tag{11}$$

where the generalized stress vector is composed of:

$$\sigma^{0e} = \{N^{0e}, M_1^{0e}, M_2^{0e}\} \tag{12}$$

The elastic domain for each RVE, which encapsulates the compatibility requirements, is characterized as an ellipsoidal volume within a three-dimensional framework, with its primary axes defined by the following boundary constraints:

$$\begin{aligned} N_y^- < N < N_y^+ \\ M_{1y}^- < M_1 < M_{1y}^+ \\ M_{2y}^- < M_2 < M_{2y}^+ \end{aligned} \tag{13}$$

In this formulation, the indices iy^+ and iy^- denote the positive and negative yield thresholds for the generalized stress components within the element's cross-sectional plane.

To determine these limits, the RVE is subjected to natural boundary conditions, where nodal forces are applied to a specific cubic face; these forces act normal to the surface for axial limits and parallel to it for shear limits. Furthermore, essential boundary conditions are implemented via periodic displacement

constraints, ensuring a consistent and repetitive stress field across the continuum. Based on this beam-element RVE model, the derived elastic stress vector is defined as follows:

$$\sigma^e = \{N^e, M_1^e, M_2^e\} \tag{14}$$

By scaling the applied loads with a scalar factor k, the collapse load multiplier s_c is determined through the following optimization program:

$$s_c = \max_{k,\sigma^{0e} \in \mathrm{Null}(E_{eq})} k \quad \text{subject to:} \quad \begin{pmatrix} N_y^- < kN^e + N^{0e} < N_y^+ \\ M_{1y}^- < kM_1^e + M_1^{0e} < M_{1y}^+ \\ M_{2y}^- < kM_2^e + M_2^{0e} < M_{2y}^+ \end{pmatrix} \tag{15}$$

The peak force derived from the program identifies the yield stress, representing the intersection of the homogenized material's elastic domain with the stress axes.

This approach bypasses iterative, path-dependent methods, directly identifying the stress limit as the supremum of the lower bound. By applying this procedure to various lattice geometries, the collapse multipliers are determined, defining the axes of a six-dimensional hyper-ellipsoidal limit locus. It is important to clarify that this domain is defined within a special stress space based on the RVE's cubic faces, distinct from the Haigh–Westergaard representation. The normal-to-shear stress limit ratio was estimated by the von Mises criterion to be $\sqrt{3}$, whereas such a σ_0/τ_0 ratio was numerically found to be violated repeatedly, depending on PC and BCC proportions. This suggests that no plastic isotropy existed.

3 Method

3.1 Automated RVE Generation Framework

The proposed method incorporates AI for automatic Representative Volume Element (RVE) generation, significantly decreasing the reliance on manual CAD modeling.

A schematic representation or input image is used to identify zones containing material through a learning-based technique. This process trains the AI algorithm to recognize structural designs and distinguish between solid regions and voids. However, the AI cannot assess the feasibility of constructing the generated structures. Therefore, AI-driven generation is integrated with computational procedures through a comprehensive multi-stage pipeline (see Fig. 4).

In Stage 1, deep learning techniques, specifically vision alters and convolutional neural networks (CNNs), are employed to segment input images into 2D masks. These masks are then extruded to create raw 3D geometries.

The AI component approaches the identification of structural features as a dense, pixel-wise classification problem. For semantic segmentation, the algorithm assigns a discrete class label $c \in \{1, \ldots, K\}$ to every pixel x_i (representing

material or void), where the network outputs a continuous tensor of logits $z_{i,c}$. These logits are converted into a probability distribution using the Softmax function:

$$P(y_i = c|X) = \frac{\exp(z_{i,c})}{\sum_{k=1}^{K} \exp(z_{i,k})} \tag{16}$$

where X is the input image and y_i is the predicted class for pixel i. The final predicted class $\hat{y}_i$ is the one that maximizes this probability: $\hat{y}_i = \arg\max_c P(y_i = c|X)$. This ensures a precise transition from raw pixel intensities to discrete physical components like load-bearing struts.

To refine the model's accuracy during the training phase, a categorical Cross-Entropy ($\mathcal{L}_{CE}$) loss function is minimized over all N pixels:

$$\mathcal{L}_{CE} = -\frac{1}{N} \sum_{i=1}^{N} \sum_{c=1}^{K} y_{i,c} \log(P(y_i = c|X)) \tag{17}$$

where $y_{i,c}$ is the binary indicator (0 or 1) if class label c is the correct classification for pixel i. This rigorous mathematical optimization allows the pipeline to maintain high geometric fidelity, which is essential for the subsequent multiscale mechanical analysis.

Due to the inherently stochastic nature of AI generation, an essential structural admissibility filter is applied in Stage 2 to eliminate configurations that exhibit geometric inconsistencies or mechanical instability. Stage 3 involves parameterizing the admissible geometries into either discrete node-and-strut networks or continuous implicit surfaces. Finally, in Stage 4, finite element analysis (FEA) is conducted on the multiscale models to derive homogenized elastic properties, calculate collapse multipliers, and determine the macroscopic yield domain using finite element limit analysis (FELA).

Due to the stochastic nature of AI-generated outputs, a filtering stage is required. Generated RVEs may include:

- geometrically inconsistent structures,
- mechanically unstable (labile) configurations,
- disconnected or non-manufacturable geometries.

A selection process is implemented to retain only structurally admissible Representative Volume Elements (RVEs). This step guarantees that the modeling and analysis phases are conducted on configurations that are physically meaningful.

Discrete RVEs are represented as networks of nodes and struts, with each node defined by its spatial coordinates.

$$\mathbf{P}_i = (x_i, y_i, z_i) \tag{18}$$

Nodes are approximated as spheres (or polyhedral approximations such as icosahedra), defined by:

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 \leq R_{\text{joint}}^2 \tag{19}$$

Struts connecting nodes P_1 and P_2 are modeled as cylindrical elements whose axis is defined parametrically:

$$\mathbf{L}(t) = \mathbf{P}_1 + t(\mathbf{P}_2 - \mathbf{P}_1), \quad 0 \leq t \leq 1 \tag{20}$$

The strut surface is obtained by enforcing a constant radial distance from the axis, see Fig. 2.

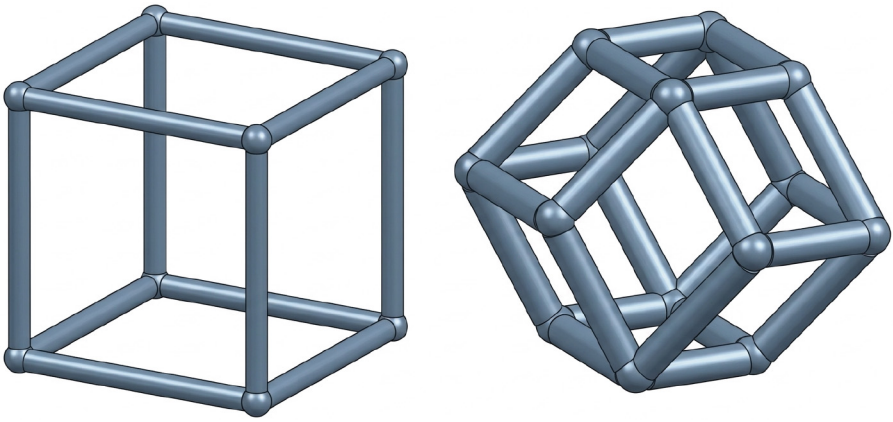

Fig. 2. Example of strut-based lattice geometry

3.2 Implicit Geometry: Surface-Based Metamaterials

Implicit geometries are defined through continuous scalar fields over a discretized 3D domain. The spatial coordinates are scaled as:

$$X = \omega x, \quad Y = \omega y, \quad Z = \omega z \tag{21}$$

A scalar field $F(X, Y, Z)$ is evaluated, and the geometry is extracted as an iso-surface:

$$F(X, Y, Z) = c \tag{22}$$

The discretization uses the Marching Cubes algorithm to reconstruct complex geometries, such as Triply Periodic Minimal Surfaces (TPMS).

Image segmentation is used to convert pixel-based information into structural geometry. The image domain is partitioned into regions R_i satisfying:

- completeness,
- exclusivity,
- homogeneity,
- separability.

Deep learning models, such as CNNs or Vision Transformers, are used to assign class labels to each pixel. The Softmax function computes the probability distribution over these classes:

$$P(y_i|X) \tag{23}$$

The final classification utilizes maximum likelihood prediction. Individual structural components are differentiated through instance segmentation. The Intersection over Union (IoU) metric is employed to assess the quality of segmentation:

$$IoU(A, B) = \frac{|A \cap B|}{|A \cup B|} \tag{24}$$

Geometric fidelity is represented by high IoU-values.

4 Results

4.1 Image-to-Geometry Conversion

Input images are effectively transformed into 3D geometries by the trained AI algorithm, with discretization algorithms being used for the extrusion and processing of segmentation masks into solid models.

The standard formats for the exportation of the obtained geometries include (Fig. 3):

- `.dwg` (CAD),
- `.obj` (mesh-based),
- `.stl` (additive manufacturing),
- `.stp` (FEM).

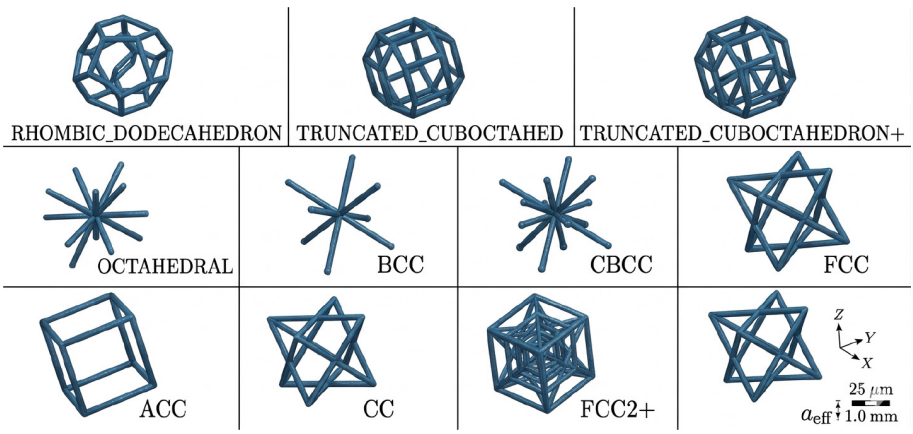

Fig. 3. Example of strut-based lattice geometry

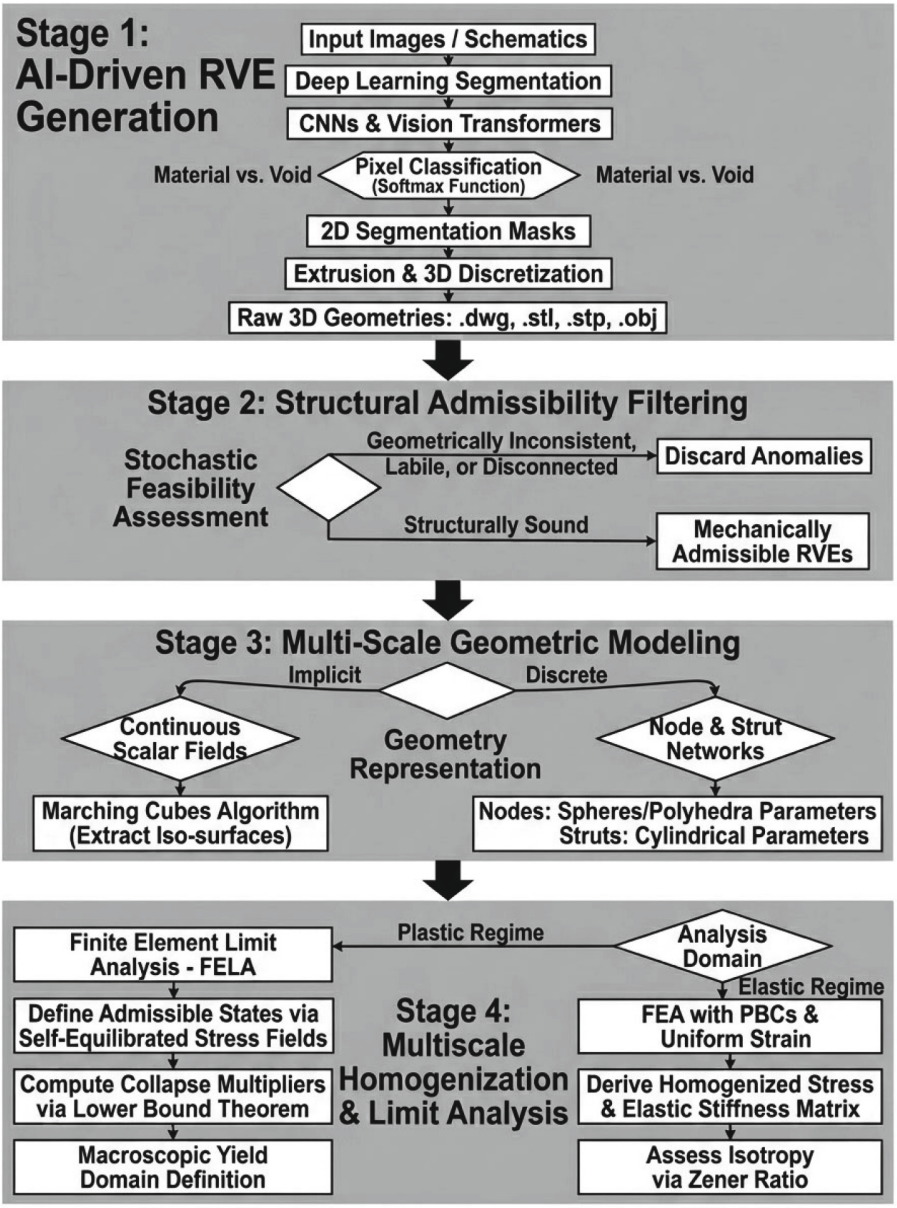

Fig. 4. Diagram of automated generation, structural filtering, geometric modeling, and multiscale mechanical assessment of metamaterial RVEs

4.2 Generated RVEs

The pipeline produced a number of RVEs. Drawing on this procedure, highly complex geometries with marginal manual intervention can be generated.

Preprocessing is remarkably accelerated by directly using such geometries in FE analysis.

This study evaluated a cantilever beam comprising isotropic truss RVEs.

$$\kappa = \frac{h}{\delta} \tag{25}$$

The effect of the geometric parameter on mechanical performance was analyzed, with h and δ denoting the characteristic cell size and strut thickness, respectively.

5 Conclusions

This study combines artificial intelligence (AI) and computational mechanics to develop a method for the automatic generation, filtering, and analysis of Representative Volume Elements (RVEs) for mechanical metamaterials. The integrated approach converts image-based inputs directly into 3D geometries suitable for finite element (FE) analysis and machine learning (ML). By using automated renovator algorithms alongside learning-based segmentation, this method quite reduces the demand for manual CAD modeling, thereby speeding up the preprocessing stage.

Filtering is a vital part of this approach, as it makes certain that the architectures generated by AI are mechanically valid. This is essential for applying data-driven generation techniques to real-world engineering problems. Homogenization was applied to evaluate the mechanical performance of representative volume elements (RVEs) in both elastic and limit states. It was shown that geometric parameters, particularly the ratio of cell size to strut thickness, are highly dependent on key properties. The modulus of elasticity obtained was significantly lower than that of the base material, and the numerical results were in good assent with experimental data obtained in [37–39] (error $\approx 7\%$).

Additionally, the represented method demonstrated a notable calculable improvement; the computational cost was 95% lower than standard modeling techniques, as fewer elements were used for complex lattice designs. The computational cost for highly intricate unit cells was even lower.

Several limitations were encountered in the study. First, only a single material and a limited number of lattice design classes were analyzed. Second, the AI algorithm did not guarantee the feasibility of the structures, indicating the need for external validation and filtering processes.

It is recommended that researchers expand the proposed approach to include multimaterial systems to improve the robustness of AI-based generation. Additionally, incorporating physics-informed constraints into the learning process could be beneficial. Exploring more complex loadings and real-scale structural applications is also suggested.

Overall, the proposed method considerably contributes to the automation of metamaterial design, which enables the development of efficient, scalable, and data-driven methods for advanced structural engineering.

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Temporal Decay Functions for Clickstream Session Representation: A Comparative Analysis of Linear and Exponential Weighting Strategies

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Abstract. Clickstream data from e-commerce platforms offers valuable insights into how users browse. Applications such as user analytics, recommendation systems, and behavioral segmentation depend on modeling these sequential interactions. However, many existing session representation techniques use straightforward averaging to produce session embeddings. These tactics ignore the timing of interactions within a session. In fact, events that occur near the end of a session often provide stronger indications of the user's immediate intent. This implies that the creation of useful session representations may depend on time information. This work examines the impact of temporal decay functions on the development of session embeddings for clickstream analytics. The study examines the effects of various decay strategies on behavioral clustering performance. We propose a session modeling framework that combines explicit temporal weighting techniques with transformer-based event embeddings to address these issues. Linear and exponential temporal decay functions are studied to understand how different weighting strategies affect clustering quality. Experiments on real-world clickstream datasets show that session representations with temporal weighting generally outperform traditional averaging methods. In particular, exponential temporal decay offers the best clustering performance across different embedding models. These results highlight how important it is to consider time in session representation learning. They also show that concentrating on recent interactions greatly improves behavioral clustering in clickstream analytics.

Keywords: clickstream analytics · session representation · user behavior modeling · temporal decay functions · behavioral clustering

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 599–618, 2026.
https://doi.org/10.1007/978-3-032-30524-4_37

1 Introduction

The rapid expansion of e-commerce platforms has led to the generation of massive volumes of user interaction data, commonly referred to as clickstream data. These data consist of sequential records of user actions such as product views, searches, and cart operations performed during a browsing session. Understanding behavioral patterns embedded within these sequences is essential for applications including recommendation systems, user segmentation, purchase prediction, and personalization. Consequently, representing user sessions in a compact numerical form that captures meaningful behavioral signals has become a fundamental problem in clickstream analytics and web usage mining.

A wide range of approaches have been proposed in the literature to model sequential behavioral data obtained from user interactions. Early studies relied on frequency-based representations and term-weighting techniques originally developed in information retrieval to capture the relative importance of elements within a dataset [1]. With the advancement of representation learning, embedding techniques have become widely used to map discrete events into continuous vector spaces that preserve contextual relationships. Recent developments in transformer-based architectures have further improved the ability to model sequential dependencies and contextual information in event sequences. In parallel, several studies have explored embedding techniques as an effective tool for capturing semantic relationships between behavioral events in large-scale datasets [2].

Previous studies conducted by our research group have extensively investigated embedding-based approaches for modeling user navigational behavior in clickstream environments. In particular, graph-based embedding techniques and sequence-based representation learning methods have been applied to convert user browsing events into numerical vectors suitable for downstream analytics tasks such as clustering, prediction, and intelligent prefetching [3,4]. These studies demonstrated that embedding-based representations can effectively capture structural relationships between user interactions and provide meaningful representations of browsing behavior in e-commerce and digital service platforms. Furthermore, several works have explored predictive modeling and sequential learning approaches for understanding user actions and navigation patterns in digital platforms [5–7]. In addition, recent studies have investigated the integration of frequency-based and time-sensitive weighting mechanisms within embedding pipelines to enhance the modeling of user behavioral patterns and improve session-based behavioral analysis [8].

Despite these advances, important limitations remain in existing session representation approaches. In many embedding-based models, session representations are constructed using simple averaging or uniform aggregation of event embeddings. Such approaches assume that all events within a session contribute equally to the resulting representation. However, in real-world clickstream environments, user interactions often follow a dynamic pattern in which actions occurring later in the session may reflect stronger behavioral signals regarding the user's immediate intent. Ignoring such temporal dynamics may therefore

lead to diluted session representations and reduce the discriminative power of behavioral clustering models.

Motivated by this limitation, this study investigates how the temporal position of events within a session can be incorporated into the construction of session representations. In particular, the study examines whether assigning different importance levels to events according to their temporal positions can improve the quality of behavioral clustering. Two key research questions guide the investigation. First, we examine whether temporally weighted session representations provide more discriminative clustering structures compared to standard unweighted aggregation approaches. Second, we analyze how different temporal decay functions influence clustering performance in modeling users' navigation behavior within clickstream sessions.

This study creates a modular framework for session modeling that integrates temporal weighting and event embeddings in order to investigate these questions. This framework uses transformer-based models to represent each event in a user session as a numerical vector. Each event's contribution is then modified based on its position during the session. Plain aggregation, linear weighting, and exponential weighting, which give more weight to more recent interactions, are the three weighting approaches taken into consideration.

Event embedding generation, temporal weighting, session vector construction, and clustering comprise the four stages of the methodology's modular workflow. Four transformer-based models, BERT4Rec, SASRec, BERT-base-uncased, and ALBERT-base-v2, are used to create event embeddings in order to compare how various models depict user behavior. The aforementioned weighting techniques are then used to aggregate these event-level embeddings into session-level vectors. The clustering analysis uses the resulting fixed-length session representations.

Clickstream datasets gathered from e-commerce platforms are used for clustering experiments to assess the suggested representation framework. K-Means and Bisecting K-Means are used to analyze session vectors produced from various combinations of embedding models and weighting techniques. Standard internal validation metrics are used to evaluate cluster quality, with special focus on the Silhouette score. The right number of clusters is chosen using the Elbow method. With this configuration, the separability and consistency of behavioral clusters can be investigated in relation to temporal weighting.

The study's findings yield a useful method for generating session representations for clickstream analytics. Session representations that better represent user behavior are produced by combining transformer-based event embeddings with time-aware weighting. In large-scale e-commerce environments, these representations can facilitate behavioral segmentation and provide a practical means of modeling short-term user intent.

Although the experimental setup is built around clickstream data, the underlying problem is more general: a session can be viewed as a discrete realization of a time-dependent process in which the informational value of past states fades as new ones are observed. Similar formulations arise in sensor streams, event logs,

and short-horizon state descriptors used in data-driven modeling of dynamical systems, where the choice of decay function plays a role conceptually close to that of a memory kernel.

This is how the rest of the paper is structured. The literature on clickstream analytics, embedding-based user behavior modeling techniques, and session representation techniques is reviewed in Sect. 2. The suggested approach, which includes session vectorization, temporal weighting, event embedding creation, and the clustering framework, is presented in Sect. 3. The implementation and experimental setup, the evaluation procedure, and the clustering results obtained with various embedding models and weighting strategies are all described in Sect. 4. The paper is finally concluded in Sect. 5, which also explores potential future research directions.

2 Literature Review

In our earlier work, we explored several embedding-based approaches for modeling user navigational behavior in clickstream data. We first focused on graph-based methods such as Word2Vec, Node2Vec, and Struct2Vec to represent browsing patterns and group similar behavioral sequences [3]. These studies showed that embedding models can transform high-dimensional clickstream data into compact vector representations while preserving structural relationships among user interactions. Later, we extended this line of work to predictive modeling, where embedding-based representations were combined with deep learning methods to model customers' digital footprints and anticipate future actions on digital platforms [6]. More recent studies in our group incorporated temporal aspects into session representations. This included aging-based weighting methods that gave greater emphasis to recent interactions in session modeling [8]. We also examined other ways of representing user intent in clickstream sessions, including recency-weighted embeddings and sequential neural representations [7]. In addition, embedding-based navigation models were applied to predictive prefetching in data-intensive systems [4]. When combined, these studies imply that complex behavioral patterns in extensive web navigation data can be captured by embedding-based representations. Building on this work, the current study combines transformer-based embeddings with explicit temporal weighting strategies to investigate how various temporal decay functions affect the efficacy of session-based embedding representations in clickstream analytics.

Modeling user behavior from clickstream data has been a recurring topic in web usage mining and recommender systems research. Early work largely relied on statistical and frequency-based methods to represent user sessions. Approaches such as term weighting, association rule mining, and sequential pattern analysis were commonly applied to identify navigational patterns. The TF-IDF scheme proposed by Salton and Buckley [1] became one of the more widely adopted techniques for estimating the relative importance of elements in both document collections and behavior-based datasets. Similarly, early web usage mining studies explored Markov models and sequential pattern mining to characterize how users navigate through websites [9]. While these methods provided

useful descriptive insights, their reliance on sparse representations made it difficult to capture more nuanced semantic relationships between events.

Representation learning offered a different way to model user interaction data. Methods such as Word2Vec [10] introduced the idea of representing discrete entities as dense vectors, allowing semantic similarity to be preserved in a continuous space. This framework was subsequently extended to graph and network-structured data. Approaches such as DeepWalk [11] and Node2Vec [12] proposed scalable techniques for learning node representations directly from network topology. These methods were gradually adopted in recommender systems and behavioral analytics, where they proved useful for capturing relationships among users, items, and interaction events.

Embedding techniques have also been applied to session modeling in clickstream contexts. Actions such as product views, searches, and purchases can be mapped to continuous vectors, making it possible to surface latent behavioral patterns. Prior work suggests that such representations can support tasks including clustering, recommendation, and purchase prediction, largely by encoding similarity relationships across interaction sequences [13]. At the same time, many session representation methods still rely on simple aggregation schemes such as mean pooling or uniform averaging. In practice, this means that all events are treated as if they contribute equally to the final session representation.

At the same time, research on session-based recommendation systems introduced sequential neural architectures. These architectures model the dependencies among user interactions. One of the earliest neural approaches is GRU4Rec [14]. It uses recurrent neural networks to predict the next interaction in a session. Later studies suggested other architectures, including convolutional models [15] and hybrid neural methods, to better capture sequential dependencies. These models showed that taking the order of interactions into account greatly improves the way short-term user preferences are represented compared to static session representations.

More recently, transformer-based architectures have greatly improved sequential user behavior modeling. The Transformer model proposed by Vaswani et al. [16] allows for effective modeling of long-range dependencies using self-attention mechanisms. Several transformer-based models have been developed for sequential recommendation tasks, including SASRec [17], BERT4Rec [18], and related transformer-based frameworks for session-based recommendation [19]. These models create contextualized representations of interaction sequences by modeling dependencies across the entire session together. Although transformer architectures have performed well in recommendation tasks, their use in behavioral clustering and session segmentation is still quite limited.

Another important research direction concerns weighting mechanisms for modeling the importance of events within behavioral data. Traditional information retrieval methods like TF-IDF focus on informative elements based on frequency statistics [1]. In recommender systems, a range of importance-weighting strategies has been introduced to give greater emphasis to certain interactions within user sessions. Among these, attention-based mechanisms assign different

levels of contribution to individual events in the formation of user representations [20]. Most existing weighting strategies are mainly made for prediction or recommendation tasks. They are not designed for clustering-based behavioral analysis.

Temporal dynamics are also important in modeling user behavior in session-based environments. Earlier studies indicate that user preferences are not static over time and that recent interactions may carry more informative signals for short-term user intent. For example, Koren [21] incorporated temporal dynamics into collaborative filtering models to improve recommendation accuracy. Similarly, Campos et al. [22] provided a comprehensive overview of time-aware recommender systems, highlighting the importance of temporal information in modeling user interactions.

Recent research has also explored how contextual embeddings can be combined with sequential modeling frameworks. For example, Quadrana et al. [23] introduced hierarchical recurrent models that capture both session-level and user-level dynamics in recommendation systems. In a similar direction, industrial frameworks such as Transformers4Rec illustrate how transformer architectures can be used in real-world recommendation settings by bringing together contextual embeddings and sequential interaction modeling [24].

Despite these advances, several limitations remain in existing session representation approaches. Many embedding-based methods construct session representations using uniform aggregation strategies that ignore the temporal importance of interactions. Moreover, while time-aware recommender systems incorporate temporal signals for prediction tasks, relatively few studies investigate how temporal weighting influences behavioral clustering or session segmentation. To address these limitations, this study proposes a temporally sensitive session representation framework that integrates transformer-based event embeddings with explicit temporal weighting strategies. By combining contextual embedding models with analytically defined temporal decay functions, the proposed approach aims to construct more discriminative session representations that improve clustering-based behavioral segmentation in clickstream analytics.

3 Methodology

In this study, user sessions obtained from e-commerce platforms are analyzed using a clustering-based approach on clickstream data. Clickstream data refer to a time-ordered record of successive interactions (events) performed by a user during a single visit, and they contain important cues reflecting the user's intentions. The primary objective of this work is to generate vector representations (session embeddings) for user sessions using different methods and to systematically evaluate the impact of these representations on clustering performance. In particular, the effect of assigning different weights (linear, and exponential) to events within a session based on their temporal positions on the quality of cluster separation is investigated in detail.

The proposed method is built upon a modular structure consisting of event embedding generation, temporal weighting, session vectorization, and clustering

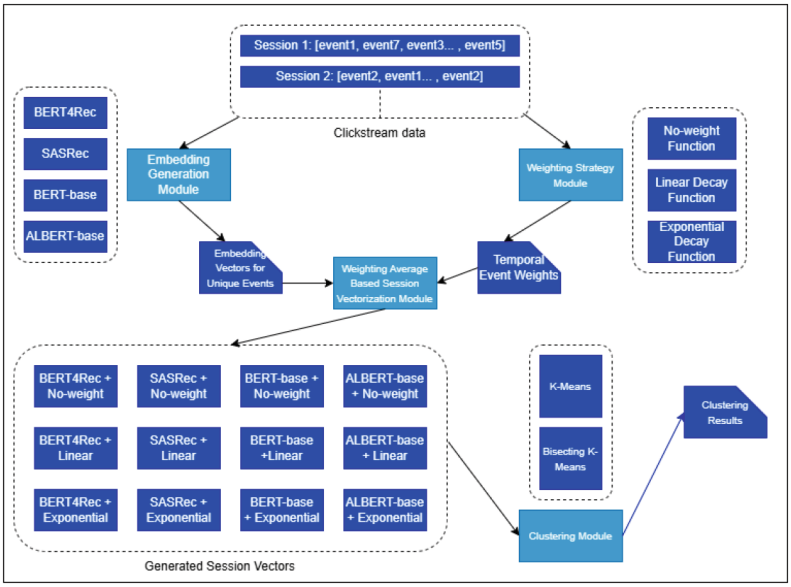

Fig. 1. Overview of the proposed methodology and its modular workflow

steps, starting from raw clickstream data. This modular structure and the data flow between components are illustrated in the flow diagram summarizing the general methodological framework of the study (Fig. 1). The flow diagram holistically presents the operations applied at each stage and how different method combinations are generated.

In the datasets employed, each observation represents a single session belonging to a user. Each session is defined as a sequence of consecutive events performed by the user during a visit, and these sequences are stored in chronological order. During the preprocessing stage, incomplete or erroneous records were removed from the dataset; subsequently, the event sequences for each session were parsed, and empty or invalid values were cleaned. As a result of these procedures, each user session was transformed into a cleaned list of events suitable for analysis. In this study, we use the following notation for a user session:

$$S = [e_1, e_2, \ldots, e_L] \tag{1}$$

where e_i denotes the i-th event within the session, and L denotes the length of the session (i.e., the total number of events). This notation serves as the fundamental representation for both event-level embedding generation and session-level vectorization processes. In the following subsections, each module in the flow diagram is discussed in detail. The components of the proposed method are explained.

Embedding Generation Module: The goal of this stage is to represent each user interaction (event) as a numerical vector, making it suitable for further analysis. Clickstream data has a categorical and sequential structure, so it is important to embed this information into a continuous vector space. In this study, four different embedding approaches are used: BERT4Rec, SASRec, BERT-base-uncased, and ALBERT-base-v2. These approaches are compared based on their ability to represent the data.

BERT4Rec and SASRec are Transformer-based sequential recommender models specifically designed to model sequences of user interactions. Through the self-attention mechanism, both approaches are capable of learning long-range dependencies among events within a session and generating contextualized representations for each interaction. BERT4Rec employs a bidirectional Transformer architecture and a masked item prediction strategy, treating the session sequence holistically and representing each event by considering both preceding and succeeding interactions. In contrast, SASRec utilizes a unidirectional self-attention mechanism that explicitly accounts for temporal order, effectively modeling sequential dependencies based on the user's past behavior. In this study, using these transformer-model based embedding approaches, 64-dimensional vector representations were obtained for each event. Consequently, representations that reflect the sequential and contextual patterns in clickstream data and detailedly encode user behaviors were produced.

On the other hand, the BERT-base-uncased and ALBERT-base-v2 models are contextual language models built upon the Transformer architecture and pre-trained on large-scale text corpora. Since these models are designed for natural language inputs, each clickstream event was first converted into natural language sentences to reflect its semantic structure. For instance, an event such as "add_to_cart" was represented by the phrase "add product to shopping cart." When these sentences are provided as input to the model, hidden state vectors are generated for each token. In this study, the vector corresponding to the special [CLS] token, which is prepended to the sentence and trained to represent the entire sequence, was utilized as the embedding representation of the corresponding event. Since the [CLS] token aggregates the contextual information derived from the entire sentence into a single vector, it provides a summary that holistically represents the semantic content of the event. In this way, events defined through natural language are transformed into context-aware and semantically rich vector representations.

Weighting Strategy Module: The objective of this module is to assign varying degrees of importance to events within a user session by considering their temporal positions, thereby ensuring that session representations better reflect the user's current intent. In clickstream data, it is widely accepted that interactions occurring toward the end of a session more strongly represent the user's short-term interest. Therefore, weighting events based on their order within the session can produce more discriminative session vectors compared to plain averaging approaches. In this study, two distinct temporal weighting strategies, each

representing a different assumption, are evaluated: linear decay, and exponential decay. The weighting process depends only on the timing of the events, not on their content. A user session is labeled as S, with L indicating the total number of events. This sequence goes into the weighting module. The result is a set of normalized weights that matches the session length L. Each weight corresponds to a specific event in the sequence.

Plain (No-weight) Weighting: In the plain weighting approach, it is assumed that all events within a session possess equal importance. This approach serves as a baseline method where temporal information is completely disregarded. In this case, the weight value for each event is defined as:

$$w_i = \frac{1}{L}, \quad i = 1, 2, \ldots, L \tag{2}$$

In this approach, the sum of all weights equals one:

$$\sum_{i=1}^{L} w_i = 1 \tag{3}$$

In the implementation, this strategy is applied by generating unit weights for all events and dividing them by the session length.

Linear Weighting: In the linear weighting approach, weights are assigned to events in a linearly increasing manner according to their temporal order within the session. This approach relies on the assumption that events occurring toward the end of the session are more important, but this increase occurs in a controlled and gradual manner. First, the normalized position of each event within the session is defined as follows:

$$p_i = \frac{i-1}{L-1}, \quad i = 1, 2, \ldots, L \tag{4}$$

Here, p_i takes values in the range $[0, 1]$ and increases monotonically from the beginning to the end of the session. The linear weight value for each event is then calculated as:

$$\tilde{w}_i = a + b \cdot p_i \tag{5}$$

Here, a and b represent hyperparameters that control the initial level and the slope of the weight distribution, respectively. The resulting weights are then normalized to make sure their total adds up to one. This normalization step is important for keeping the scale the same across sessions of different lengths and for maintaining the consistency of the generated session vectors' magnitudes:

$$w_i = \frac{\tilde{w}_i}{\sum_{j=1}^{L} \tilde{w}_j} \tag{6}$$

Using this method, events that happen toward the end of the session get more weight. In contrast, the impact of early-stage events is lessened.

Exponential Weighting: The exponential weighting approach is a more aggressive strategy. In this method, the importance of time increases exponentially instead of linearly. In this method, the representational power of events near the end of the session is significantly amplified, making the user's most recent interactions dominant. First, normalized temporal positions are defined as in the linear method:

$$p_i = \frac{i-1}{L-1} \tag{7}$$

Subsequently, the exponential weight value for each event is calculated as follows:

$$\tilde{w}_i = \exp(\lambda \cdot p_i) \tag{8}$$

where λ is a positive hyperparameter that controls how rapidly the weights increase. Higher λ values make the influence of events near the end of the session even more dominant. The obtained exponential weights are normalized similarly to the linear method:

$$w_i = \frac{\tilde{w}_i}{\sum_{j=1}^{L} \tilde{w}_j} \tag{9}$$

Thanks to this normalization, the sum of the weights is equalized to one, ensuring comparability across sessions of different lengths.

The output of the weighting module is a weight vector for each session, having the same length as the number of events L:

$$\mathbf{w} = [w_1, w_2, \ldots, w_L] \tag{10}$$

This weight vector is combined with the event embedding vectors in the subsequent Session Vectorization Module to construct a single vector representation at the session level.

The two schemes differ in a way that matters in practice. Linear weighting is additive: every event keeps a non-negligible share of the final representation regardless of its position. Exponential weighting is multiplicative, with a fixed ratio between consecutive weights, so the tail of the session can dominate the aggregation once λ is large enough.

Session Vectorization Module: The objective of this module is to reduce multiple event embedding vectors contained within a user session into a single fixed-size session representation. Since clustering algorithms operate in fixed-dimensional vector spaces, it is necessary to represent variable-length event sequences with a singular vector. Accordingly, a weighted average-based vectorization process is applied for each session using the event embedding vectors obtained in the previous stages and the temporal weights generated from the weighting module. The final vector representation ($\mathbf{s}$) for a user session is computed using a weighted summation approach. In this process, the normalized coefficient (w_i) derived from the weighting module represents the temporal importance of the corresponding event, while the vector ($\mathbf{v}_i$) obtained from the

embedding module represents its semantic content. The session vector is obtained through the following equation:

$$\mathbf{s} = \sum_{i=1}^{L} w_i \cdot \mathbf{v}_i \tag{11}$$

This operation makes sure that event vectors are first scaled based on their time importance. Then, they are combined into a single vector. As a result, events happening towards the end of the session, which carry more weight, have a stronger influence on the final session representation.

To increase computational efficiency during the clustering stage and to enable a fair comparison between representations obtained from different models, the dimensions of all session vectors were standardized. In this study, the sequential recommendation models (BERT4Rec and SASRec) were set up to create 64-dimensional vectors during training with the RecBole library. As a result, no further dimensionality reduction was applied to the session vectors from these models. In contrast, a different approach was adopted for the pre-trained language models (BERT-base-uncased and ALBERT-base-v2), which naturally produce 768-dimensional vectors due to their architectures. To project these high dimensional vectors into the same dimensional plane (64 dimensions) as the recommendation models and to alleviate the computational burden, Principal Component Analysis (PCA) was applied. Since different weighting strategies (plain, linear, exponential) create distinct distributions in the vector space, the PCA process was performed separately for each strategy. Consequently, regardless of the source model, each user session is represented by a fixed 64-dimensional vector ($\mathbf{s}$), making it ready for the clustering module.

Clustering Module: The final stage of the proposed framework aims to identify groups of user sessions exhibiting similar behavioral patterns in clickstream data. The session vectors generated in the previous stages are used as inputs to clustering algorithms in order to identify groups of users with comparable navigation behaviors. These clustering methods help show how various temporal weighting strategies affect the separability of session representations.

In this study, the centroid-based K-Means algorithm is used as the main clustering method. K-Means divides session vectors into k clusters by repeatedly assigning each session to the closest centroid. It updates cluster centroids until it reaches a stable state. The aim of the algorithm is to form clusters whose members are similar to one another while remaining distinct from other clusters. In addition to K-Means, the study also considers Bisecting K-Means as an alternative clustering method. This approach follows a hierarchical divisive strategy. It begins by treating the entire dataset as a single cluster and then recursively splits it into smaller groups. At each stage, the selected cluster is divided using K-Means with $k = 2$. The process continues until the desired number of clusters is reached. Bisecting K-Means is included because it can produce more balanced cluster structures when behavioral patterns in the data are relatively diverse.

Selecting an appropriate number of clusters is an important part of clustering-based behavioral analysis. To guide this choice, the study uses both the Elbow method and Silhouette analysis. The Silhouette score evaluates clustering quality by considering both within-cluster cohesion and separation between clusters. The Elbow method, in contrast, examines how within-cluster variance changes as the number of clusters increases. In this study, clustering experiments were carried out with different values of k, and the final cluster configurations were determined by considering the results of these two methods together.

4 Implementation and Evaluation

4.1 Datasets

The proposed clustering approach was evaluated on two real-world e-commerce datasets. These datasets differ notably in terms of session volume, event diversity, and sequence characteristics, which makes it possible to examine the behavior of the method under different data conditions. The main statistical properties of both datasets are summarized in Table 1.

The first dataset contains roughly 197,000 user sessions. It includes a relatively small set of event types, with only nine distinct categories. Even so, it stands out for its high level of interaction within each session. As reported in Table 1, the average session length is 47.15 events, which is relatively high. The maximum sequence length is over 15,000, suggesting that some users remain active on the platform for long periods while repeatedly engaging in a limited set of core actions. The second dataset is larger, with over 547,000 sessions, but exhibits a different behavior pattern than Dataset 1. It offers a much richer diversity of interactions with 37 unique event types (e.g., detailed filtering, campaign interactions). In contrast, the average session length (16.56 events) is significantly shorter. This structure suggests that users exhibit more fragmented and goal-oriented browsing behavior characterized by shorter visits.

Table 1. Statistical Characteristics of the Experimental Datasets

Statistical Metric	Dataset 1	Dataset 2
Total Session Count	197,518	1,002,230
Total Event Volume	9,313,563	9,070,291
Number of Unique Event Types	9	37
Average Session Length	47.15	16.56
Maximum Sequence Length	15,221	2,500
Minimum Sequence Length	1	1

4.2 Implementation Details

The proposed framework was implemented in Python 3.10 within a cloud-based environment using Google Colab Pro. To support the computational demands of deep learning training and clustering on high-dimensional data, the experiments were run with a Tesla T4 GPU with 16 GB of VRAM and high-memory CPU resources. The implementation followed a modular design and made use of several open-source libraries suited to sequential data analysis and machine learning. Two separate approaches were used to generate event embeddings. For the sequential recommendation models, SASRec and BERT4Rec, the *RecBole* library (v2.0.1) was used. Both models were trained on the Next Item Prediction task with the same configuration: a hidden size of 64, an inner size of 256, 2 attention heads, and 2 transformer layers. Training was carried out for 5 epochs with a batch size of 2048, using the Adam optimizer and a learning rate of 0.001.

For the pre-trained language models (BERT and ALBERT), *Hugging Face Transformers* library was utilized. The `bert-base-uncased` and `albert-base-v2` models were deployed to extract semantic features. Custom text templates (e.g., "User performed [event] action") were mapped to event tokens, and the hidden state of the [CLS] token was extracted as the event representation. Following the embedding generation, session representations were constructed using the proposed temporal weighting strategies (Plain, Linear, and Exponential), implemented using the *NumPy* and *Pandas* libraries. To standardize the dimensionality across different models—specifically to reduce the 768-dimensional vectors from language models to a comparable 64-dimensional space—Principal Component Analysis (PCA) was applied using the *Scikit-learn* library. The clustering phase was engineered to support both CPU and GPU execution to handle large-scale session data. The *RAPIDS cuML* library was utilized for GPU-accelerated K-Means and DBSCAN algorithms, significantly reducing the computation time for hyperparameter tuning. For the Bisecting K-Means algorithm, the implementation provided by *Scikit-learn* was used on the CPU. The optimal number of clusters (k) was determined dynamically within the range of $k \in [3, 15]$ by evaluating Silhouette, Davies-Bouldin, and Inertia (Elbow) metrics iteratively.

4.3 Evaluation

One of the most important parameters that directly affects the clustering performance of the K-Means and Bisecting K-Means algorithms is the number of clusters (k). In this study, Silhouette analysis, which is widely used in the literature, was employed to determine the optimal number of clusters for both clustering approaches. Within the scope of the experiments, the number of clusters was systematically evaluated in the range of $k = 3$ to $k = 15$, and the results obtained by applying both K-Means and Bisecting K-Means algorithms for each k value were analyzed.

Silhouette analysis evaluates clustering quality by comparing the similarity of each data point to its assigned cluster with its distance to other clusters. A higher

Silhouette score indicates that clusters are both internally coherent and well-separated from each other. In the experiments conducted, the Silhouette scores were analyzed to determine the point where the clustering structure achieves maximum separation and consistency.

The final number of clusters used in the experiments was chosen based on the level of separation indicated by these scores. This provided a more stable basis for selecting an appropriate cluster count for both datasets and helped ensure that the resulting partitions were aligned with the underlying structure of the data.

Table 2. Clustering Performance of SAS4Rec on Dataset 1

Weighting Strategy	K-Means (Sil.)	Bisecting K-Means (Sil.)
Plain	0.475	0.443
Linear	0.517	0.488
Exponential	**0.566**	0.539

Table 3. Clustering Performance of ALBERT on Dataset 1

Weighting Strategy	K-Means (Sil.)	Bisecting K-Means (Sil.)
Plain	0.466	0.430
Linear	0.507	0.469
Exponential	**0.532**	0.513

Table 4. Clustering Performance of BERT (bert-uncased) on Dataset 1

Weighting Strategy	K-Means (Sil.)	Bisecting K-Means (Sil.)
Plain	0.467	0.439
Linear	0.508	0.482
Exponential	**0.547**	0.511

The clustering results for Dataset 1 and Dataset 2 are reported in eight tables, with four tables for each dataset. For both datasets, the analysis includes four embedding models: SASRec, ALBERT, BERT, and BERT4Rec. Session representations were constructed using three temporal weighting strategies (Plain, Linear, and Exponential). Clustering was then carried out with both K-Means and Bisecting K-Means, and cluster quality was evaluated using the Silhouette

Table 5. Clustering Performance of BERT4Rec on Dataset 1

Weighting Strategy	K-Means (Sil.)	Bisecting K-Means (Sil.)
Plain	0.473	0.427
Linear	0.523	0.480
Exponential	**0.557**	0.523

Table 6. Clustering Performance of SAS4Rec on Dataset 2

Weighting Strategy	K-Means (Sil.)	Bisecting K-Means (Sil.)
Plain	0.548	0.543
Linear	0.603	0.566
Exponential	**0.639**	0.605

score. This metric was used as an internal validation measure because it reflects both the compactness of clusters and the degree of separation between them.

Tables 2, 3, 4 and 5 for Dataset 1 and Tables 6, 7, 8 and 9 for Dataset 2 show a consistent pattern across models and datasets. Among the three weighting strategies, Exponential weighting gives the highest Silhouette scores in all experimental settings under both K-Means and Bisecting K-Means. Linear weighting usually performs better than plain averaging, but it does not reach the same level as the exponential scheme. These findings suggest that placing more emphasis on recent events may improve session representations for clustering-based analysis.

Overall, the results suggest that temporal sensitivity plays a meaningful role in session-based clustering. Assigning greater weight to recent interactions through exponential weighting is associated with improved clustering performance, reflected in clusters that tend to be more compact and better separated. The consistency of this pattern across different embedding models, datasets, and clustering algorithms indicates that the proposed weighting scheme is not specific to a particular experimental configuration. These findings suggest that temporal weighting may help capture session-level behavioral patterns more effectively than uniform aggregation.

Average Silhouette scores were calculated for $k = 3$ to $k = 15$ to provide a better assessment of clustering performance across different cluster setups. For each embedding model and dataset, we then calculated relative improvement

Table 7. Clustering Performance of ALBERT on Dataset 2

Weighting Strategy	K-Means (Sil.)	Bisecting K-Means (Sil.)
Plain	0.550	0.566
Linear	0.589	0.571
Exponential	**0.617**	0.582

Table 8. Clustering Performance of BERT (bert-uncased) on Dataset 2

Weighting Strategy	K-Means (Sil.)	Bisecting K-Means (Sil.)
Plain	0.557	0.541
Linear	0.597	0.562
Exponential	**0.630**	0.580

Table 9. Clustering Performance of BERT4Rec on Dataset 2

Weighting Strategy	K-Means (Sil.)	Bisecting K-Means (Sil.)
Plain	0.546	0.527
Linear	0.604	0.549
Exponential	**0.631**	0.607

ratios compared to the Plain (no-weight) baseline. By combining performance over various values of k, this approach lessens the impact of changes linked to individual cluster counts. It also allows us to examine the overall behavior of temporal weighting strategies in a more steady and accurate way. Therefore, the reported improvement ratios show general performance trends rather than results linked to a particular clustering setup.

The average percentage improvements for the sequential embedding models, SAS4Rec and BERT4Rec, are shown in Table 10. The results for the language-model-based embeddings, BERT and ALBERT, are in Table 11. For all the models tested and both datasets, temporally weighted session representations show higher average Silhouette scores than the unweighted baseline. In particular, Exponential weighting achieves the largest improvements in every case. Linear weighting offers more modest but steady gains.

These results show that including temporal position information in session representations improves clustering quality in a consistent way. The continued improvements across various cluster counts suggest that the benefits of temporal weighting are not limited to specific values of k, but instead represent a general increase in cluster separation and compactness. Overall, the results confirm that focusing on temporal dynamics, especially with exponential weighting, leads to stronger and more stable session-based clustering results.

Table 10. Avg. Silhouette Improvement Compared to No-Weight using K-Means (SAS4Rec vs BERT4Rec)

Weighting	SAS4Rec		BERT4Rec	
	Dataset 1 (%)	Dataset 2 (%)	Dataset 1 (%)	Dataset 2 (%)
Linear	9.87%	5.33%	9.59%	5.77%
Exponential	18.88%	15.27%	16.04%	13.90%

Table 11. Avg. Silhouette Improvement - Compared to No-Weight using K-Means (Bert vs Albert)

Weighting	BERT		ALBERT	
	Dataset 1 (%)	Dataset 2 (%)	Dataset 1 (%)	Dataset 2 (%)
Linear	8.51%	8.50%	9.61%	7.58%
Exponential	15.53%	17.26%	15.67%	13.72%

The experimental results offer a basis for addressing the research questions outlined in this study. The first question concerns the effect of temporal weighting on the segmentation performance of sequential embedding models. To examine this, session representations generated using Plain, Linear, and Exponential weighting schemes were compared across all evaluated models. The results indicate that incorporating temporal information is generally associated with improved clustering quality. Temporally weighted representations tended to produce higher Silhouette scores than the unweighted Plain baseline, suggesting that accounting for the positional order of events within a session may contribute to more coherent and better-separated clusters.

The second research question concerns the effect of different temporal decay functions on model performance. Linear and Exponential weighting were evaluated on both datasets under the same experimental conditions. While Linear weighting shows a modest improvement over Plain averaging, Exponential weighting tends to produce the most favorable results across the evaluated models and datasets. The corresponding increase in Silhouette scores suggests that stronger emphasis on recent interactions may improve the representation of short-term user intent. In this respect, the results point to the temporal decay function as an important design choice in session segmentation.

4.4 Discussion and Limitations

The consistent ordering of the three schemes admits a simple reading: linear weighting preserves the influence of early exploratory actions whose link to the user's final intent is often weak, whereas the exponential scheme acts as a soft selection mechanism in which the tail of the session dominates the aggregation. The same ordering across four embedding models, two datasets, and two clustering algorithms suggests that the effect is driven by the weighting mechanism itself rather than by a particular configuration. Three limitations should be noted: clustering quality is judged through internal validation only; the decay rate λ is fixed across sessions rather than tuned per session or learned jointly with the embedding model; and both datasets, although structurally different, come from e-commerce platforms.

5 Conclusion and Future Work

This study explores how temporal decay functions affect the construction of session representations in clickstream analytics. It focuses on whether the position of events within a session can make session embeddings more useful for behavioral clustering. It also examines how different temporal decay strategies influence this process. To address these questions, a modular session modeling framework was proposed that integrates transformer-based event embeddings with explicit temporal weighting mechanisms. The framework has four main components: embedding generation, temporal weighting, session vectorization, and clustering. Event embeddings were created using four transformer-based models, BERT4Rec, SASRec, BERT-base-uncased, and ALBERT-base-v2. Three temporal weighting strategies, plain, linear, and exponential, were tested to examine their effect on session representation quality and clustering performance.

Experiments took place on two real-world clickstream datasets, which included hundreds of thousands of user sessions and varied interaction patterns. We examined the session representations using K-Means and Bisecting K-Means clustering algorithms. We assessed clustering quality with the Silhouette score. The results show that temporally weighted session representations consistently outperform the baseline unweighted aggregation method across all tested embedding models and datasets. Specifically, exponential temporal weighting achieves the best clustering performance in almost all experimental configurations. This demonstrates that placing more importance on recent user interactions significantly improves the separation and compactness of behavioral clusters. These findings confirm that adding temporal decay methods to session-based embeddings improves behavioral clustering performance. More aggressive decay methods, like exponential weighting, capture users' short-term intent more effectively than slower approaches, such as linear decay.

Beyond the specific research questions, this study offers a practical approach to constructing time-sensitive session embeddings in clickstream analytics. The combination of contextual transformer-based embeddings with explicit temporal weighting provides a structured means of representing user behavior in large-scale e-commerce settings. The results suggest that incorporating temporal importance during session aggregation can improve clustering quality across different embedding models and datasets. Together, these findings point to the relevance of temporal dynamics in session-based behavioral modeling.

Several directions remain open. Temporal importance is currently captured through ordinal position alone; richer signals such as elapsed time between events and overall session duration, together with an adaptive or learned decay rate, are natural next steps. The decay-weighted aggregation is also not tied to clickstream data in any essential way and can be applied to event logs in process mining, sensor traces, or short-window state descriptors in data-driven modeling of dynamical systems, where the weighting function plays a role analogous to a memory kernel. The same representations can also support recommendation, anomaly detection, and purchase prediction.

Acknowledgements. This study was supported by the Trendyol Research and Development Center. Generative AI tools, specifically Google Gemini and ChatGPT, were used only for language editing and improving readability. The authors remain fully responsible for the scientific content of the study.

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The Intersection of Finite Element Limit Analysis and Physics-Informed Machine Learning for Structural Vulnerability Assessment

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Abstract. Recent advances in computational mechanics and artificial intelligence have expanded the range of tools available for structural engineering. While conventional elastoplastic iterative algorithms can be computationally demanding, limit analysis offers an efficient way to estimate ultimate load capacity. This paper investigates the use of 3D FELA with a physics-informed machine learning workflow to predict structural vulnerability. The learning component is a multi-output multilayer perceptron surrogate, while the physics-informed aspect is introduced through the FELA-based generation of training data and targets derived from the static theorem of plasticity. The methodology is validated across five architectural morpho-types: Rectangular, L-type, C-type, Asymmetrical C-type, and H-atrium buildings. Within the investigated dataset, the proposed scheme removes repeated iterative analyses in parametric studies, achieves correlation coefficients above $R^2 = 0.995$, and reduces average analysis time by more than a factor of 1,200. These results indicate that the proposed PIML workflow can support rapid structural assessment and urban-scale seismic micro-zoning.

Keywords: Limit Analysis · Finite Element Method · Physics-Informed Machine Learning · Structural Vulnerability

1 Introduction

Artificial intelligence and machine learning are increasingly used in structural engineering for design support, response prediction, and data-driven assessment (Málaga-Chuquitaype, 2022). These methods complement traditional statistical tools, especially when relationships between variables are strongly non-linear or difficult to model explicitly (Suryawanshi et al., 2025). In parallel, direct limit

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 619–635, 2026.
https://doi.org/10.1007/978-3-032-30524-4_38

analysis has become an efficient alternative to incremental elastoplastic procedures for estimating structural capacity through mathematical programming (Spiliopoulos and Dais, 2012). To reduce the limitations of purely data-driven "black-box" models, recent studies have introduced physics-informed machine learning approaches that couple learning algorithms with mechanics-based constraints, simulations, or data-generation procedures (Imani et al., 2025). In the present study, the machine-learning model itself remains relatively standard, while the physics-informed character of the workflow is provided primarily by the FELA-based generation of training data. In the context of seismic vulnerability assessment, this combination is relevant because it can support rapid evaluation of large building stocks (Zona et al., 2025).

1.1 Evolution of Computational Mechanics

Over the last three decades, computational mechanics and artificial intelligence have substantially influenced structural engineering practice (Chen, 2021). Advances in high-performance computing have enabled sophisticated numerical models for the analysis of complex three-dimensional systems under severe loading conditions (Ferrari, 2017). However, detailed building-by-building modeling remains difficult to deploy quickly at the urban scale, particularly for seismic vulnerability assessment (Imani et al., 2025). Early computational approaches relied on step-by-step elastoplastic analyses, which required substantial time and computational resources. Limit analysis emerged as a more efficient alternative for estimating ultimate load-bearing capacity directly (Zona and Minutolo, 2025). Based on the theorems of plasticity, it avoids incremental elastic-plastic calculations and focuses instead on the collapse state of the structure (Bleyer,2013). The integration of the finite element method with limit analysis through linear and non-linear mathematical programming has therefore produced effective tools for structural assessment. (Makrodimopoulos, 2008). At the same time, machine learning has become a useful tool for identifying complex non-linear patterns in large structural datasets (Bishop, 2006). Deep neural networks and related architectures are increasingly used to predict structural response, detect damage, and support recovery planning after extreme events (Karniadakis et al., 2021; Sun et al., 2021). However, purely data-driven models may be difficult to interpret physically and can perform poorly when extrapolating beyond the domain represented in the training data. (Senders et al., 2018; Di Bonito et al., 2024). These concerns have motivated the development of explainable and physics-informed approaches, especially for safety-critical applications (Zheng et al., 2025; Gondaliya et al., 2025). In particular, embedding lower-bound finite element procedures into the learning framework helps preserve consistency with the governing mechanics. (Murashko and Tkachov,2025). For emergency planning, generating high-resolution numerical models for every building is often computationally prohibitive (Ferranti et al., 2024). Large-scale vulnerability studies therefore require methods that are both simplified and reliable. Traditional workflows also depend on extensive manual data collection, which limits their applicability in rapid assessments (Zona et al., 2025). Machine learning can help classify

buildings according to expected vulnerability by exploiting patterns in empirical and simulated datasets (Ahmad et al., 2026; Seo et al., 2012). Within this broader context, structural capacity information remains essential for risk management and loss reduction. Performance-based urban planning further benefits from grouping existing structures into representative morpho-types defined by geometric, mechanical, and historical attributes (Spence et al., 2005; Alipour et al., 2011). Such classifications can support seismic micro-zoning maps that identify urban sectors with similar structural vulnerabilities and can guide long-term regeneration strategies (Lagomarsino and Podestà, Cardellicchio et al., 2023; 2006).

2 Method and Materials

The procedure adopted in this research combines a mechanics-based structural analysis framework with a data-driven machine learning process. A core computational system performs elastic analysis and plastic limit analysis of three-dimensional frames to estimate the global collapse factor and the local collapse modes. To avoid the cost of repeated analyses over a large parameter space, a regression-based neural network is trained to predict the target quantities from a normalized dataset of geometric and physical input parameters.

2.1 Structural Analysis Core and the Static Theorem Framework

Instead of finite element analyses with elemental stress limits against yielding, this analysis package determines the state of the whole structure failure using the static theorem of limit analysis. The whole structure domain is conceptualized as a system of spatial joints where the elements are the structure members idealized as 3D Euler-Bernoulli beams. These members are connected at their ends providing to each joint 12 degrees of freedom, considering their full 3D kinematics along with the 6 degrees of freedom at both the start and the end node of each beam element. The internal forces included in the analysis comprise axial force, weak and strong axis bending moments and shears, and torque. These structures are constrained to their respective spatial domains by setting to zero selected nodal degrees of freedom such as restraints for translations and rotations of nodal points that represent rigid foundations and supports. Finding the maximum load capacity is expressed as an extremely large linear programming optimization problem, for which the primal optimization problem aims at maximizing globally collapsing load multiplier λ, which refers to the safety factor regarding total plastic collapse subject to equality constraints of global equilibrium, which is stated as:

$$\mathbf{Hx} = \lambda \mathbf{F}_{var} + \mathbf{F}_{perm} \tag{1}$$

In which $\mathbf{H}$ is the overall equilibrium matrix, $\mathbf{x}$ is the overall vector of internal forces, $\mathbf{F}var$ is the vector of variable loads for which the external actions are scaled to provide plastic collapse and $\mathbf{F}perm$ is the vector of loads for permanent

load (due to the gravity effect on dead load). Superposition is handled automatically by the solver. It calculates an elastic response to permanent load, and adds this to the variable load case using a load combination factor before trying to solve for the plastic collapse. The overall stiffness and equilibrium matrices are constructed in an efficiently vectorized form and do not involve an iterative algorithmic loop for computational reasons.

2.2 Piecewise Linear Yield Surface and Interaction Domains

In order to guarantee that internal forces vector x does not violate the structural framework capacity. The inequality constraint are set strictly on the boundaries of the optimization problem. The structure yield point formation or plastic hinge is mathematically formulated by eight-faced linear piecewise yield surface. This domain clearly includes the cross-section interaction of axial force with multi-axial moments bending. The physical constraints of orthogonal frontiers for the individual linear facet are based on the geometric cross-section properties as well as material properties given to the member components. For the building morphotypes analyzed here, the constraints that form boundaries of the optimization have been selected as a symmetrical $275.0MPa$ as max compression and max axial tension limits. In addition, algorithm succeeded to sum-in the dead loads by a combination factor of 0.3 prior to the determination of the lateral plastic collapse states, the plasticity yield constraint in the LP bounds is defined as follows:

$$\mathbf{A}_{yield}\mathbf{x} \leq \mathbf{b}_{capacity} \tag{2}$$

Here $\mathbf{A}yield$ is a matrix that transforms the directed normal vectors from the eight faceted polyhedron and $\mathbf{b}capacity$ contains the axial and moments limits. This mathematical surface is then used in the post-processing where it becomes possible to establish exactly which facet of the surface has been violated and where in the mechanism collapse occurs, in addition with each distinct yield mode separated based upon the interaction that controls the failure.

2.3 Data Preprocessing and Matrix Normalization

The structural data fed into the neural network is derived from six distinct input files that define the three-dimensional frame. A summary of these required input files, their mathematical formats, and structural engineering significance is presented in Table 1 and detailed below.

Table 1. Summary of required input files, their mathematical formats, and structural engineering significance.

File Type	Format	Description/Engineering Concept
Node Coordinates	Matrix $[N_{nodes} \times 3]$	Defines the global X, Y, and Z coordinates for all structural joints in the 3D wireframe.
Element Connectivity	Matrix $[N_{elements} \times 4]$	Defines the structural topology by linking start/end nodes, and assigning section and load IDs.
Boundary Conditions	Vector $[(N_{nodes} \times 6) \times 1]$	Locks specific nodes to the foundation by defining 6 degrees of freedom as free (1) or fixed (0).
Nodal Loads	Vector $[(N_{nodes} \times 6 \times N_{cases}) \times 1]$	Contains the vertically stacked external forces, separated into permanent dead loads and variable loads.
Beam Orientation	Matrix $[N_{elements} \times 3]$	Provides the perpendicular normal vector to determine the strong and weak bending axes.
Section Properties	Matrix $[N_{sections} \times 11]$	Defines material stiffness and physical strength limits dictating when and where plastic hinges form.

- **Node Coordinates:** This file translates the physical structure into a numerical wireframe. It records the exact locations in 3D space where columns and beams intersect or touch the foundation.
- **Element Connectivity:** This file establishes the structural members. It maps out the connections between specific starting and ending nodes, while also assigning the designated cross-sectional shapes and external load identifiers to each physical beam or column.
- **Boundary Conditions:** This file serves as the restraints for the computational model, preventing the structure from undergoing infinite rigid body translation or rotation under applied forces. It establishes constraints for all 6 spatial degrees of freedom at every node, identifying which joints are free to move and which are glued to an immovable foundation.
- **Nodal Loads:** This file defines the external mechanical actions exerted on the building's joints. The data is stacked to apply permanent loads, which represent the constant gravity effect of the structure's own weight, followed by the variable loads representing wind or seismic forces that are scaled to determine the safety factor.
- **Beam Orientation:** This file defines the spatial rotation of each element. By providing a vector perpendicular to the main axis of the beam, it ensures the solver correctly identifies the strong axis and weak axis for bending, which fundamentally controls the element's structural stiffness.
- **Section Properties:** This file assigns the physical and material thresholds for the cross-sections used in the elements. It provides the elastic stiffness parameters alongside the critical plastic limits for axial compression, axial tension, and multiaxial bending moments. When the internal forces reach these designated strength limits, the elements yield and form rotating plastic hinges instead of snapping.

While the exact mechanisms of collapse may be completely identified by means of direct linear programming solvers, a full exploration of the parametric design space requires too much computational expense. Therefore, a deep learning regression model is developed to estimate, rapidly, the six values that define the lateral variable loads along both principle planar directions and the elastic

and plastic multipliers associated with the fixed loads. Training and validation sets for both the features and the target matrix are separated using a ratio of eighty to twenty. To prevent large-scaled input features with high numerical values from unduly dominating the gradient of optimization, statistical scaling is applied to the features. Calculation of mean μ_j and variance σ_j and normalization of the input features occurs via computation of the empirical mean and standard deviation of the features.

$$\mu_j = \frac{1}{N}\sum_{i=1}^{N} X_{i,j} \tag{3}$$

$$\sigma_j = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(X_{i,j} - \mu_j)^2} \tag{4}$$

Every input tensor is subsequently normalized via a standard transformation:

$$X_{i,j}^{(scaled)} = \frac{X_{i,j} - \mu_j}{\sigma_j} \tag{5}$$

These scaling coefficients are stored and serialized for use by deployment applications to ensure the mathematical consistency of the models when they are inferred in the future.

The predictive surrogate model is in the form of a fully connected multilayer perceptron intended to capture the extremely non-linear relations that exists between frame geometry and its plastic capacity. A completely connected fully connected multilayer perceptron network comprised of an input layer matching the shape of the feature set, three contracting fully connected dense hidden layers, each containing 64, 32, and 16 neurons, is used in the prediction:

$$f(z) = \max(0, z) \tag{6}$$

The structural data is then fed through the parameters in the network in a fixed sequence of matrix transformations, as outlined below:

First Hidden Layer:

$$\mathbf{H}_1 = \max(0, \mathbf{X}_{scaled}\mathbf{W}_1 + \mathbf{b}_1) \tag{7}$$

Second Hidden Layer:

$$\mathbf{H}_2 = \max(0, \mathbf{H}_1\mathbf{W}_2 + \mathbf{b}_2) \tag{8}$$

Third Hidden Layer:

$$\mathbf{H}_3 = \max(0, \mathbf{H}_2\mathbf{W}_3 + \mathbf{b}_3) \tag{9}$$

The output layer: since the structural load multipliers are continuous real numbers over the entire elastic and collapse behavior regions of operation, the output layer has six neurons giving the linear combinations directly without any limitations on activation:

$$\hat{\mathbf{Y}} = \mathbf{H}_3\mathbf{W}_4 + \mathbf{b}_4 \tag{10}$$

In which the matrix $\hat{\mathbf{Y}}$ readily gives the prediction vectors for the structural response, respectively.

The parameters that can be learned are the internal matrices of weight and bias for this neural network, which are optimized through minimization of a specific empirical risk. Specifically, the objective function which is minimized is the mean squared error that severely punishes major discrepancies between the predictive output and the true structural capacities. To reflect the specific physical parameters being predicted—the elastic (λ_e) and collapse (λ_c) load multipliers under permanent, lateral X, and lateral Y conditions—the loss function is explicitly defined as:

$$\mathcal{L}_{MSE} = \frac{1}{N_{batch}} \sum_{i=1}^{N_{batch}} \sum_{j\in\{perm,sx,sy\}} \left[\left(\lambda_{e,j}^{(i)} - \hat{\lambda}_{e,j}^{(i)}\right)^2 + \left(\lambda_{c,j}^{(i)} - \hat{\lambda}_{c,j}^{(i)}\right)^2 \right] \tag{11}$$

Meanwhile, the model also calculates the mean absolute error as its main tracking criterion. This value provides a direct interpretation of the prediction deviation on the true physical scale of the structural load multipliers:

$$\mathcal{M}_{MAE} = \frac{1}{N_{batch}} \sum_{i=1}^{N_{batch}} \sum_{j\in\{perm,sx,sy\}} \left[\left|\lambda_{e,j}^{(i)} - \hat{\lambda}_{e,j}^{(i)}\right| + \left|\lambda_{c,j}^{(i)} - \hat{\lambda}_{c,j}^{(i)}\right| \right] \tag{12}$$

The optimizer is driven by an adaptive moment estimation algorithm with initial learning rate at 0.001. The training is carried out for a defined maximum number of steps, during which training and validation loss are both recorded to verify smooth mathematical convergence.

Three concurrent protocols are used to constrain the gradient descent loop in such a way that the neural network generalizes well and correctly maps un-seen structures rather than memorizing.

Learning rate scheduling: The convergence of the gradient descent path to the minimum value is ensured using dynamic learning rate. Validation loss is observed, and whenever the minimum has been reached and stagnant for certain steps, the learning rate is divided by two geometrically. The process continues until an absolute minimum learning rate is reached to control the optimization weights accurately.

$$\alpha_{new} = \begin{cases} 0.5 \times \alpha_{old} & \text{if } \Delta\mathcal{L}_{val} \approx 0 \text{ for threshold epochs} \\ \alpha_{old} & \text{otherwise} \end{cases} \tag{13}$$

Early stopping: We prevent over-fitting of the model-where the algorithm still decreases training error but not validation error-by early stopping the optimization. This mechanism is implemented based on monitoring of the generalization gap - the discrepancy between the empirical risk on the training data $Jtrain(\theta)$

and risk on an independent data set, $Jval(\theta)$. Early stopping depends on patience parameter τ - a discrete interval of epochs. Stopping criteria are reached at epoch t when the validation error is not decreased during τ consecutive iterations:

$$\min\{J_{val}(\theta_{t-\tau}), \ldots, J_{val}(\theta_{t-1})\} \leq J_{val}(\theta_t) \tag{14}$$

In a more mathematical formulation, suppose that θ^* are the parameters that obtain the minimum on the whole past of training up to time t.

$$\theta^* = \arg \min_{\theta \in \{\theta_1, \ldots, \theta_t\}} J_{val}(\theta) \tag{15}$$

When the termination condition is met, the parameters matrices of that specific iteration is manually reset to the one that returned the global minimal error in validation and thus eliminates the effect of further parameter updates on the degraded generalization. Therefore, by resetting the network to its most predictive states for structural limit analysis, one ensures that the returned θ^* parameters is that which is closest to the physical relation between structural geometry and collapse multiplier:

Optimal State Preservation: This protocol complements the training loop. The states are examined and archived at the end of each training step. Archiving events to serialize the final mathematical graph is initiated only when the current validation error surpasses a new absolute minimum in the validation loss terrain (Fig. 1).

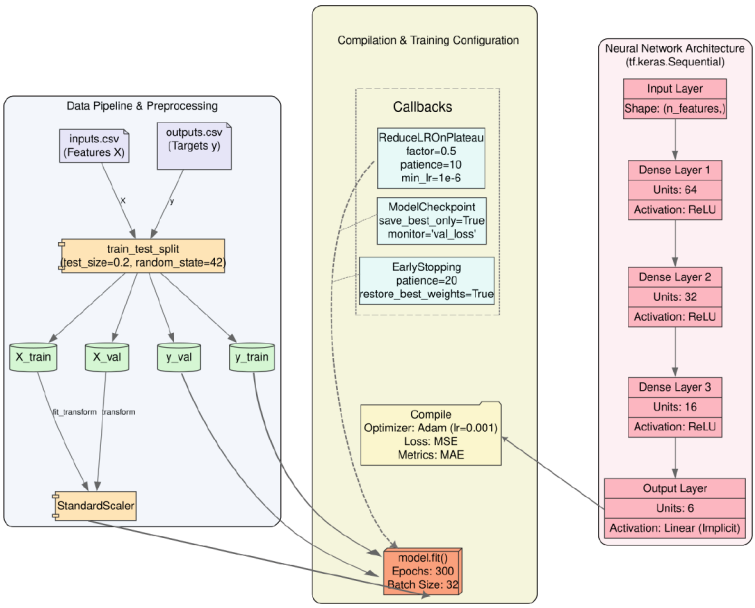


Fig. 1. Schematic representation of the Neural Network architecture, illustrating the integration of limit analysis constraints within the loss function for structural vulnerability assessment.

2.4 Surrogate Model Deployment and Inference

This deployment stage provides a dramatic departure from the economics of computationally evaluating response for intricate 3D frames. The linear programming simplex algorithm would otherwise have to run with increasingly indeterminate stiffness matrices and solve for many structures with each new geometry, but the neural network performs the forward pass approximation instantly. In essence, we have transformed the problem from constraint-based optimization to a deterministic functional map, which allows for "real-time" structure evaluations. This inference pipeline takes as an input an unobserved vector $\mathbf{x}_{new} \in \mathbb{R}^n$ which corresponds to a structure with a particular geometry and material response. It is important to provide the input vector as a transformation of an input in a space compatible with the model-meaning the input vector is subjected to an identical affine transformation using the distribution's parameters collected during the training phase:

$$\mathbf{x}_{scaled} = (\mathbf{x}_{new} - \boldsymbol{\mu}) \div \boldsymbol{\sigma} \tag{16}$$

where $\boldsymbol{\mu}$ and $\boldsymbol{\sigma}$ are the vector of means and standard deviation for each feature respectively. The main part of the deployment is the application of the trained neural operator F_θ. The predicted value $\hat{\mathbf{y}}$ is computed via a composite sequence of nonlinear functions:

$$\hat{\mathbf{y}} = \mathbf{W}_L \cdot \sigma_{L-1}(\mathbf{W}_{L-1} \ldots \sigma_1(\mathbf{W}_1 \mathbf{x}_{scaled} + \mathbf{b}_1) \cdots + \mathbf{b}_{L-1}) + \mathbf{b}_L \tag{17}$$

Given the specific architecture of the surrogate model, where σ represents the Rectified Linear Unit (ReLU) activation function, the internal state of each hidden layer l is computed as:

$$\mathbf{h}_l = \max(0, \mathbf{W}_l \mathbf{h}_{l-1} + \mathbf{b}_l) \tag{18}$$

The inference here is computationally less complex from the $\mathcal{O}(n^3)$ or $\mathcal{O}(2^n)$ needed in iterative limit analysis solvers, and can be expressed as a series of matrix-vector multiplications that require complexity $\mathcal{O}(\sum l = 1^L nlnl - 1)$, where nl is the number of neurons in layer l. The recovered neural structure evaluates the entire array of elastic and plastic load multipliers at once, and the resulting vector $\hat{\mathbf{y}}$ is transformed back into physical space:

$$\hat{\mathbf{y}} = [\lambda_{e,perm}, \lambda_{e,sx}, \lambda_{e,sy}, \lambda_{c,perm}, \lambda_{c,sx}, \lambda_{c,sy}]^T \tag{19}$$

This set of analytic data is organized and extracted as needed. Structural response and failure locations can be immediately predicted, using only the initial geometry and material information, and these can be rapidly communicated for immediate use in the fight against natural hazards.

Multi-output Regression Architecture. The surrogate model is a feedforward Multi-Layer Perceptron (MLP) that has been trained to predict multiple structural responses at the same time. Instead of determining the damage levels separately, the network has been trained as a multi-output regression model to directly approximate the six key response quantities that need to be predicted: the elastic multipliers associated with dead loads, X- direction earthquake loads, Y- direction earthquake loads and their associated plastic collapse multipliers. The mapping can be expressed mathematically as follows:

$$\hat{\mathbf{y}} = f(\mathbf{X}; \boldsymbol{\theta}) \tag{20}$$

In which $\mathbf{X}$ is the normalized matrix of structural input features, $\hat{\mathbf{y}} \in \mathbb{R}^6$ is the target vector predicted by the network, and $\boldsymbol{\theta}$ is composed of the network's weights and biases.

3 Results

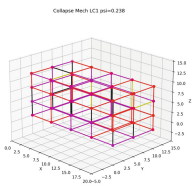
This section presents the quantitative validation of the proposed framework using high-fidelity ground truth generated by the 3D Frame Limit Analysis Suite. The results are organized into four parts: structural response, surrogate-model convergence, predictive accuracy, and computational efficiency.

3.1 Structural Response and Collapse Mechanisms

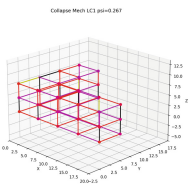
Before training the machine learning model, the physical consistency of the ground-truth dataset was checked by simulating the response of several three-dimensional structural topologies under different load conditions. Although the framework can be applied to broader classes of buildings, this study focuses on five morpho-types: Rectangular, L-type, C-type, Asymmetrical C-type, and H-atrium. Their corresponding collapse mechanisms are shown in Fig. 2.

Table 2 summarizes the elastic and collapse multipliers obtained from the lower-bound formulation. During the solution of the large equilibrium systems, the SVD-based reduction stabilized the constraint matrices. The matrix rank increases with structural complexity, from 231 for the L-type case to 1248 for the H-atrium configuration.

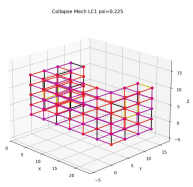
Comparing the C-type and Asymmetrical C-type frames under lateral Load Combinations 2 and 3 shows a marked reduction in collapse multiplier for the asymmetric configuration ($\lambda_{collapse} = 3.9636 \times 10^{-2}$ versus 8.6473×10^{-2} for LC2). This result indicates higher sensitivity to lateral loading in the asymmetric case. The plastic reserve ratios reported in Table 2 also suggest lower redundancy in the Asymmetrical C-type frame, where torsional effects and earlier mechanism formation reduce the post-yield reserve. The idealized capacity curves support the same interpretation. Although limit analysis does not resolve the full incremental degradation path, the initial elastic stiffness $K = \lambda/\Delta_e$ still provides a useful reference for relating elastic response to collapse capacity.



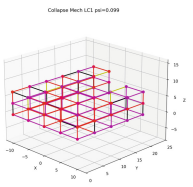
(a) Rectangular (LC1, $\psi = 0.238$)



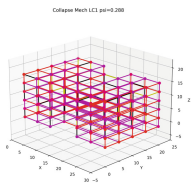
(b) L-type (LC1, $\psi = 0.267$)



(c) C-type (LC1, $\psi = 0.225$)



(d) Asym. C-type (LC1, $\psi = 0.099$)



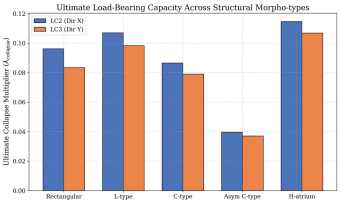
(e) H-atrium (LC1, $\psi = 0.288$)

Fig. 2. 3D frame limit-analysis results for five structural morpho-types under Load Combination 1 (LC1). The figure reports the collapse mechanism and load multiplier (ψ) for each geometry: (a) Rectangular, (b) L-type, (c) C-type, (d) Asymmetrical C-type, and (e) H-atrium.

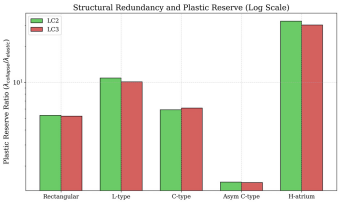
Table 2. Summary of structural load multipliers and equilibrium matrix constraint reduction across the five distinct building morpho-types.

Morpho-Type	Load Combination	Eq. Matrix Rank	$\lambda_{elastic}$	$\lambda_{collapse}$	$\lambda_{collapse}/\lambda_{elastic}$
Rectangular	LC 2 (Dir X)	360	1.8139×10^{-2}	9.6167×10^{-2}	5.302
	LC 3 (Dir Y)	360	1.5975×10^{-2}	8.3392×10^{-2}	5.220
L-type	LC 2 (Dir X)	231	9.8123×10^{-3}	1.0694×10^{-1}	10.900
	LC 3 (Dir Y)	231	9.7168×10^{-3}	9.8255×10^{-2}	10.110
C-type	LC 2 (Dir X)	625	1.3109×10^{-4}	8.6473×10^{-2}	5.906
	LC 3 (Dir Y)	625	1.2161×10^{-4}	7.9018×10^{-2}	6.105
Asym C-type	LC 2 (Dir X)	435	2.7002×10^{-2}	3.9636×10^{-2}	1.468
	LC 3 (Dir Y)	435	2.5470×10^{-2}	3.7022×10^{-2}	1.454
H-atrium	LC 2 (Dir X)	1248	3.5236×10^{-3}	1.1458×10^{-1}	32.520
	LC 3 (Dir Y)	1248	3.5326×10^{-3}	1.0678×10^{-1}	30.230

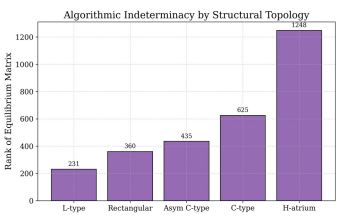
The numerical results define the response regime of each structure. For clarity, the tabulated quantities are also presented graphically in Fig. 3, which highlights the relation between topology, load-carrying capacity, and structural redundancy across the considered morpho-types.



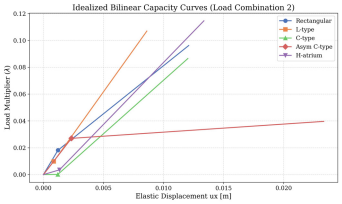
(a) Ultimate Load-Bearing Capacity



(b) Plastic Reserve Ratio (Log Scale)



(c) Equilibrium Matrix Rank



(d) Smooth Idealized Capacity Curves

Fig. 3. Quantitative comparison of the five architectural morpho-types: (a) ultimate load-bearing capacity, (b) plastic reserve ratio, (c) equilibrium matrix rank, and (d) idealized capacity curves.

3.2 Surrogate Model Training and Convergence

The training history of the multi-output multilayer perceptron surrogate is shown in Fig. 4. To capture the non-linear relation between structural geometry and limit capacity while reducing overfitting, regularization was introduced during optimization. The Mean Squared Error ($\mathcal{L}_{MSE}$) is reported on a log scale and shows smooth convergence for both the training and validation sets.

Dynamic learning-rate scheduling helps stabilize optimization by refining the parameter updates as training progresses. Early stopping identifies the onset of overfitting and retains the parameter set associated with the minimum validation loss, which in this case occurs at epoch 202 ($\min \mathcal{L}_{val} = 1.3801 \times 10^{-2}$). The corresponding optimal weights ($\boldsymbol{\theta}^*$) are then used for inference.

The predictive capability of the framework was assessed by comparing surrogate-model outputs with the ground truth generated by finite element limit analysis (FELA). Figure 5 presents parity plots for the six target variables, with FELA values on one axis and neural-network predictions on the other.

The predicted values lie close to the identity line ($y = x$), indicating limited systematic bias across both the elastic and collapse regimes. Quantitatively, the coefficients of determination are above 0.995 for all target variables and above 0.9999 for the elastic multipliers. The corresponding MAEs are on the order of 10^{-4} and 10^{-6} for the load multipliers. Within the analyzed parameter space, these results show that the multi-output multilayer perceptron can reproduce the

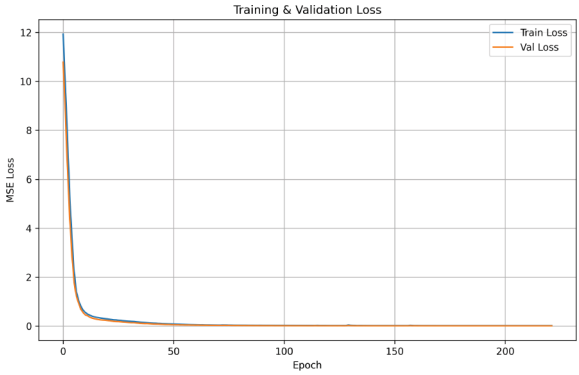


Fig. 4. Training and validation loss curves for the surrogate model. Early stopping selects the best-performing weights at epoch 202.

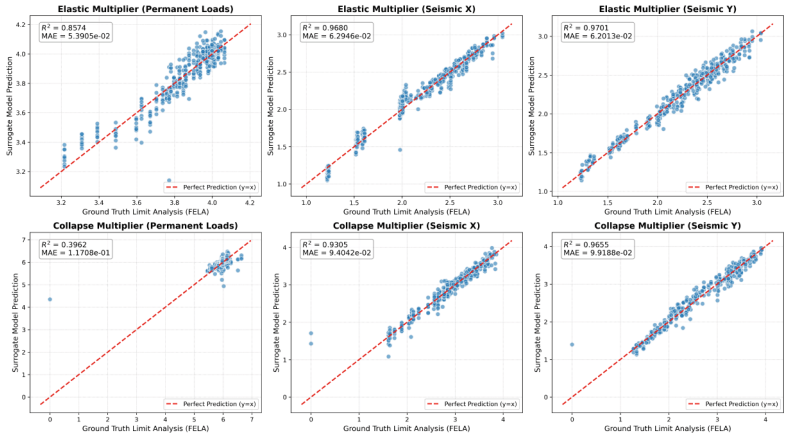


Fig. 5. Parity plots comparing neural-network predictions with finite element limit-analysis ground truth for six target variables. Each panel reports R^2 and MAE.

FELA-based target responses with high accuracy from geometric and material inputs alone.

3.3 Computational Efficiency and Application

The motivation for combining physics-informed machine learning with standard limit analysis is to reduce the computational cost associated with large-scale territorial risk assessment. Table 3 compares the conventional solver with the deployed surrogate model.

With the original solution strategy, estimating ultimate load-bearing capacity requires assembling highly indeterminate stiffness matrices, generating piecewise-linear yield surfaces, and solving a linear-programming problem. The

Table 3. Comparative analysis of algorithmic execution efficiency and underlying mathematical complexity.

Methodology	Mathematical Complexity	Avg. Time per Analysis (s)	Acceleration Factor
Finite Element Limit Analysis	$\mathcal{O}(n^3)$ or $\mathcal{O}(2^n)$	2.450	Baseline
Multi-Output Surrogate Model	$\mathcal{O}(\sum_{l=1}^{L} n_l n_{l-1})$	0.002	1,225x

resulting computational burden, of the order of $O(n^3)$ or higher depending on the problem structure, limits exhaustive scans of large parameter spaces in emergency-planning applications.

Using the pre-trained multilayer perceptron changes the computational workflow to a deterministic sequence of matrix-vector operations through the network layers, with cost scaling as $O(\sum_{l=1}^{L} n_l n_{l-1})$. Based on the values reported in Table 3, the surrogate-model inference is more than 1200 times faster than the original solver. This reduction in runtime supports near-real-time structural capacity assessment and makes the workflow more suitable for seismic micro-zoning studies at the city scale.

4 Discussion

The proposed framework integrates physical mechanics with machine learning in a consistent PIML workflow. In this formulation, the machine-learning component is a standard multi-output multilayer perceptron, whereas the physics-informed aspect arises mainly from the FELA-based generation of the training data and target responses. The surrogate model achieves $R^2 > 0.995$ with small MAE values, indicating that it captures the non-linear relation between input parameters and the FELA-derived responses with high accuracy within the analyzed domain. As shown in Fig. 5, the model response remains close to the identity line over both elastic and collapse states.

The framework also reduces computational cost substantially. The observed speedup of more than 1,200 times helps address one of the main limitations of conventional iterative analyses when applied to large building inventories. By moving most of the computational effort to an offline training stage, the pre-trained surrogate model enables near-real-time structural capacity evaluation during deployment. This property is relevant for rapid parametric scans, building-stock categorization, and the preparation of seismic micro-zoning maps.

4.1 Limitations and Future Directions

Despite the strong predictive performance, the presented PIML model remains constrained by the range and distribution of its training data. As an empirical surrogate, it is expected to be most reliable within the parameter space spanned by the structural geometries, load conditions, and material properties used for

training. Extrapolation to unseen topologies, materially different systems, or substantially different loading scenarios may reduce accuracy. In addition, the surrogate inherits the assumptions embedded in the FELA ground truth, including the adopted boundary conditions, idealizations in material behavior, and the use of the static theorem as the reference description of collapse. A further limitation is that the present evaluation focuses on agreement with the FELA-generated targets and computational efficiency, but it does not include systematic comparisons with alternative surrogate models or other regression architectures. Such comparisons would help clarify whether the observed performance is specific to the chosen multilayer perceptron or can also be achieved by simpler or different models. These limits should be considered when extending the workflow to other structural classes or operating conditions.

Subsequent work can address these limitations by broadening the training space to include a wider variety of morpho-types, such as anisotropic historical masonry and damaged composite structures. It would also be useful to benchmark the present multilayer perceptron against alternative surrogate models, including simpler regression baselines and other non-linear learning architectures, to better position the method within the broader model-selection landscape. Further extensions may incorporate dynamic time-history targets and structural health monitoring data to update the surrogate model over time within a digital-twin framework.

5 Conclusion

This paper presents an integrated computational framework that combines Finite Element Limit Analysis (FELA) with a data-driven surrogate model for large-scale seismic vulnerability assessment. The objective is to reduce the computational cost that limits repeated analyses across wide parametric spaces. By formulating collapse through the static theorem of plasticity, adopting piecewise-linear yield surfaces, and stabilizing the equilibrium system with Singular Value Decomposition, the workflow generates consistent databases of ultimate load-carrying capacity for complex structural topologies.

A multi-output multilayer perceptron surrogate model was then trained to reproduce the non-linear relation between structural geometry, loading, and limit multipliers. In this sense, the learning architecture is relatively standard, while the distinguishing feature of the workflow lies in its coupling with physics-based FELA data generation. The framework was evaluated on five morpho-types: Rectangular, L-type, C-type, Asymmetrical C-type, and H-atrium. The quantitative results show high predictive accuracy, with all reported R^2 values above 0.995 and very small absolute errors across the analyzed targets.

By replacing repeated constraint-oriented linear-programming analyses with a sequence of matrix-vector operations, the proposed framework reduces average evaluation time from 2.450 s to 0.002 s per analysis, corresponding to a speedup of more than 1200 times. Within the investigated domain, this computational gain makes rapid structural vulnerability assessment feasible for geometrically diverse

building configurations. At the same time, broader benchmarking against alternative models would strengthen the evaluation and clarify the relative advantages of the proposed surrogate choice. The workflow may therefore support structural engineers, city planners, and emergency managers in large parametric studies, seismic micro-zoning, and related decision-making tasks.

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

The Suburban Label Gap: Triangulating Place-Of-Residence Labels with CORINE Land Cover Exposure in Poland

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Abstract. Monitoring urban sprawl and land artificialisation is typically grounded in land-cover indicators and administrative boundaries, yet suburbanisation is also mediated by how residents label and communicate their living environment. This paper proposes a parsimonious perception-environment triangulation that combines (i) CORINE Land Cover (CLC 2018) exposure at geocoded respondent postal codes, (ii) self-reported settlement-size context, and (iii) self-declared place-of-living labels and residential preferences from a national Polish survey (N = 1,480; 2020). The land-cover baseline places 66.7% of respondents in artificial surfaces, with 59.7% located specifically in discontinuous urban fabric, highlighting the prevalence of fragmented built-up forms captured by CLC. Despite this monitoring signal, only 2.1% describe their current residence as 'suburbs of a large city', while 12.9% select suburban options as their preferred location. Settlement size and place labels are strongly associated (Cramer's V = 0.608), yet systematic relabelling across categories suggests that 'suburbs' operates as an interpretive boundary rather than a stable territorial descriptor. This mismatch is conceptualised as a suburban label gap: the weak uptake of 'suburbs' as a current self-description despite the prevalence of discontinuous built-up land-cover contexts. The gap matters for planning because land-cover and land-take indicators may lose communicative clarity when translated into socially ambiguous place labels. More broadly, the findings show that suburbanisation cannot be inferred from any single classification system and point to the need to complement land-cover and settlement-hierarchy indicators with perception-sensitive, function-oriented measures such as accessibility, congestion and service capacity.

Keywords: Suburbanisation · Urban Sprawl · Land Take · CORINE Land Cover · Discontinuous Urban Fabric · Residential Self-Identification · Place Labels · Poland

1 Introduction

Monitoring dispersed development and land artificialisation increasingly relies on land-cover datasets and indicator families that translate remotely sensed surfaces into categories such as "artificial", "urban" or "discontinuous urban fabric". Yet even when these

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 639–656, 2026.
https://doi.org/10.1007/978-3-032-30524-4_39

categories are technically robust, their interpretation still depends on how settlement types are understood in social and policy practice. Land-cover classes are distinct from lived categories such as "city", "village" or "suburbs", which people use to describe where they live, what services they expect and what they consider "urban". The result is a recurring interpretive gap: land-cover monitoring can detect spatial patterns associated with dispersed settlement, while residents may label (or refuse to label) the same environments in ways that do not align with administrative or morphological proxies.

This gap is particularly relevant to suburbanisation because "suburbs" are not merely physical forms or administrative zones, but multidimensional constructs shaped by morphology, functional relations and social identity. Suburban areas often extend beyond municipal boundaries, and their degree of functional integration with urban cores varies across contexts, making the concept difficult to operationalise through any single criterion. At the same time, place labels are not neutral descriptors. Research on boundaries and place definition has shown both that borders are porous and imprecise [1] and that "place" may be meaningfully defined through user naming rather than solely through official categories [2]. In other words, the suburban condition may be identified through land-cover patterns and functional linkages, but it may also be accepted, rejected or reinterpreted through everyday language and identity.

A growing strand of work therefore argues that self-declared categories should not be treated as straightforward spatial measurements. Rather, they function at least in part as statements of identity: residents may live in environments that are objectively integrated into urban systems yet still describe their place as "village-like", "in-between" or simply "not urban" in order to preserve social status, lifestyle aspirations or local belonging [3]. From the perspective of land artificialisation policy and resilience-oriented spatial governance, this matters because policy communication and policy acceptance depend on socially meaningful categories. Where shared names are missing or contested, places can become "invisible" to public debate and therefore hard to govern [4].

This paper develops and demonstrates a parsimonious perception–environment triangulation that complements land-cover evidence with social categorisation. The analysis is motivated by a simple but consequential observation: in a national survey, the label "suburbs of a large city" appears only rarely in respondents' current self-descriptions (c. 2%), even though suburban options become more salient when they are asked about their preferred residential location. This asymmetry suggests that "suburbs" functions not only as a spatial descriptor but also as a socially negotiated category whose uptake depends on context and framing, with implications for how land-take signals are communicated and understood [4]. The paper therefore asks: to what extent do self-declared categories align with settlement-size categories and land-cover exposure, and what do any mismatches imply for the interpretation of land artificialisation signals and for planning communication?

The analysis triangulates three complementary layers of evidence derived from a single national dataset: (i) land-cover context, measured through CORINE Land Cover exposure at geocoded respondent locations; (ii) a settlement-size classification ranging from villages to cities with more than 500,000 inhabitants; and (iii) self-declared place-of-living labels, including an explicit "suburbs" option.

Against this background, the following research questions are posed. The next section then describes the dataset and operational steps used to answer them.

RQ1. Label Gap: How frequently do residents adopt the label "suburbs" in their current self-descriptions, and how does this compare with the salience of "suburbs" in their stated residential preferences?

RQ2. Mismatch Structure: How do self-declared place-of-living categories relate to settlement-size categories, and where do systematic divergences reveal the limits of size-based classifications for describing suburbanisation-like contexts?

RQ3. Policy Meaning: Which functional concerns do respondents associate with moves to suburban and rural locations, and can these concerns provide a more socially legible planning vocabulary than the contested label "suburbs".

The contribution is both conceptual and applied. Conceptually, we frame the "suburban label gap" as one instance of a broader mismatch among administrative, functional, objective, and subjective urban classifications, showing that categories central to land-take debates may be only weakly adopted as self-descriptors even when monitoring signals and settlement context point to suburbanisation-like patterns. In practical terms, we propose a low-burden translation step that links land-cover monitoring outputs to the categories residents use to name and classify their environments. Rather than replacing established land-cover indicators, this approach makes their interpretation more socially legible, especially in contexts where "suburbs" lack operationalised survey criteria and where suburban residents can be distinguished only through the labels they choose. CLC is used here as a monitoring-oriented proxy for built-form context; its role is not to validate individual self-identification, but to make explicit where land-cover signals of dispersed development fail to translate into everyday place labels. The results show how rarely the label "suburbs" is adopted, how strongly place labels co-vary with settlement size, and how mismatches between land-cover context, settlement hierarchy and self-declared labels reveal the limits of relying on any single classification system.

2 Data and Methods

2.1 Study Design

The paper adopts a triangulation design that combines a physical-environment proxy with survey-based social categorisation. The central idea is that suburbanisation and dispersed development are simultaneously reflected in (i) land-cover context, (ii) settlement hierarchy, and (iii) everyday place labels. Rather than treating any single layer as definitive, the analysis compares their alignment and divergence to identify where widely used planning concepts (e.g., "suburbs") operate as stable descriptors and where they function as contested or weakly adopted labels.

2.2 Data Sources

This study combines a land-cover description of respondents' residential context using CORINE Land Cover (CLC) and self-reported residential context from a national online questionnaire survey.

The physical environment context is characterised using the CLC 2018 dataset, the most recent full CLC inventory available for Poland at the time of analysis, produced within the Copernicus Land Monitoring Service and implemented nationally in Poland by the Chief Inspectorate of Environmental Protection (GIOŚ) [5]. CLC provides a harmonised, pan-European land-cover inventory with a three-level hierarchical nomenclature and 44 Level-3 classes. At the detailed level, it differentiates land-cover types such as continuous and discontinuous urban fabric (111, 112), industrial and commercial units (121), transport infrastructure (122), non-irrigated arable land (211), pastures (231), and forest classes including deciduous (311), coniferous (312), and mixed forests (313). Poland applies the standard CLC nomenclature without national modifications, ensuring comparability across European countries [6, 7]. The dataset is designed for regional and national-scale analysis, and its minimum mapping unit of 25 ha implies spatial generalisation that can limit the detection of small or fragmented features, including dispersed settlements [8]. In this study, CLC 2018 is used to derive a contextual land-cover profile of respondent locations by linking geocoded survey points to CLC polygons and summarising their distribution across land-cover classes.

The survey component draws on a national online questionnaire survey conducted in Poland in 2020. Data were collected from a panel sample of working-age adults aged 18–64 with quota controls applied to ensure comparability with the national population structure by age, gender, education and region. In the Polish context, the regional quota refers to voivodeships, the country's first-level administrative regions. The questionnaire covered respondents' housing situation, as well as residential preferences and perceptions related to the living environment.

2.3 Conceptual Framework

To avoid conflating "objective" and "subjective" measures, the residential environment is analysed through three complementary layers:

Physical Environment (Land-cover Context). Land-cover classes derived from CLC, summarised as counts of geocoded residential postal-code locations in each land-cover class (e.g., continuous and discontinuous urban fabric, agricultural classes, forests, water).

Settlement Context (Quasi-objective Proxy). Settlement size category (number of inhabitants), measured through a survey item where respondents select the size band of their current settlement (village → cities above 500,000 inhabitants). Although self-reported in the survey, this measure reflects an administrative/demographic property and is treated as a contextual proxy rather than a perception.

Perceived Label (Social Categorisation). Self-declared place-of-living type, measured by the survey item "Is the place where you live…?" with categories including "suburbs of a large city." This variable is treated as a perception (label) measure rather than a physical description.

2.4 Operationalisation

Survey Measures. The survey is used to capture social categorisation of residential context and its relationship to settlement hierarchy and built form. Two measures are

central and intentionally independent: (i) settlement-size context (population-size bands) and (ii) self-declared place-of-living label (including "suburbs"). Residential preference is used to assess whether "suburbs" is more salient under an aspirational framing than as a present-tense self-label. Finally, a multiple-response item on perceived negative effects provides an "impact layer" linking categorisation patterns to socially legible consequences (mobility, service capacity, social participation) relevant to planning.

2.5 CORINE Land Cover Exposure Profile

Land-Cover Context and Geospatial Processing. To represent the physical environment, respondent postal codes were geocoded to point locations and linked to CLC polygons. The land-cover component is used to construct a land-cover exposure profile: the distribution of respondent locations across land-cover classes. This profile is interpreted as contextual physical environment information that complements survey-based categorisation. It provides a monitoring-oriented "what kind of land-cover context dominates where respondents live" backdrop for interpreting the social categorisation results.

The workflow follows a standard point-in-polygon summarisation procedure:

- postal codes → geocoded point layer (excluding geocoding failures),
- point-in-polygon overlay with CLC polygons,
- class-wise counting of points,
- aggregation of counts (and percentages) at the land-cover class level.

Figure 1 maps the geocoded respondent locations against the CLC layer to provide spatial context.

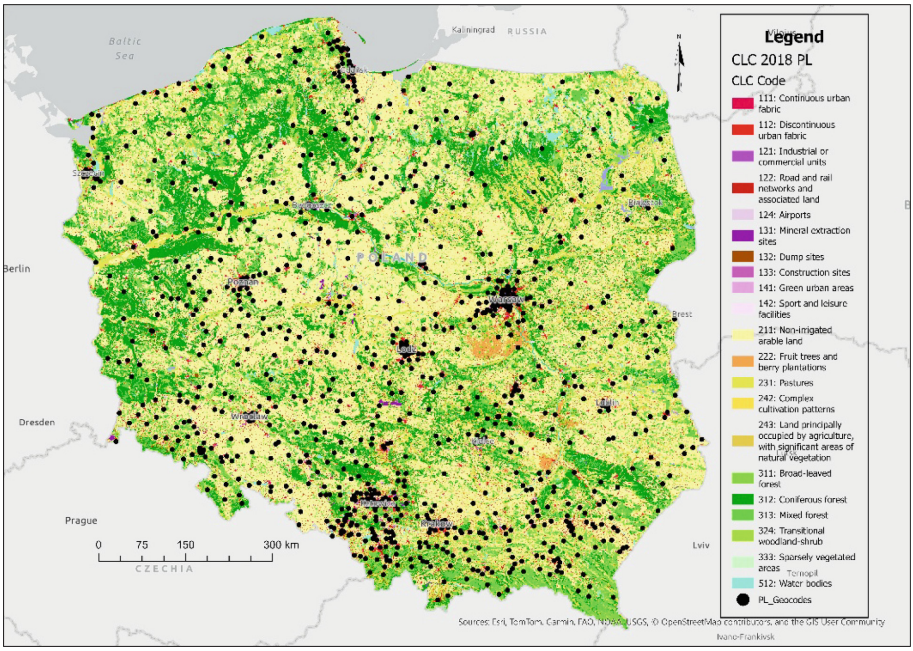

Fig. 1. Spatial distribution of respondent locations overlaid on land-cover classes (CORINE Land Cover 2018).

2.6 Analytical Approach

The analysis proceeds in three integrated steps, aligned with the research questions.

First, it reports the distributions of settlement-size categories, self-declared place labels, and key land-cover classes from the exposure profile. This establishes the empirical starting point for discussing category prevalence and land-cover context.

Second, we evaluate how self-declared place labels relate to settlement-size categories using contingency analysis (cross-classification of categorical variables) and report the strength of association using Pearson's chi-square test and Cramer's V. This step captures both the overall structure (how strongly labels and settlement context co-vary) and the substantive mismatches (where they diverge in systematic ways).

Finally, we summarise perceived negative effects as a ranked "impact layer" that connects category patterns to planning-relevant consequences.

A key interpretive concept is the "suburban label gap"—the discrepancy between land-cover exposure patterns consistent with discontinuous built environments and the low frequency of respondents selecting "suburbs" as a current self-descriptor—considered alongside the stronger presence of suburban options in stated residential preferences.

3 Results

The results are presented in the order of the triangulation framework, beginning with the monitoring-oriented land-cover baseline. Geocoded respondent locations fall predominantly within artificial surfaces (66.7%), driven mainly by discontinuous urban fabric (CLC 112; 59.7%), while a substantial share is located in agricultural classes (26.9%), especially non-irrigated arable land (CLC 211; 16.9%) (Table 1). Urban fabric classes (CLC 111–112) together account for 61.4% of all geocoded locations; within this subset, discontinuous urban fabric dominates (97.1% of CLC 111–112), indicating that the built-up environments represented in the sample are captured primarily by the generalised 'discontinuous' class rather than by continuous urban fabric.

This exposure profile provides a monitoring-based picture of the physical context in which respondents are situated: built-up locations classified as discontinuous at CLC scale and embedded within wider agricultural landscapes. Given the national-scale generalisation of CLC, with a minimum mapping unit of 25 ha, locations falling in agricultural classes should be interpreted as indicators of contextual land-cover exposure rather than of parcel-level land use. Importantly, CLC 112 is not equivalent to 'suburbs of a large city', but denotes a land-cover category spanning a broad continuum of fragmented built-up forms. The following survey results therefore examine how respondents classify their residential context through settlement-size categories and everyday place labels, and where these classifications align with or diverge from the monitoring baseline.

Table 1. Distribution of geocoded respondent locations across CORINE Land Cover classes (counts and shares).

CLC code	CLC class	Area (ha)*	Respondent locations (n)	Respondent share (%)
111	Continuous urban fabric	4,079.5	26	1.8
112	Discontinuous urban fabric	321,504.2	883	59.7
121	Industrial or commercial units	7,617.3	45	3.0
122	Road and rail networks and associated land	82.0	2	0.1
124	Airports	318.5	2	0.1
131	Mineral extraction sites	58.3	3	0.2
132	Dump sites	317.8	1	0.1
133	Construction sites	111.9	1	0.1
141	Green urban areas	337.7	11	0.7
142	Sport and leisure facilities	437.6	13	0.9
211	Non-irrigated arable land	4,534,895.7	250	16.9
222	Fruit trees and berry plantations	679.2	2	0.1
231	Pastures	38,072.3	56	3.8
242	Complex cultivation patterns	5,156.8	61	4.1
243	Land principally occupied by agriculture, with significant areas of natural vegetation	2,906.4	29	2.0
311	Broad-leaved forest	6,156.8	17	1.1
312	Coniferous forest	663,976.5	38	2.6
313	Mixed forest	6,270.0	26	1.8
324	Transitional woodland-shrub	4,591.0	9	0.6
333	Sparsely vegetated areas	50.4	1	0.1
512	Water bodies	1,081.9	4	0.3
	Total	**5,598,701.8**	**1,480**	**100.0**

Table 2 reports the distribution of settlement-size categories, which are often used as proxies for 'urbanity'.

Table 2. Distribution of respondents by settlement size.

Category	n	%
Village	594	39.6
Town/city up to 20,000	195	13.0
Town/city 20,000-49,999	166	11.1
Town/city 50,000-99,999	122	8.1
City 100,000-199,999	122	8.1
City 200,000-499,999	121	8.1
City over 500,000	180	12.0
Total	**1500**	**100.0**

Note. Question: 'What is the size of the locality in which you live?' n = observed frequency; % = percentage of all respondents; $N = 1{,}500$.

The sample covers the full settlement hierarchy and closely reflects the national settlement-size distribution (rural c. 40.5%; cities under 20,000 c. 13%; 20,000–100,000 c. 18.7%; over 100,000 c. 27.8% [9]), enabling a robust assessment of how settlement size relates to self-labelling. Read alongside the CLC exposure baseline, settlement size functions as a quasi-objective proxy for settlement hierarchy: it is self-reported, but it refers to a demographic classification and should not be treated as a direct synonym for land-cover class or functional metropolitan position.

Table 3. Self-declared place-of-living categories.

Category	n	%
Open rural area	96	6.4
Village or small town	662	44.1
Medium-sized city	359	23.9
Large city	351	23.4
Suburbs of a large city	32	2.1
Total	**1500**	**100.0**

Note. Question: 'Is the place where you live …?' n = observed frequency; % = percentage of all respondents; $N = 1{,}500$.

The next step therefore introduces the core label variable, which captures how respondents describe their residential environment in everyday terms, including whether they adopt the socially specific category 'suburbs of a large city' (Table 3). Because this wording narrows the concept of suburbs to large metropolitan centres, the low proportion selecting this option should be interpreted as limited uptake of this label. In light of the prominence of suburbanisation in planning debates, the limited uptake of the label

'suburbs of a large city' in current self-description is consistent with a suburban label gap. This interpretation is reinforced by the preference question, in which suburban options are selected more frequently than in current self-identification. When juxtaposed with the CLC exposure profile dominated by discontinuous urban fabric (CLC 112), the low uptake of the label 'suburbs of a large city' reveals a translation gap between monitoring-oriented land-cover categories and everyday place labelling.

The relationship between settlement-size context and self-declared place labels is then examined using an association analysis of categorical variables (Table 4), while Fig. 2 illustrates the compositional patterns across settlement-size groups.

As expected, settlement-size category and self-declared place-of-living type are strongly associated (Pearson χ^2 (24, N = 1500) = 2219.476, p < .001; Cramer's V = 0.608), indicating that perceived labels broadly track settlement context. At the same time, the "suburbs of a large city" label remains rare in self-description. This supports the interpretation that "suburbs" function as a socially ambiguous category rather than a straightforward territorial descriptor. The label is concentrated in the largest settlements: 11.1% of respondents in cities with 500,000 or more inhabitants select this label, while smaller but non-zero shares also appear in cities of 200,000–499,999 inhabitants (3.3%) and even in villages and small towns ($\leq$1%). At the same time, substantial relabelling occurs across the smaller-town categories; for example, 28.7% of respondents from towns with up to 20,000 inhabitants describe their place of residence as a 'medium-sized city'. This pattern supports treating labels such as 'suburbs' and 'city' primarily as social identifications rather than purely morphological categories.

Read column-wise, the label 'suburbs of a large city' is concentrated in the largest settlement-size categories, but is not confined to them. Since settlement-size category is not equivalent to functional metropolitan location, the presence of this label in villages and small towns should not be read as contradictory. Rather, it suggests that suburban self-identification may extend across settlement forms located within broader metropolitan contexts. The adjusted residuals support this reading: respondents in cities with more than 500,000 inhabitants are markedly overrepresented among those selecting the suburban label (adjusted residual = 8.9), whereas villages are significantly underrepresented (-3.2). By contrast, the residual for cities of 200,000–499,999 remains modest (0.9), indicating that the strongest concentration is in the largest settlement category.

Table 4. Relationship between settlement-size categories (rows) and self-declared place-of-living labels (columns).

Size category	Statistic	Open rural	Village / small town	Medium city	Large city	Suburbs (large city)	Total
Village	Count	94	496	0	0	4	594
	Expected	38.0	262.2	142.2	139.0	12.7	594.0
	Row %	15.8%	83.5%	0.0%	0.0%	0.7%	100.0%
	Col %	97.9%	74.9%	0.0%	0.0%	12.5%	39.6%
	Adj. resid.	12.1	24.9	-17.6	-17.3	-3.2	
≤20K	Count	2	132	56	3	2	195
	Expected	12.5	86.1	46.7	45.6	4.2	195.0
	Row %	1.0%	67.7%	28.7%	1.5%	1.0%	100.0%
	Col %	2.1%	19.9%	15.6%	0.9%	6.3%	13.0%
	Adj. resid.	-3.3	7.1	1.7	-7.7	-1.1	
20K-50K	Count	0	34	127	3	2	166
	Expected	10.6	73.3	39.7	38.8	3.5	166.0
	Row %	0.0%	20.5%	76.5%	1.8%	1.2%	100.0%
	Col %	0.0%	5.1%	35.4%	0.9%	6.3%	11.1%
	Adj. resid.	-3.6	-6.5	16.8	-7.0	-0.9	
50K-100K	Count	0	0	105	17	0	122
	Expected	7.8	53.8	29.2	28.5	2.6	122.0
	Row %	0.0%	0.0%	86.1%	13.9%	0.0%	100.0%
	Col %	0.0%	0.0%	29.2%	4.8%	0.0%	8.1%
	Adj. resid.	-3.0	-10.2	16.8	-2.6	-1.7	
100K-200K	Count	0	0	71	51	0	122
	Expected	7.8	53.8	29.2	28.5	2.6	122.0
	Row %	0.0%	0.0%	58.2%	41.8%	0.0%	100.0%
	Col %	0.0%	0.0%	19.8%	14.5%	0.0%	8.1%
	Adj. resid.	-3.0	-10.2	9.3	5.0	-1.7	
200K-500K	Count	0	0	0	117	4	121
	Expected	7.7	53.4	29.0	28.3	2.6	121.0
	Row %	0.0%	0.0%	0.0%	96.7%	3.3%	100.0%
	Col %	0.0%	0.0%	0.0%	33.3%	12.5%	8.1%
	Adj. resid.	-3.0	-10.2	-6.4	19.9	0.9	
>500K	Count	0	0	0	160	20	180
	Expected	11.5	79.4	43.1	42.1	3.8	180.0
	Row %	0.0%	0.0%	0.0%	88.9%	11.1%	100.0%
	Col %	0.0%	0.0%	0.0%	45.6%	62.5%	12.0%
	Adj. resid.	-3.7	-12.7	-8.0	22.1	8.9	
Total	Count	96	662	359	351	32	1500
	Expected	96.0	662.0	359.0	351.0	32.0	1500.0
	Row %	6.4%	44.1%	23.9%	23.4%	2.1%	100.0%
	Col %	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Note. *Count* = observed frequency; *Expected* = expected count; *Row %* = percentage within settlement-size category; *Col %* = percentage within self-declared place-of-living label; *Adj. resid.* = adjusted residual; *K* = thousand.

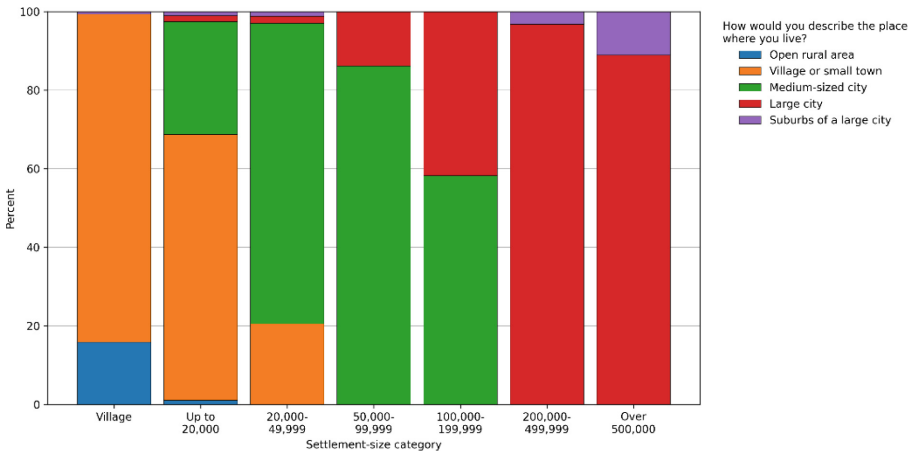

Fig. 2. Self-declared place-of-living categories by settlement-size category (row percentages).

The figure visualises the label gap directly: even where settlement-size category indicates an urban context, respondents often select labels that imply a different 'felt' residential identity.

To distinguish between current self-identification and residential aspiration, Table 5 presents the distribution of preferred place of residence. In a counterfactual preference question '*If you could choose your place of residence now …*', suburban options are selected substantially more often than in current self-identification. While only 2.1% of respondents currently describe their place of residence as 'suburbs of a large city', 12.9% identify suburban locations as their preferred residential setting, including 5.7% who choose the suburbs of a medium-sized city and 7.2% who choose the suburbs of a large city. This suggests that 'suburbs' is a salient category in respondents' mental repertoire, even if its use as a descriptor of current residence remains limited, consistent with boundary ambiguity and competition between labels rather than with simple non-recognition.

Table 5. Preferred place of residence.

Category	n	%
In the countryside	515	34.3
In a small town	243	16.2
In a medium-sized city	191	12.7
In the suburbs of a medium-sized city	86	5.7
In a large city	196	13.1
In the suburbs of a large city	108	7.2
Hard to say	161	10.7
Total	1500	100.0

Note. Question: 'If you could choose your place of residence now, where would you prefer to live?' n = observed frequency; % = percentage of all respondents; N = 1,500.

While the preceding results establish how respondents position their residential context in terms of settlement size and self-declared labels, the next step is to clarify why these categories matter. To do so, we examine perceived negative effects of residential moves from cities to suburban and rural locations as an 'impact layer' linking categorisation to the everyday burdens of dispersed settlement. As Table 6 shows, these perceptions are dominated by concerns about mobility and service capacity.

Table 6. Perceived negative effects of moves from cities to suburban and rural locations.

Negative effect	n	% of respondents
Increased congestion due to more car travel	904	61.1
Harder to organise public transport with longer commuting	577	39.0
Shortages in schools, kindergartens and clinics in suburban areas	434	29.3
Lower participation in cultural activities	419	28.3
Weaker ties with family and friends	411	27.8
Depopulation of city centres	362	24.5
Total	3107	210.0

Note. Question: 'What negative effects may result from moving from cities to suburban or rural locations?' Respondents could select up to three answers. n = observed frequency; % = percentage of respondents; $N = 1{,}480$.

The ranking reveals a clear hierarchy of perceived downsides. The most salient concern is mobility: 61.1% of respondents point to increased congestion resulting from greater reliance on car travel, while 39.0% highlight the difficulty of organising public transport under conditions of longer-distance commuting. A second tier shifts from transport to service provision, with 29.3% indicating shortages of schools, kindergartens and clinics in suburban areas. The remaining items point to broader social and urban-structural consequences, including reduced participation in cultural activities (28.3%), weaker ties with family and friends (27.8%) and the perceived depopulation of city centres (24.5%). Taken together, this pattern suggests that suburbanisation is understood primarily through everyday functional burdens, while a substantial minority also associate it with wider social and centre-periphery dynamics. In this sense, suburbanisation appears less as an abstract planning category than as a set of lived trade-offs spanning mobility, services and social life.

Because respondents could select up to three items from a closed list, the ranking should be interpreted as a measure of relative salience among predefined effects rather than as an exhaustive inventory; percentages therefore do not sum to 100.

4 Discussion

4.1 What the 'Suburban Label Gap' Actually is, and What it is Not

The core empirical pattern in this study is not that residents 'misreport' where they live, but that the same residential reality can be legitimately described through different classification logics. Settlement size and self-declared place-of-living type are strongly

associated, indicating that self-labelling is not random: respondents generally align their declarations with the demographic hierarchy of settlements. Yet within this overall consistency, the category ‘suburbs’ is rarely used in current self-description, even though respondents clearly understand ‘suburbs’ as a meaningful concept (see below). This combination, namely strong structure in responses but weak uptake of the ‘suburbs’ label, suggests that the label gap concerns not factual error but uneven adoption of a socially available category.

For planning, this is important because physically identifiable patterns of dispersed settlement do not necessarily correspond to the terms residents use to describe where they live. The results therefore point to a gap between environmental classifications and everyday self-description. In this sense, the ‘suburban label gap’ is not evidence that suburbanisation is absent, but evidence that its socially recognised labels are unevenly taken up.

4.2 Why Residents May Avoid the ‘Suburbs’ Label Even When Suburbanisation is Present

The literature provides several mechanisms that can plausibly explain the low share of ‘suburbs’ in self-identification.

First, self-declared residential categories often operate as spatial representations, that is, expressions of identity, belonging and status, rather than as objective measurements. Fortin and Després (2008) describe the ‘just middle’ (le juste milieu), a self-positioning between city and countryside that may be stable and attractive precisely because it avoids the stigma or ambiguity of ‘suburb’ [3]. Rousseau (2015) further links such representations to the defence of a lifestyle and local social order, which can translate into resistance towards policies framed as ‘densification’ or ‘anti-sprawl’ [10]. In this reading, the ‘suburbs’ label may be avoided not because residents misunderstand geography, but because it does not fit the identity they wish to claim.

Second, the category itself is intrinsically ambiguous and method-dependent. Different delimitation methods yield different ‘suburbs’ [11]. This is not only a technical issue; it becomes a social one when people cannot clearly recognise what counts as ‘the suburb’ in everyday experience. Category ambiguity is therefore structural rather than accidental, because ‘where the city ends’ is often negotiated through practice and belonging rather than through formal boundaries or indicators [1, 12].

Third, labels may also carry ideological weight. In some contexts, terms that describe peripheral growth are used as political tools, such as ‘sprawl’, ‘informal’ or ‘disorderly’, which may discourage self-identification with the category [13]. Even if Poland’s suburbanisation context differs from Mediterranean cases, the broader point remains: when a category is associated with critique or ‘bad development’, residents may prefer more neutral alternatives such as ‘village’, ‘small town’ or ‘city’.

4.3 Triangulation as a Planning Translation Tool, not a ‘Validation Test’

A key implication is methodological: the perception–environment approach should be framed less as a strict validation of survey declarations and more as a triangulation between classification systems that serve different purposes. There are good reasons not

to treat self-reports as direct measurements of spatial reality. Empirical work in other domains shows that self-reported proxies can produce substantial misclassification of exposure and distance [14]. In urban studies, however, the reverse problem is equally important: physically valid mapping may still fail to capture the categories through which residents interpret and discuss their surroundings. This is consistent with multi-dimensional approaches to sprawl measurement, in which land cover, density, continuity, centrality, proximity and functional relations capture different aspects of dispersed development rather than interchangeable categories [15–20]. Similar distinctions are embedded in functional urban area and degree-of-urbanisation approaches, which classify territories through density, contiguity or commuting integration rather than through residents' own place labels [21–27].

From this perspective, the value of triangulation lies in identifying where translation breaks down, namely where a land-cover signal suggests dispersed development, but the available social categories do not provide a matching label that residents recognise [28–30]. In this study, the monitoring layer is dominated by discontinuous urban fabric (CLC 112), a generalised land-cover category that captures fragmented built-up patterns but does not correspond to a single socially stable label and is not equivalent to the survey's narrow option "suburbs of a large city." This becomes especially relevant when planning instruments rely on persuasion and behavioural change, for example mobility shifts or service reorganisation, because in such cases category resonance may matter as much as spatial accuracy.

4.4 The Concept of 'Suburbs' Becomes More Visible When Asked as a Preference

An important nuance is that 'suburbs' become more visible when respondents are asked about preferred residential location rather than current self-identification. In the preference question, where respondents choose where they would rather live if they could, the two suburban options jointly account for a noticeably larger share than the self-identifying as suburban. This difference suggests that 'suburbs' function more as an imagined lifestyle category, that is, a future-oriented aspiration, than as a stable present-tense identity label.

This aligns with the 'just middle' logic: the suburban ideal can be attractive as a balance between access and tranquillity, while the 'suburbs' label may remain contested or unnecessary for describing one's current place of residence. In policy terms, this asymmetry is crucial. Residents may support suburban-style preferences and housing forms even if they do not accept 'suburbanisation' as a label for their own area. That disconnect can complicate communication around land-take reduction, because the policy frame of limiting suburban sprawl may not align with how people narrate their own choices.

4.5 Perceived Negative Effects as an 'Impact Layer' that Makes the Label Gap Policy-Relevant

Mobility concerns dominate. Increased congestion from greater car travel is selected most frequently (61.1%), followed by the difficulty of organising public transport under longer-distance commuting (39.0%). This ordering is consistent with the idea that travel

burdens are experienced repeatedly and are therefore readily available when respondents are asked to identify negative consequences. For the paper's core argument, the implication is communicative and diagnostic rather than causal. Mobility and essential service capacity do not 'prove' suburbanisation, but they provide a shared, non-identity-loaded language through which dispersed settlement is discussed and evaluated. Where 'suburbs' is rarely adopted as a self-description, policy narratives built primarily around the suburbanisation label may struggle to resonate as descriptions of present-day lived reality. By contrast, congestion, public transport feasibility and service capacity are interpretable across settlement types and social identities, making them useful entry points for communicating the costs of dispersed development and for linking land-take monitoring to concerns that residents readily recognise [4].

4.6 Planning Implications: Translating Contested Labels into Functional Concerns

The practical implication of the suburban label gap is that concepts such as suburbanisation, sprawl or land take, require translation into socially recognisable terms. If "suburbs" is weakly adopted as a current self-description, policy communication based primarily on the suburbanisation label may not correspond to how residents describe their own environments. This is especially relevant for policies that depend on public acceptance, such as densification, limits on greenfield development, parking restraint, public transport reorganisation or the coordination of schools, kindergartens and healthcare facilities.

Three recommendations follow. First, land-cover and settlement-hierarchy indicators should be complemented by perception-sensitive survey items distinguishing current self-description, residential preference and perceived functional burdens. Second, communication around land artificialisation should focus more on consequences that residents recognise directly, especially congestion, car dependence, public transport feasibility and service capacity. Third, planning diagnostics should combine morphological, functional and subjective indicators rather than treating any single classification as sufficient. CLC can identify discontinuous built-up contexts, settlement-size data can locate respondents within the urban hierarchy, functional data can capture accessibility and service provision, and place labels can reveal whether expert categories are socially recognised.

5 Conclusion

By triangulating CORINE Land Cover exposure with settlement-size context and self-declared place labels, this paper demonstrates that suburbanisation cannot be inferred from any single classification system. The monitoring layer captures predominantly discontinuous urban fabric, a necessarily coarse signal given CLC's minimum mapping unit, yet the metropolitan label 'suburbs' remains weak as a descriptor of current residence. Rather than indicating misreporting, this pattern is interpreted as a translation gap between nominal, planner-facing categories and the socially meaningful ways in which people understand, imagine and value where they live. The concept of the suburban label gap captures this mismatch.

The approach is replicable beyond Poland. Its main requirement is the availability of three comparable layers: a land-cover or built-form indicator, a settlement-hierarchy or administrative-context variable, and a survey item capturing residents' own place labels or residential self-identification. In other contexts, CORINE Land Cover could be replaced or complemented by Urban Atlas, national land-cover datasets, cadastral data or gridded built-up indicators, while settlement size could be substituted by degree-of-urbanisation classes, functional urban area membership or commuting-zone classifications. The relevant label would need contextual adaptation, since "suburb", "peri-urban area", "commuter belt", "urban fringe" or locally specific equivalents may carry different meanings across planning cultures. Replication would therefore allow comparison not only of suburbanisation as a spatial process, but also of how far its policy labels are socially recognised.

In this sense, the suburban label gap can be treated as a transferable diagnostic problem: wherever expert classifications and everyday residential labels diverge, planning communication may require an additional translation layer.

Acknowledgments. The survey data used in this article were collected within the project A New Model of Urbanization in Poland: Practical Implementation of the Principles of Responsible Urbanization and a Compact City (NEWURBPACT), co-funded by the National Centre for Research and Development (NCBR), grant no. 1/384689/20/NCBR/2019.

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

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A Structured Review of Methodologies for Measuring Socio-Economic Impacts of Unequal Urban Opportunity for Women

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Abstract. Women's fear in urban space is increasingly recognized not only as a safety issue, but as a socio-economic constraint affecting mobility, access to opportunities, and participation in urban life. However, the literature remains fragmented in the way it translates women's perceived insecurity into measurable impacts relevant for urban planning. This paper presents a structured review of the methodological approaches used to operationalize the socio-economic impacts of women's fear in cities as part of a broader systematic literature review. Rather than focusing exclusively on safety perception, the review investigates how studies measure the downstream effects of fear through indicators and proxies related to restricted mobility, reduced access to jobs and services, time and travel burdens, additional financial costs, lower use of public space, and unequal urban participation. The paper maps the main methodological families emerging from the literature, including perception-based surveys, participatory and audit-based approaches, GIS and built-environment assessments, spatial-statistical models, and transport accessibility frameworks. The review argues that existing studies are stronger in identifying correlates of perceived insecurity than in constructing robust and transferable indicator systems able to capture its socio-economic implications. The paper outlines the basis for a gender-sensitive and spatially explicit framework to measure how fear reshapes access, mobility, and urban opportunity.

Keyword: women's fear in the city · socio-economic impact · gender-sensitive planning

1 Introduction

Urban space is not experienced equally by all its users. A growing body of research shows that women's everyday interactions with streets, public transport, parks, public facilities, and other urban environments are shaped by gendered perceptions of risk, embodied vulnerability, and unequal conditions of access and exposure [1, 2]. For this reason, women's fear in the city should not be interpreted merely as an individual or psychological response to unsafe surroundings [3–5]. Rather, it should be understood as a structural expression of urban inequality, one that affects how space is perceived,

© The Author(s), under exclusive license to Springer Nature Switzerland AG 2026
O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 657–674, 2026.
https://doi.org/10.1007/978-3-032-30524-4_40

navigated, and used, and therefore influences the real opportunities women can access in everyday urban life [6–12]. This perspective is also consistent with the international policy agenda: UN Women's Safe Cities and Safe Public Spaces programme treats women's safety as a condition for the full use of public space and urban participation, while the wider Sustainable Development Goals (SDGs) framework links gender equality, inclusive cities, and freedom from violence in public and private spheres [13–17]. Recent literature further shows that women's perceived safety is shaped by the interaction of physical, social, individual, and temporal factors, and therefore cannot be treated as a neutral or isolated variable. Public space may be formally open to all, but not equally accessible in practice. Women's use of streets, parks, transit spaces, and other urban environments is often influenced by everyday risk management, prior experiences, care responsibilities, and unequal conditions of access. This also calls for an intersectional perspective, since safety perceptions vary according to age, socio-economic position, ethnicity, caregiving roles, and other overlapping dimensions. Women's fear can therefore be read as part of a broader condition of everyday urban inequality rather than as a simple fear-of-crime response [18–20]. This shift in perspective is important because fear does not only affect perception; it also reshapes behaviour and access. Women may avoid certain places or time slots, alter routes, rely on more costly or less efficient transport solutions, reduce their use of public space, or limit participation in work, education, leisure, and civic life. In this sense, gendered urban insecurity has socio-economic effects that can be expressed through longer travel times, higher mobility costs, reduced access to jobs and services, lower frequency of public-space use, and diminished urban autonomy. Here the key issue is not mobility per se, but accessibility and opportunity. The Organisation for Economic Co-operation and Development/International Transport Forum (OECD/ITF) explicitly define accessibility in terms of access to opportunities, goods, and services, while World Bank research shows that the accessibility, availability, and safety of public transport affect women's labour-market outcomes and broader economic participation [15, 16, 18, 19, 21, 22]. Such a perspective is especially relevant for urban planning. While the literature has become increasingly sophisticated in measuring women's perceived safety and its environmental correlates, much less attention has been devoted to the methodological question of how fear, constrained mobility, and restricted use of space can be translated into measurable socio-economic impacts and planning-oriented indicators [11, 23–25]. Existing studies remain fragmented across urban studies, transport research, geography, public health, criminology, and gender studies; as a result, methods are often either rich in subjective insight but weak in spatial comparability, or strong in spatial modelling but less able to capture the lived and unequal character of fear. This paper responds to that gap by presenting a structured review of the methodologies used to operationalize the socio-economic implications of gendered urban insecurity in urban contexts. It does not aim to represent the whole literature, but to reconstruct the methodological architecture of a targeted subsample in which women-centred studies and transferable methodological studies are analysed together. This contribution is conceived as a starting point for a broader and more complex research programme currently under development. For this reason, the wider body of literature will be further expanded, systematized, and discussed in a separate and more comprehensive review paper. The contribution of the paper is twofold. First, it offers a

structured methodological reading of a literature that is often discussed thematically but less frequently organized in terms of how it constructs measurable evidence. Second, it lays the groundwork for future research aimed at developing more integrated, gender-sensitive, and spatially explicit frameworks for urban planning. In this sense, the next challenge is not simply to document that women feel unsafe in cities, but to measure how that insecurity produces unequal access to opportunities, additional daily burdens, and socio-economic disadvantage in ways that planning can meaningfully address.

2 Review Method

As per the classical Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) criteria have been implemented as per PRISMA guidelines [26] that helps to systematically report literature reviews and critically synthetize and analyse the information highlighted. The present work will present a subsample of the total systematic review, focusing on the methodologies topic. The original research has been undertaken to explore how socio-economic impacts are measured in the view of woman perception and enjoyment of the city public space. The criteria of PRISMA utilize a comprehensive methodology to find, evaluate, filter and complete research literature in a very systematic manner. This approach has been widely used in areas like social and economic equity, digital inclusion and technology-driven societal change among others. The following actions have been implemented for the search strategy: *(i)* Determining the original body of literature; *(ii)* Implementing a strict screening procedure; *(iii)* Evaluating the effectiveness of particular studies; *(iv)* Finalizing the *corpus* for the examination. The research technique, inclusion and exclusion criteria, and data extraction procedure are thoroughly explained in the part that follows.

2.1 Search Strategy

A systematic search strategy was applied across Scopus as the main bibliographic database, complemented by Google Scholar and Mendeley as literature discovery tools, to ensure broad coverage of the literature on socio-economic impact indicators and women's fear in urban contexts. In particular, Google Scholar was used to identify relevant non-indexed works, given that parts of the social sciences and psychology—particularly in the Italian academic context—are not fully covered by bibliometric databases. The corpus was further refined through backward snowballing, by screening the reference lists of key review papers and highly relevant methodological contributions. The main search terms used were "women" AND "urban safety" AND "socio-economic impact"," "women's fear" AND "public space" AND "economic impact", "women geography AND social equity," "women AND economic AND equity," "women" AND "urban vulnerability" AND "economy", "women fear" AND "socio-economic impact", "gender-sensitive planning" AND "socio-economic impact" and similar term combinations. These terms were chosen to include studies that specifically focus on gender lens in urban planning, women unequal access to opportunities, fear barriers in pedestrian pathways in the cities and highlight the role of economy in widening or narrowing the social and economic equity, thereby addressing systemic biases in evaluation, planning

and assessment applications. The search was conducted in January 2026, with a restriction on publication date from 2020 to focus on the most contemporary research. The search queries were formulated using a combination of keywords and Boolean operators to ensure coverage of pertinent literature. Specific inclusion and exclusion criteria have been established to refine the corpus of studies (Fig. 1).

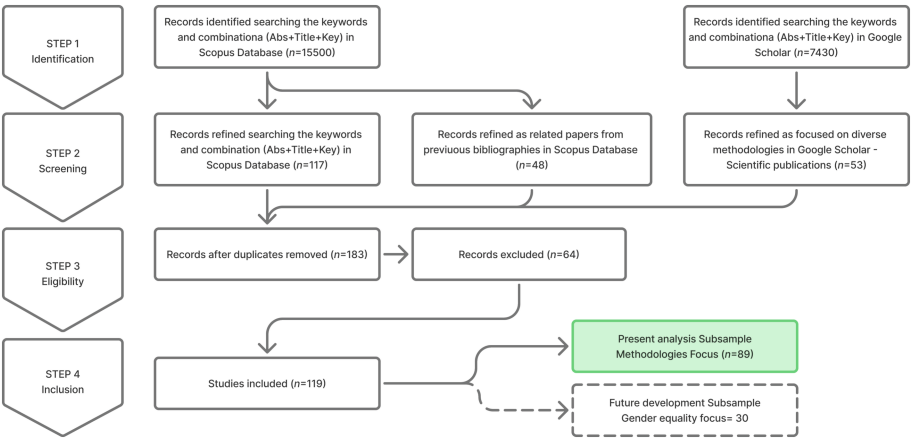

Fig. 1. PRISMA steps applied to the present research (Author elaboration)

2.2 Inclusion/Exclusion Criteria

The screening and selection process followed a two-step procedure. First, titles, abstracts, and keywords were examined against predetermined inclusion and exclusion criteria in order to remove records that were not relevant to the aims of the study. The review considered journal articles, conference papers, book chapters, and selected reports, while excluding posters, editorial commentary, opinion pieces, and non-peer-reviewed contributions. Priority was given to peer-reviewed and indexed publications, whether open access or accessible through the author's university subscriptions; however, non-indexed works were also considered when relevant, since the scientific corpus related to these social-science questions cannot be treated as purely bibliometric. To be included, studies had to focus on urban contexts, explicitly address women, women's safety, or gendered urban insecurity, and present a recognizable methodological component, such as measurement, operationalization, indicator design, modelling, accessibility assessment, burden analysis, or the use of socio-economic proxies. Studies were excluded if they were purely criminological, or if they focused mainly on labour-market or health issues without spatial relevance or planning significance. Only studies written in English or Italian and available in full text were considered. Records that passed the first screening stage were then subjected to full-text review in order to verify their thematic relevance, methodological rigor, and contribution to the methodological debate on gendered urban insecurity and socio-economic inequality in cities. Once the *corpus* was finalized, a structured coding procedure was used to extract the main analytical features of each study,

including research questions and objectives, the methodological and analytical techniques employed, and the main findings regarding the relationship between women's urban insecurity, access, mobility, and broader issues of social and economic justice, as well as the implications for more equitable planning and assessment frameworks. Finally, a narrative synthesis was adopted to integrate findings across the selected studies and provide an overall account of the main methodological trends, recurring themes, and research gaps in the field.

2.3 Coding Protocol

A structured coding protocol was developed to classify each study included in the formalized database according to its methodological and planning relevance. The classification into CORE, METHOD_SUPPORT, and CONTEXT was defined in relation to the specific focus of this proceedings. CORE papers are those directly addressing gender-sensitive urban accessibility through spatial or data-driven methodological approaches and linking indicator construction to the socio-economic impacts of inequality. METHOD_SUPPORT papers are studies that provide transferable methodological tools for analysing these issues, even when they do not fully address the same substantive focus. CONTEXT papers include contributions on broader gender-equality policies and strategies in urban settings, which provide conceptual and policy background but are not central to the methodological architecture of this review. In order to preserve comparability across the *corpus*, each paper was coded along the following analytical dimensions: urban domain (street, park, transit, neighborhood, public space, or mixed urban environment), core phenomenon (fear, perceived safety, insecurity, avoidance, mobility constraint, or restricted use of space), socio-economic dimension (access to jobs, access to services, time burden, transport cost burden, participation, stay behavior, wellbeing, or labor outcomes), data source (survey, interview, safety audit, participatory mapping, app/crowdsourcing, GIS/open data, street-view imagery, or administrative/transport data), method family (descriptive statistics, factor analysis, GIS overlay, accessibility indicators, composite index, OLS, GWR, SEM, ML, or mixed methods), output (score, map, index, model, typology, or dashboard), planning use (diagnosis, prioritization, design support, accessibility appraisal, or policy evaluation), spatial scale (point, street segment, neighborhood, or city), and validation strategy (none, model fit, sensitivity, spatial validation, expert validation, or triangulation). Because the *corpus* also includes review papers, reports, and methodological essays, an auxiliary study-design field was added and, where strictly necessary, review-based values such as review/document *corpus* and review synthesis were used to avoid forcing non-empirical studies into purely empirical categories.

3 Results: Taxonomy of Methodologies

In order to incorporate findings from several studies and provide an initial but complete overview of themes, trends, and research gaps in the filed a narrative syntesis was used. The total *corpus* includes 119 records and provides a methodologically useful snapshot of the recent literature at the intersection of women's perceived safety, urban space,

accessibility, and socio-economic implications. The corpus is strongly contemporary: the temporal distribution of the full database clearly highlights the growing relevance of the topic over time. After a sporadic presence in the earlier years (2008–2020), the number of publications increases markedly from 2021 onward, with a particularly sharp rise in 2023–2025 and a peak of 33 records in 2025 alone. In document-type terms, journal articles dominate, followed by review papers and a smaller but important group of conference papers and reports. This distribution suggests that the field is rapidly expanding and remains strongly method-driven, with methodological innovation often outpacing conceptual consolidation. To spatially locate the literature, the analysis considered the geographical location of the case studies rather than the institutional affiliations of the authors. Two main clusters emerge: one centred on China (14 papers) and another including studies of global or international scope (15 papers), the latter reflecting the strong presence of review and theoretical contributions based on multiple case studies. Beyond these two clusters, the most represented countries are India, Italy, and Iran. A notable feature is the hybrid composition of the *corpus*. The database does not consist only of studies directly centred on women's fear or gendered urban insecurity and six overlapping methodological-lexical groupings emerge. These should not be interpreted as mutually exclusive thematic clusters, since the same study may belong to more than one grouping (Table 1).

Table 1. Tematic clustering of corpus of literature – 119 records (Author elaboration)

Grouping	N
Papers using a lexicon related to planning/policy/decision-making	50
Papers placing women/gender/gender differences/gender inequality at the centre of the analysis	49
Papers explicitly referring to machine learning/deep learning/computer vision/GeoAI	36
Papers revolving around street-view imagery/visual perception/image-based analysis	34
Papers including survey/questionnaire/intercept survey/participants/crowdsourcing	26
Papers using or explicitly referring to GWR, MGWR, GIS, spatial statistics, kernel methods, or spatial modelling	14

For the purposes of this paper, the analysis focuses on a methodological subsample composed of CORE and METHOD_SUPPORT studies only. This makes it possible to reconstruct the methodological architecture of the field while distinguishing between studies directly centred on women's urban insecurity and studies that provide transferable methods from adjacent domains. Within this subsample, CORE papers represent the analytically central inner core, while METHOD_SUPPORT papers are used to frame the broader methodological repertoire adopted or adapted in the field (Total 89 paper). The VOSviewer term map based on titles, author keywords, index keywords, and abstracts in the final methodological subsample of 89 papers confirms that the dominant vocabulary of the corpus is still centred on visual urban perception, computational methods, and built-environment analysis (Fig. 2).

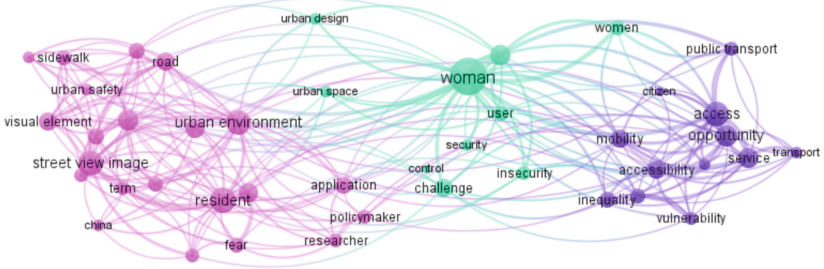

Fig. 2. Dominant lexical markers in the final *corpus* of 89 papers (author's elaboration with VOSviewer software)

The map includes 44 items organized into 3 clusters, showing the strong interconnection between terms related to women and gender, urban environment and visual perception, and access, mobility, and opportunity. Terms such as street-view or image-based visual analysis (31 papers), machine learning (20), deep learning (16), and semantic segmentation (10) occur frequently, while built environment appears in 18 papers. At the same time, the subsample shows a substantial gender-sensitive component, with 34 papers explicitly referring to gender, women, or female perspectives, and a relevant planning-oriented dimension, with 29 papers using a planning or urban-planning lexicon. By contrast, the socio-economic vocabulary remains less consolidated than the perception-oriented and computational one. These frequencies should be interpreted as overlapping lexical markers rather than as exclusive thematic categories, since the same paper may contribute to more than one strand. While the coding protocol (§ 2.3) was applied to the whole *corpus,* but Table 2 reports only the results of the CORE subset coding, which allows a partial but still meaningful interpretive reading of the literature.

Table 2. CORE (12 records) *corpus* coded (Author's elaboration).

ID	urban domain	core phenomenon	socio-economic dimension	data source	output	planning use	spatial scale
[27]	street; transit	perceived safety; mobility constraint	access to services	survey; street-view imagery	score; index	accessibility appraisal; design support	street segment; neighborhood
[28]	transit; street	insecurity; perceived safety; mobility constraint	access to services	survey; street-view imagery	score; model	diagnosis; design support; accessibility appraisal	point; street segment
[12]	street; mixed urban environment	perceived safety; insecurity	wellbeing	street-view imagery; GIS/open data; survey	model; map; score	diagnosis; policy evaluation	street segment; city
[29]	street; public space; mixed urban environment	perceived safety; insecurity; mobility constraint	participation	app/crowdsourcing; GIS/open data; safety audit	index; map; dashboard	prioritization; policy evaluation; design support	point; street segment; city

(*continued*)

Table 2. (*continued*)

ID	urban domain	core phenomenon	socio-economic dimension	data source	output	planning use	spatial scale
[30]	mixed urban environment; transit	mobility constraint	access to jobs; access to services	review/document corpus	typology; model	accessibility appraisal; diagnosis	city
[31]	transit; mixed urban environment	mobility constraint; perceived safety	access to jobs; access to services; time burden; transport cost burden; labor outcomes	review/document corpus	typology; index; model	policy evaluation; accessibility appraisal; prioritization	city
[32]	transit	mobility constraint; perceived safety; insecurity	access to services; participation	review/document corpus	typology	policy evaluation; accessibility appraisal	city
[33]	transit	insecurity; mobility constraint	access to jobs; participation; labor outcomes	survey; interview; administrative/transport data	typology; model	policy evaluation; prioritization	city
[34]	mixed urban environment; transit	mobility constraint	access to jobs; access to services; participation	survey; interview	index; model	accessibility appraisal; policy evaluation	city; neighborhood
[35]	public space; transit; mixed urban environment	insecurity; mobility constraint	participation	review/document corpus; GIS/open data	typology; map	policy evaluation; design support	city
[18]	transit; mixed urban environment	mobility constraint; perceived safety	access to jobs; access to services; time burden; transport cost burden; labor outcomes; participation	survey; interview; administrative/transport data; safety audit	model; typology	accessibility appraisal; policy evaluation	city
[36]	transit; mixed urban environment	mobility constraint	access to jobs; access to services; time burden; transport cost burden; participation; labor outcomes	review/document corpus	index; model; typology	accessibility appraisal; policy evaluation; prioritization	city

The coding of the CORE corpus highlights a coherent methodological landscape, in which women's fear, perceived safety, and gendered urban insecurity are clearly positioned at the centre of the analysis. Within this subset, the literature remains strongly oriented toward the measurement of perceived safety through surveys, spatial analysis, and, increasingly, computational and image-based methods; however, approaches explicitly translating these phenomena into socio-economic impacts, accessibility constraints, and planning-ready indicators are still comparatively less developed. Overall,

the literature is dominated by approaches that attempt to operationalize perceived safety through measurable proxies.

3.1 Methodologies - Overview

Given the methodological focus of this paper, the analysis of the methodological subsample (89 records) identifies five main methodological families. As reported in Table 3, these families are not mutually exclusive, but partially overlapping, since several papers contribute to more than one methodological strand.

Table 3. Five main methodological families in the 89-paper methodological subsample (author's elaboration)

Methodological families	Main focus	Typical methods
1. Methodologies for operationalizing fear and perceived insecurity in urban spaces	Measuring fear, perceived safety, insecurity, and their visual-spatial correlates	Likert scales, fear questionnaires, perception scores, structured interviews, psychometric approaches, pairwise comparisons, image-based prediction, GeoAI
2. Methodologies for capturing avoidance, constrained mobility, and restricted use of space	Understanding how insecurity reshapes route choice, mobility timing, park/public-space use, and everyday behaviour	Path-choice studies, avoidance behaviour, nighttime mobility restrictions, walkability/stay behaviour, route deviation, behavioural proxies, mixed methods
3. Methodologies for measuring accessibility to socio-economic opportunities	Assessing unequal access to jobs, services, amenities, and everyday opportunities	Location-based accessibility indicators, cumulative opportunity measures, potential accessibility, transport accessibility frameworks, opportunity-based metrics
4. Methodologies for measuring time, cost, and mobility burden	Capturing the burdens produced by insecurity in terms of time, money, dependency, and mode choice	Travel time burden, additional travel cost, mode substitution, escorted mobility/dependency, affordability analysis, temporal penalties linked to avoidance
5. Methodologies for linking urban insecurity to socio-economic participation	Connecting insecurity to participation, labour outcomes, service access, wellbeing, and unequal urban opportunity	Labour-market outcomes, access to education/services, reduced public-space use, social participation, wellbeing proxies, composite or integrated indicators

Within the 89-paper methodological subsample, the most visible and consolidated family is computational and hybrid perception modelling, but the overall coding also shows a broader umbrella methodological architecture built around street-view imagery, computational and visual methods, deep learning, computer vision, GeoAI, semantic segmentation, surveys, GIS/spatial statistics, and mixed methods. This confirms that the field is not organized around a single technique, but around a hybrid methodological ecosystem in which visual-computational approaches are increasingly central. In particular, computational perception modelling includes street-view imagery, computer vision, deep learning, semantic segmentation, GeoAI, multimodal modelling, and image-based prediction used to infer perceived safety or fear of crime from the visual built environment. It is represented by studies such as Kim et al. [37], Kang et al. [38], Zhang et al. [39], Zhu et al. [12], and Zhang et al. [40], and reflects the broader trend highlighted by Dubey et al. [15], who emphasize the growing role of emerging technologies in the assessment of women's perceived safety. At the same time, the umbrella coding shows that computational approaches do not exhaust the field. A second major family is represented by survey, interview, participatory, and behaviour-oriented methods, including structured questionnaires, intercept surveys, interviews, thematic analysis, randomized image-based experiments, and crowdsourced perception data. A third important family consists of spatial-statistical and mixed-method approaches, which connect subjective perceptions to spatial evidence through GIS, GWR/MGWR, composite indices, and integrated visual-spatial frameworks, as in Gargiulo et al. (2020). Finally, the subsample also includes a smaller but strategically significant group of studies oriented toward accessibility indicators, transport equity, and burden analysis, particularly in work such as Rahmah et al. [41], Bhandari et al. [31], Oviedo et al. [42], and Dumedah et al. [43]. Overall, the subsample is methodologically strongest in modelling perceived safety and its visual-spatial correlates, while approaches more directly concerned with access, burden, and socio-economic participation remain comparatively less consolidated.

3.2 Methodologies for Operationalizing Fear and Perceived Insecurity in Urban Spaces.

The strongest strand in the 89-paper subsample concerns the operationalization of fear, perceived safety, and insecurity in urban environments. Here the literature is methodologically rich and highly heterogeneous. On the more traditional side, studies rely on Likert scales, fear questionnaires, psychometric inventories, structured interviews, and perception scores, as in Valera Pertegas and Guàrdia Olmos [44] and Navarrete-Hernandez et al. [45]. On the more recent side, these instruments are increasingly complemented or replaced by pairwise image comparisons, street-view-based perception models, GeoAI pipelines, multimodal large language models, and explainable computer-vision systems, as in Kim et al. [37], Kang et al. [38], and Zhang et al. [39]. The result is a rapidly expanding repertoire of ways to make perceived insecurity measurable and spatially explicit. However, this richness is accompanied by fragmentation. Dubey et al. [15] explicitly note that women's perceived safety is measured through diverse data types and formats and that lack of standardisation remains a persistent problem; te Braak and van Tienoven [16] similarly show that the literature varies widely across settings, scales, and methods. For this reason, the field is strong in capturing lived and perceived insecurity, but still

weaker in producing standardized and comparable metrics that can be directly mobilized in planning-oriented evaluation.

3.3 Methodologies for Capturing Avoidance, Constrained Mobility, and Restricted Use of Space

A second, smaller but conceptually decisive strand examines how insecurity reshapes women's actual urban behaviour. In the 89-paper subsample, this includes studies on path choice, walking routes, avoidance behaviour, nighttime restrictions, constrained mobility, park use, and reduced stay behaviour. Methodologically, this strand is built through route-based evaluations, self-reported mobility adjustments, behavioural proxies, surveys on transport or park use, and mixed-method designs. Good examples include Cui et al. [27] on women-oriented evaluation of walking routes to mass transit, Panahi et al. [46] on women's walking behaviour, Kaştaş-Uzun and Şenol [47] on women's park use, Raina and Mandal [48] on women's experiences in urban parks, and Saigal et al. [49] on the role of safety in declining public-transport use. This strand is analytically crucial because it makes visible the transition from perceived insecurity to restricted urban practice: fear does not remain an attitude, but becomes altered route choice, selective use of public space, temporal withdrawal, or modified travel behaviour. Reviews by Dubey et al. [15] and te Braak and van Tienoven [16] both underline that women's safety concerns reduce the use of public space, limit outdoor activity, and affect everyday mobility. Yet methodologically the strand remains less consolidated than perception modelling. In many studies, behavioural consequences are identified descriptively or through isolated variables, but are not yet converted into standardized indicators of burden, constrained access, or loss of autonomy.

3.4 Methodologies for Measuring Accessibility to Socio-Economic Opportunities

A further strand in the subsample addresses accessibility to jobs, services, amenities, and other urban opportunities. This family is especially important because it introduces a shift from mobility-centred to opportunity-centred thinking. Rather than asking only where women feel unsafe, it enables the question of which opportunities become less reachable because of insecurity, time constraints, mode limitations, and unequal transport systems. In methodological terms, the subsample includes location-based accessibility indicators, cumulative opportunity measures, potential or gravity-based accessibility, transport accessibility frameworks, and capability-based approaches. Rahmah et al. [30] are particularly important here, because their systematic review shows that only a small subset of accessibility studies explicitly focuses on women, and that most of those studies rely on catchment-based methods. Menon [34] extends this discussion by proposing a capability-based framework for women's mobility inequity, while Noor and Iamtrakul [32] connect women's access to public transport with institutional and policy constraints. More broadly, accessibility and equity-oriented reviews such as Dumedah et al. [43], alongside transport-indicator work such as OECD/ITF [19, 22], provide a methodological repertoire—cumulative, gravity-based, activity-based, and constraint-based measures—that is directly relevant for this agenda. The limitation, however, is that these tools are still only partially integrated with the women's safety literature. The

methodological building blocks exist, but the bridge between perceived insecurity and unequal access to socio-economic opportunities is still underdeveloped.

3.5 Methodologies for Measuring Time, Cost, and Mobility Burden

Among the 89 papers, the least developed but most policy-relevant family concerns the measurement of time, cost, and mobility burden. This strand focuses on how insecurity generates additional travel time, safer but more expensive modal choices, greater dependence on accompaniment, affordability problems, and temporal penalties linked to route or activity avoidance. The relevant methods are drawn mainly from transport equity, affordability, and gender-equity measurement rather than from women's safety studies in a narrow sense. Bhandari et al. [31] explicitly identify access, travel behaviour, public transit, mode choice, safety, cost, and time as key dimensions for measuring gender equity in transportation. Oviedo et al. [42] show that affordability and accessibility are closely linked and review how transport affordability has evolved into a framework for understanding barriers to access, forgone trips, and transport-related social exclusion. Dumedah et al. [43] likewise frame equitable transport access in terms of affordability, reliability, safety, and participation in valued activities, while Noor and Iamtrakul [32] and Araya et al. [50] bring these issues closer to women's lived experiences in public transport. Even so, the strand remains thin in operational terms. Only a small subset of the subsample actually formalizes indicators such as extra travel time, additional transport expenditure, escorted mobility dependence, or explicit temporal penalties. In most cases, burden is acknowledged conceptually, but not translated into standardized and comparable metrics.

3.6 The Big Gap: Methodologies for Linking Urban Insecurity to Socio-Economic Participation

The least consolidated and most innovative area of the 89-paper subsample concerns the link between insecurity and socio-economic participation. This is the point at which the literature moves beyond measuring fear, unsafe environments, or constrained mobility, and begins to ask how insecurity affects participation in work, education, services, leisure, and broader urban life. In the subsample, this strand appears through labor-market and employment outcomes, access to services and education, reduced public-space use, wellbeing proxies, transport participation, and early attempts at composite or integrated indicators. Araya et al. [50] explicitly connect personal safety in public transport to women's participation and employment; Alam and Bagnoli [51] discuss the role of public transport in women's economic empowerment; Kurshitashvili et al. [36, 52] move toward a mobility and gender index; and several reviews show that reduced safety and constrained access have consequences for wellbeing, participation, and urban opportunity [15, 30, 43]. Yet this strand remains methodologically uneven. Existing studies are much stronger in measuring insecurity than in quantifying what insecurity costs in terms of access, participation, burden, and unequal opportunity. In the current subsample, the socio-economic dimension appears as an emerging horizon rather than a fully stabilized methodological field. This is precisely the main gap identified by the proceedings: the

next step is not only to map unsafe places more accurately, but to build robust indicators that show how fear redistributes urban opportunities in unequal ways.

4 Discussion

The 89-paper methodological subsample shows a clear imbalance. The literature is now methodologically strong in measuring women's fear, perceived insecurity, and their visual, spatial, and environmental correlates, through surveys, interviews, GIS-based mapping, street-view imagery, GeoAI, and multimodal models [15, 16, 37, 38, 53, 54]. By contrast, far fewer studies translate these conditions into indicators of accessibility, burden, opportunity, or participation. Even when insecurity is linked to avoidance, constrained mobility, or reduced use of public space, these effects are rarely operationalized in standardized and planning-ready terms. In this sense, the literature remains stronger in diagnosing women's fear than in measuring its socio-economic implications. In this paper, socio-economic impact is understood not in terms of aggregate economic performance, but as the effect of gendered urban insecurity on access, burden, and unequal opportunity. The most relevant impacts therefore include reduced accessibility to jobs and services, additional travel time and costs, dependence on safer but less efficient mobility options, reduced use of public space, and lower participation in work, education, leisure, and civic life [30, 31, 33, 42]. The review shows that the literature is beginning to identify these effects, but is still weak in converting them into robust indicator systems. The main methodological gap is therefore not the measurement of fear itself, but the limited ability to show how fear produces measurable inequalities in access to urban opportunities.

5 Conclusions

This paper has examined the methodological landscape through which women's fear, perceived insecurity, and gendered urban inequality are currently studied in urban contexts. The review shows that the literature has made substantial progress in the measurement of women's perceived insecurity and in the modelling of its visual-spatial correlates. Within the methodological corpus, methods for capturing fear and perceived safety are now highly developed and increasingly hybrid, combining surveys, interviews, spatial analysis, street-view imagery, computational perception modelling, and other data-driven approaches. This confirms that the field is no longer limited to conventional fear-of-crime questions, but has evolved into a more complex methodological domain capable of integrating built-environment, social, individual, and visual dimensions.

At the same time, the review highlights a clear imbalance in the current state of the literature. Existing studies are considerably stronger in measuring perceived insecurity than in quantifying what insecurity costs in terms of access, participation, burden, and unequal urban opportunity. A first important strand captures the transition from perceived insecurity to restricted urban practice, showing how fear reshapes route choice, avoidance behaviour, use of public space, nighttime mobility, and everyday patterns of movement. A second and equally important strand begins to shift the analytical

focus from unsafe places to unequal access, asking which socio-economic opportunities become less reachable because of fear, constrained mobility, and gendered urban conditions. A third, smaller and still weakly consolidated strand addresses the temporal, financial, and organizational burdens associated with insecurity, including travel time penalties, higher mobility costs, escorted dependence, and reduced autonomy. Together, these strands indicate that the key challenge is no longer simply documenting where women feel unsafe in cities, but measuring how gendered urban insecurity reshapes everyday access to opportunities across urban space.

From a methodological perspective, the review suggests that future gender-sensitive urban indicator systems should move beyond the measurement of fear alone and incorporate spatialized metrics of access, burden, participation, and unequal urban opportunity. This does not mean abandoning perception-based methods; on the contrary, it means connecting them more systematically with accessibility analysis, behavioural indicators, and socio-economic evaluation. In practical terms, such planning-ready indicators might include, for example, a Safe Access to Essential Services Index, measuring the proportion of key urban opportunities reachable under conditions perceived as safe. The most promising direction for future research lies precisely in building stronger bridges between these methodological traditions, so that fear can be understood not only as a subjective condition or a spatial pattern, but also as a mechanism that redistributes opportunities unequally across the city. A further development of this research could involve a more detailed differentiation by urban context—such as metropolitan areas, inner cities, and other urban settings—as well as a closer investigation of whether particular zones showing greater vulnerability to the phenomenon.

The main contribution of this proceedings is therefore methodological. Rather than offering a full theoretical literature review, it provides a structured reading of the methods currently used to operationalize women's perceived insecurity and its wider urban implications. In doing so, it identifies both the strengths of the field—particularly its recent visual, computational, and hybrid turn—and its main limitation, namely the still limited capacity to translate gendered urban insecurity into standardized, planning-ready indicators. The next methodological challenge is not simply to map where women feel unsafe, but to develop robust and transferable tools capable of measuring how insecurity produces additional daily burdens, constrained access, and socio-economic disadvantage in ways that urban planning can meaningfully address.

Acknowledgments. This literature review was originally developed in the context of research carried out for a Fondo Italiano per la Scienza (FIS) 2025 project proposal, which was not funded, and it now forms part of the theoretical foundation of the author's European Research Council (ERC) 2026 research project.

Funding. This research received no external funding.

Declaration of AI Usage. During the preparation of this manuscript, I used artificial intelligence-based tools to support analyses, language refinement, grammar and style improvement, and English editing. All outputs generated by these tools were critically reviewed, edited, and approved by the authors, who take full responsibility for the final content and language quality.

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

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O. Gervasi et al. (Eds.): ICCSA 2026 Workshops, LNCS 16762, pp. 675–676, 2026.
https://doi.org/10.1007/978-3-032-30524-4

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