TWIN2EXPAND

RESEARCH REPORT

DELIVERABLE 4.5

twinning towards
research excellence
in evidence-based planning
and urban design

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TWIN2EXPAND

Document Description: The Research Report [henceforth RR] presents the objectives, methodology, and outcomes of the Research Project conducted within Work Package 4 of the TWIN2EXPAND project.

This deliverable constitutes Deliverable 4.5 for Work Package 4 of the TWIN2EXPAND project.

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Executive Summary

The Research Report (Deliverable 4.5) presents the objectives, methodology, and outcomes of the Research Project conducted within Work Package 4 (WP4) of the TWIN2EXPAND project. The project addresses a central challenge in contemporary urban planning and design: how to operationalise Evidence-Based Design and Planning (EBDP) across different planning contexts, scales, and institutional environments, particularly under conditions of data scarcity, fragmentation, and climate urgency.

The report responds to two key limitations in current EBDP practice, addressed in three research packages. First, many established spatial analytical methods are highly data- and resource-intensive, restricting their applicability to data-rich regions with strong institutional capacity; addressed in Research package 1 and 2. Second, most EBDP approaches prioritise socio-economic performance while insufficiently integrating ecological dimensions, despite the growing urgency of climate change and biodiversity loss; addressed in Research Package 3.

Research Package 1 investigates the applicability of established EBDP methods across different planning contexts and scales, using Cyprus as a case study. A comprehensive data audit reveals significant fragmentation and uneven accessibility of spatial and socio-economic datasets, shaped by institutional constraints and the island's political division. Based on this audit, the project defines a minimum data model capable of supporting core EBDP analyses. Two street network modelling workflows, a hybrid, manually curated model and a fully automated, open-source model, are systematically compared. Results show that while manual models remain analytically robust, automated, less data-intensive workflows can produce comparable spatial patterns for centrality and accessibility, offering a scalable alternative. Three real-life case studies in different scales demonstrate the practical application of these methods. An EBDP Applicability Matrix is introduced as a diagnostic tool to assess technical feasibility and institutional readiness, showing that successful EBDP implementation depends on the alignment between analytical capacity and stakeholder commitment.

Research Package 2 focuses on developing less data-intensive spatial models to lower barriers to EBDP adoption. The report introduces the SOAR framework (Scalable, Open, Automated, Reproducible) as a methodological foundation for lightweight yet robust spatial analysis. Relying exclusively on open European data and automated workflows, the SOAR framework generates key indicators related to connectivity, centrality, accessibility, and functional reach. The framework demonstrates that meaningful policy-relevant evidence can be generated even in data-constrained environments, supporting early-stage planning, comparative analysis, and cross-context learning while maintaining transparency and reproducibility.

Research Package 3 extends EBDP beyond the state-of-the-art, introducing a social-ecological framework, integrating ecological performance into evidence-based planning and design. Grounded in the emerging field of Social-Ecological Urbanism, the research develops a conceptual and analytical model linking urban form to human–wildlife interactions. An empirical study using Passive Acoustic Monitoring examines the relationship between urban density and bird biodiversity in compact urban environments. Findings show that dense urban form does not inherently reduce biodiversity; instead,

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ecological outcomes depend on habitat quality, green connectivity, and spatial configuration. Besides the scientific value of the empirical findings, which challenge deterministic assumptions about density and biodiversity, this work demonstrates how social-ecological indicators can be quantitatively assessed and embedded within EBDP workflows alongside socio-economic measures.

The final chapter synthesises the methodological, empirical and policy contributions of WP4 and situates the findings within key EU policy frameworks. Collectively, WP4 report advances EBDP by demonstrating how it can be adapted, scaled, and expanded to operate across diverse planning contexts and to address both social and ecological challenges. By combining minimum data models, automated workflows, institutional diagnostics, and empirical evidence, the research provides a transferable and future-oriented EBDP framework for more resilient, inclusive, and environmentally responsible urban planning and design. The outcomes of WP4 directly support Horizon Europe priorities related to sustainable urban development, climate adaptation, biodiversity protection, and evidence-informed policymaking. By lowering technical and data barriers, the project enhances the transferability of EBDP across European regions, including small municipalities and data-constrained contexts. The integration of social-ecological performance strengthens the capacity of planning and design practices to address climate and biodiversity objectives in a holistic manner.

Apart from answering the research questions and meeting the research objectives, the project produced concrete scientific outputs such as the EBDP Applicability Matrix, the Cyprus data audit, the SOAR spatial data model, an original bird species occurrence dataset from passive audio recordings, replicable automated and manually curated modelling workflows and a conceptual and analytical model for integrating social-ecological performance in EBDP. Besides the methodological developments, new empirical evidence was produced within the project giving an original insight on a topical question between urban development and its ecological implications, focusing on biodiversity. Within this research project, four scientific papers have been published or submitted in high-ranked scientific journals. The produced workflows, codes and datasets have been published in open-access repositories. These outputs together with conference papers and presentations, policy briefs, fact sheets, popular science publications, blogs and podcasts disseminate the project's findings to the scientific community, practitioners and civic society.

Acronyms and Abbreviations

EBDP = Evidence-Based Urban Design and Planning
T2E = Twin2Expand project
RPP = Research Project Plan
WP = Work Package (of T2E project)
T = Task (of T2E project)
D = Deliverable (of T2E project)

UCY = University of Cyprus
UCL = University College London
SSL = Space Syntax Limited
SMoG = Spatial Morphology Group

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1. Introduction

1.1. Background

Contemporary cities are facing a range of complex and urgent challenges, including rapid climate change, environmental degradation, resource scarcity, mobility and accessibility issues, energy inefficiency, and deepening social and spatial inequalities. Urbanization continues to reshape territories at unprecedented speed, while the quality of urban environments remains unevenly distributed. Cities are not only sites of vulnerability but also of innovation, places where collective actions, new technologies, and adaptive governance structures can generate transformative solutions and create physical and social assets. Urban planning and design are central to addressing these challenges and capitalise on the potential. They bear the responsibility of mitigating environmental risks while creating the conditions for inclusive, liveable, and resilient urban environments. However, the multifaceted nature of urban systems demands approaches that are both analytically rigorous and contextually adaptive. Data-driven analysis, cross-disciplinary collaboration, and transparent communication of research findings are increasingly essential for effective and sustainable urban governance.

In this context, **evidence-based approaches to urban design and planning** have become essential. They provide systematic ways of ensuring that planning and design decisions are grounded in reliable research and empirical understanding of how spatial form, social behaviour, and environmental performance interact. By doing so, they reduce uncertainty, enhance accountability, and increase the likelihood of long-term success in urban interventions. By embedding rigorous analytical and evaluative methods into the design and planning process, evidence-based approaches to urban design and planning help ensure that urban development aligns with sustainability targets and societal well-being and that urban challenges are addressed effectively and sustainably, based on sound knowledge and understanding of the multidimensional impacts of design and planning decisions. Within this context, Evidence-Based Design and Planning (EBDP) has been recognised as a critical field and a concrete urban design and planning methodology to address the multifaceted challenges that cities face today, such as climate change, spatial inequality, public health, and well-being (Wiley 2017).

1.1.1. Evidence-Based Design and Planning (EBDP). Concept, Origins and Key Challenges

Evidence-Based Design and Planning (EBDP) refer to the systematic use of the best available empirical evidence to inform design and planning decisions. EBDP's intellectual lineage traces back to Evidence-Based Medicine (EBM), which revolutionized clinical practice by systematizing the use of research evidence for decision-making. The Centre for Health Design defines evidence-based design (EBD) as *"the process of basing decisions about the built environment on credible research to achieve the best possible outcomes"* (Martin, 2009). While this approach originated in healthcare architecture through seminal works such as Ulrich's (1984) study on hospital environments and patient recovery, its principles have since expanded across multiple design and planning fields.

In the context of urbanism, EBDP represents an integrative and iterative methodology that connects **scientific knowledge, design intuition,** and **stakeholder experience.** It aims to base spatial interventions not merely on precedent or professional convention, but on systematically collected and critically evaluated evidence. This process enhances both the **accountability** and **effectiveness** of urban decisions, ensuring that they contribute to measurable improvements in environmental performance, social well-being, and economic vitality (Hamilton, 2003; Mullins et al., 2015; Pilosof & Grobman, 2021).

The idea that planning should be grounded in evidence has deep intellectual roots. Patrick Geddes' survey/analysis plan framework already highlighted the importance of systematic observation and contextual analysis, advancing the principle that interventions should follow a process of "diagnosis before treatment" (Batty and Marshall, 2017). Later, critiques of modernist urban renewal by Jane Jacobs (2016) and Christopher Alexander (2018) reinforced the need to anchor planning in the lived realities of urban life rather than abstract, ideology-driven models. Their contributions provided an early foundation for iterative, feedback-oriented logics that continue to shape contemporary evidence-based approaches.

Evidence-based design and Planning have been defined in diverse ways across the literature. Davoudi (2015) describes it as a systemic approach combining data, spatial analysis, and best practices to guide urban development. Brown and Corry (2020) highlight its role in integrating quantitative and qualitative research to produce responsive and sustainable urban spaces, while Batty (2018) emphasises computational and data-driven methods, including real-time analytics and spatial modelling. Innes and Booher (2015) stress its participatory dimension, framing it as a corrective to purely expert-led processes through empirical validation and stakeholder involvement. Newman and Kenworthy (2015) define it as an iterative process where interdisciplinary assessments converge to support sustainable urban solutions while Steinitz (2012) further underlines the importance of computational intelligence and simulation for decision-making in complex urban systems.

Recent reviews (Karimi et al 2025) synthesise these perspectives, showing that while definitions of EBDP vary, they consistently converge on **three key elements: reliance on empirical evidence, integration of spatial analysis, and incorporation of stakeholder participation.** At the same time, EBDP must be understood in relation to related paradigms such as Research-Informed Design (RID) and Data-Driven Design (DDD) (Peavey & Vander Wyst, 2017). While RID draws primarily on targeted research to inform design intentions, and DDD privileges algorithmic optimisation of large-scale datasets, EBDP combines rigorous data analysis with contextual interpretation and participatory engagement, emphasising iteration and adaptability (Table 1). This combination allows EBDP to balance the analytical precision of data-driven methods with the contextual sensitivity of design thinking. In EBDP, evidence is understood in gradients, from anecdotal or precedent-based insights (low-level evidence) to causal, statistically validated findings derived from large datasets (high-level evidence). Importantly, evidence is not synonymous with "proof," thus EBDP seeks to operationalize varying levels of certainty within the real-world design constraints (Pilosof & Grobman, 2021).

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Table 1. Differences of EBDP to DDD and RID. Source: Adapted from Peavey & Vander Wyst, 2017

Approach	Evidence Base	Human Judgment	Workflow Emphasis
Research-Informed Design (RID)	Targeted, bounded research findings	High	Broadly informing design processes
Evidence-Based Design (EBD)	Diverse evidence types	Contextual	Applied narrowly to specific problems
Data-Driven Design (DDD)	Large datasets, algorithmic outputs	Low	Automated, optimisation-focused

Although EBDP's importance and necessity has been recognised, EBDP's diffusion into urban design and planning practice has been limited. As Pilosof and Grobman (2021) argue, EBDP is still far from being common practice in planning and design. Its full implementation requires fundamental shifts in how knowledge is produced, shared, and applied, as well as how professionals are trained to engage with research evidence. A recurring challenge lies in the dissemination and accessibility of evidence. Whereas medicine has built a robust infrastructure of systematic reviews, databases, and evidence hierarchies, urban disciplines lack comparable mechanisms for aggregating and evaluating design-relevant research (Sailer et al., 2009). Much of the existing knowledge about how spatial form influences social behaviour, mobility, health, or environmental performance remains dispersed across disciplines and methods, making synthesis and generalization difficult. As a result, the translation of research evidence into actionable planning knowledge remains partial and context-specific (Slunge et al., 2017; Karimi, 2020, Berghauser Pont 2024).

Slunge et al. (2017) show that a great deal of policy-relevant research is under-used or not used at all in policy planning or implementation and often research is not used to inform decisions but rather to back up decisions already made (e.g. Amara et al. 2004). Decision makers often don't 'know where to look' for evidence and struggle to distil practical implications from it (Hurleya et al. 2016). Berghauser Pont (2024) highlights the pressing need to consolidate the methodological foundations of EBD across scales and contexts. She notes that while evidence-based approaches are gaining traction, they often remain fragmented, lacking shared definitions of "evidence" and unified models that connect urban morphology, social outcomes, and ecological performance.

A further challenge lies in education and professional culture. The urban design discipline, often characterized by creative intuition and "wicked problem" solving (Rittel & Webber, 1973), must reconcile this tradition with the analytical rigour required by evidence-based methods. As Karimi (2020) observes, the design process is inherently iterative — guided alternately by logic and intuition. EBDP offers a framework to structure this process through measurable evaluation and continuous feedback, offering tools for both critical reflection and quantitative assessment. In this sense, EBDP represents both a methodological framework and a cultural shift toward more reflective, accountable, and adaptive design and planning practice. It redefines how planning and design disciplines understand "knowledge", moving from intuition-led and precedent-based practice toward a practice grounded in continuous learning, data transparency, and cross-disciplinary collaboration.

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1.1.2. The Role of Spatial Analysis and Quantitative Data in EBDP

EBDP employs a targeted application of a variety of information and methods for the generation of evidence that can guide planning and decision-making process. The generation of evidence involves the use of various sources and data inputs that contribute to the understanding of the factors that influence the built environment. A central methodological challenge in advancing EBDP lies in translating research evidence into forms that can meaningfully inform real-world spatial decisions. While the conceptual and theoretical basis of EBDP is well established, its practical implementation often depends on the availability, quality, and comparability of spatial data. **Quantitative spatial analysis**, including methods such as spatial modelling, network analysis, morphological analysis, accessibility mapping, and environmental performance simulation, provides a critical bridge between abstract research evidence and tangible design action. It offers the means to quantify relationships between urban form, human behaviour, and environmental performance, enabling planners and designers to describe the existing built environment, test hypotheses, visualize spatial outcomes, and evaluate design alternatives within a common analytical framework.

Quantitative and data-driven approaches play an essential role in overcoming another of EBDP's enduring weaknesses: its heavy reliance on context-specific or qualitative evidence that, while rich in insight, is difficult to reproduce or compare. The need to integrate social, economic, and cultural factors to physical structures of cities involves moving beyond descriptive analyses and embracing quantitative inquiries to assess urban dynamics (Karimi, 2023). By integrating measurable indicators and spatial datasets, EBDP can move toward a more systematic, transparent, and transferable practice. Spatial models are instrumental in this framework, since they offer a systematic approach to the analysis and interpretation of spatial data. Spatial models allow for the comparative assessment of urban contexts, making it possible to generalize findings across scales and geographies; a prerequisite for evidence-based planning to mature into a globally relevant methodology. These models can help planners and designers to visualize and comprehend relationships within the built environment with insights into spatial arrangements, connectivity patterns, and the general dynamics of urban spaces (Van Nes and Yamu, 2021).

However, as Meta Berghauser Pont (2024) notes, developing such analytical capacity is far from straightforward. The integration of spatial models encounters significant challenges, particularly within data-scarce urban environments (Yeh, 1991; Ahlström, Pilesjö and Lindberg, 2011; Morales et al., 2019). The diversity of data sources, the uneven availability of spatial information, and the challenges of integrating social, economic, and ecological datasets all complicate the development of a systematic evidence base for urban decision-making. The potential of spatial quantitative analysis is therefore intertwined with the need for adaptable, scalable models that can function across diverse planning contexts, from data-rich metropolitan regions to data-scarce environments.

Against this background, the present research project identifies a key opportunity: to strengthen the quantitative and spatial analytical foundations of EBDP by developing comparative, adaptable, and less data-intensive models. These models aim to, first, make evidence-based approaches more universally applicable, bridging the gap between theory and practice, and, second, align EBDP more closely with the complex socio-ecological realities of contemporary urbanism.

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1.1.3. Identified Gaps in Spatial Analytical Models for EBDP

Two major gaps have been identified through an extensive review of the state-of-the-art of current spatial analytical methodologies and data models, conducted within the Twin2Expand project (Deliverable D3.2).

1. **Limited applicability and generalisability of EBDP across contexts and scales.**

Current EBDP analytical methods are often developed for specific geographic regions (e.g., UK, northern Europe) and institutional settings with robust data infrastructures and high analytical capacity. This limits their transferability to regions where data availability, institutional resources, and planning capacities are lower. Urban data scarcity refers to the limited availability, accessibility, or reliability of spatial and statistical information, such as land-use records, building footprints, street networks, and socioeconomic indicators, that underpin analytical planning and modelling. In many regions, the absence of open, comprehensive, and up-to-date datasets, combined with weak institutional capacity and restrictive data policies, makes it difficult to carry out evidence-based analyses and hinders the broader adoption of EBDP (e.g. Morales et al. 2019). An extensive data audit carried out within the T2E project for Cyprus (see section 2.2), highlighted the multiple challenges faced regarding coverage, completeness and accessibility of national spatial data on the built environment. According to the Open Data Inventory (ODIN), open statistics regarding the built environment are even more severely lacking, giving a zero score to Cyprus as insufficient data were published to meet the minimum threshold for scoring, while Sweden scored the maximum 100 in the same category. Even in data-rich environments though, most EBDP applications focus on specific project scales, for instance, the building or neighbourhood level, with little attention to how methodologies might adapt across scales, from small interventions to metropolitan strategies. There is a clear need for **reliable, flexible, adaptive,** generalisable **and comparable analytical and data models** that can support practitioners globally, regardless of data or resource constraints and across project scales.

2. **Insufficient integration of social-ecological dimensions in EBDP approaches.**

Most established EBDP analytical methodologies (e.g. Space Syntax, Place Syntax, Spacematrix) emphasize socio-economic impacts (e.g., accessibility, walkability) but often neglect ecological effects of design and planning interventions. For example, densification projects may be assessed positively for promoting sustainable mobility, but their potential adverse impacts on microclimate, biodiversity, and green connectivity are often overlooked (Berghauser Pont et al. 2021). On the other hand, while Environmental Impact Assessments (EIAs) are now standard practice in urban development processes, they often remain procedural tools rather than integrative frameworks. EIAs typically assess environmental effects in isolation from social, spatial, or economic dynamics, focusing on compliance and mitigation rather than systemic relationships or long-term performance. As a result, they seldom capture the complex interdependencies between ecological conditions, spatial configurations, and human well-being that shape urban sustainability. Moreover, EIAs are usually applied after design decisions have been made, limiting their potential to inform early planning and design stages. Consequently, even where environmental assessments exist, they do not substitute for a holistic, evidence-based approach capable of evaluating and balancing the combined social,

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ecological, and economic impacts of urban interventions. In an **era of climate emergency**, to address sustainability holistically, EBDP must evolve towards an **integrated socio-ecological framework** capable of assessing trade-offs and synergies between environmental, social, and economic outcomes. To that end, there is a need to strengthen the analytical foundations, the data models, as well as the empirical evidence base that can support such integrated analytical and impact assessment frameworks.

1.2. Research Objectives

In response to the gaps identified in 1.1.3, the project defines three interrelated research objectives, each forming a distinct research package:

Objective 1: Assessing applicability of EBDP in different planning contexts and scales
(Led by the University of Cyprus)

The first objective is to explore how established Evidence-Based Design and Planning (EBDP) methods and practices can be adapted and applied in planning contexts with limited data availability and institutional capacity, using Cyprus as a case study. The question is 'what are the challenges and barriers of applying established EBDP analytical methods, spatial models and tools focusing on socio-economic performance in different planning contexts (e.g., data availability and quality as well as institutional capacity)?' The project investigates the application of established urban methodological and analytical approaches, such as Space Syntax and Place Syntax, to case studies in the Cypriot context at different spatial scales. In doing so, the project identifies the barriers and enablers of implementation, sets the minimum requirements for a comprehensive and reliable analytical spatial model that adheres to evidence-based principles, and outlines how different methods best fit specific project types, scales, and institutional conditions. The question is 'how does a less data-intensive analytical model perform in the assessment of urban interventions in comparison to a data-intensive model?'. Answering this question gives insights on how the challenges can be overcome in other data challenging or data scarce urban environments. This objective is pursued via Research package 1.

Objective 2: Developing less data-intensive EBDP models
(Led by University College London)

The second objective is to investigate the use of open analytical models that are less data-demanding but still rigorous and reliable. The objective is to reach new adaptive, comparable, and generalisable EBDP methods suitable for diverse planning environments and governance frameworks. These models aim to make EBDP more accessible to practitioners working in data-scarce environments and to enhance its flexibility across different types of projects. The question is 'what should a 'light-weight model' include at the minimum to be effective and accurate in assessing the impacts of design and planning interventions from a socio-economic and a social-ecologic perspective'? This objective is pursued via Research package 2. Besides the independent outcomes of this research package, the developed data models and workflows feed into Research Package 1 and Research Package 3.

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Objective 3: Integrating social-ecological performance in EBDP
(Led by Chalmers University of Technology)

The third objective is to expand the EBDP framework to include social-ecological dimensions by developing a new conceptual model, measures, spatial models and tools capable of assessing urban interventions in terms of their combined social and ecological impacts. The objective is to exemplify a comprehensive analytical framework from conceptual modelling to real-world data collection that can support model validation and integrated social-ecological assessment. In doing so the project identifies the methodological challenges regarding the integration of social-ecological assessment in EBDP. The third objective is pursued via Research Package 3.

1.2.1. Overall research design of WP4

The research objectives of WP4 (Application of EBDP in Different Planning Contexts) are pursued with 3 interrelated Research Packages (Research Package 1, 2 and 3) These respond to Tasks 4.2. and 4.3., which include the research activities of WP4 (Figure 1). In addition, Tasks 4.1 and 4.4 supported, coordinated and disseminated WP4's research activities and findings. This Research Report (RR, Deliverable 4.5) primarily reports on the research conducted within Tasks 4.2 and 4.3 and disseminated via Task 4.4.

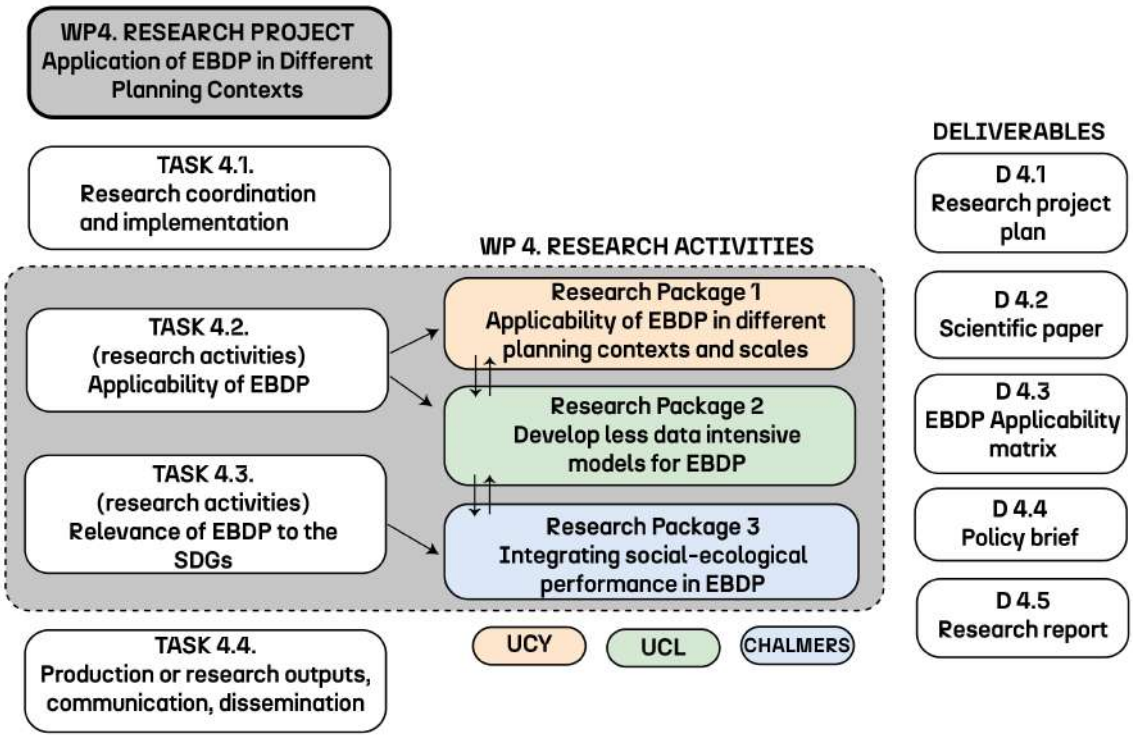

Figure 1. Pert chart of WP4. Colours indicate the leading partner

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1.3. The Case of Cyprus: Context and Institutional Challenges

To assess the applicability of the Evidence-Based Design and Planning (EBDP) framework in environments marked by data constraints and institutional fragmentation, **Cyprus** was selected as a representative case study. As an island nation, situated at the intersection of Europe, Asia, and Africa, Cyprus presents a uniquely complex geopolitical and urban landscape where historical preservation, rapid urbanisation, and environmental pressures converge. The country's planning system operates within a fragmented and uneven data environment: spatial datasets vary in accessibility, official information is often incomplete or siloed across ministries, and data auditing processes frequently lack transparency (see section 2.2. for complete Data audit). These limitations restrict the reliability of conventional, manually developed urban models and underline the need for adaptive and collaborative frameworks that can bridge both **data gaps** and **institutional divides**.

Cyprus is the third largest and third most populous island in the Mediterranean and comprises six major urban areas: Nicosia, Famagusta, Kyrenia, Larnaca, Limassol, and Paphos. Since the 1974 political division, the island has been separated into the internationally recognised Republic of Cyprus in the south and the occupied northern area, which lacks international recognition. Nicosia, the capital, remains the last divided city in Europe, split by the UN-administered buffer zone. This geopolitical division poses a significant challenge for spatial analysis: many official datasets cover only the southern part of the island, while data for the north rely primarily on volunteered geographic information sources. Consequently, the territorial fragmentation of Cyprus directly affects data coverage, consistency, and the ability to develop unified analytical models.

The Cypriot case reflects the broader structural barriers faced by many small and medium-sized states in implementing data-driven and evidence-based planning. These challenges extend beyond the availability or quality of spatial data to encompass institutional capacity, inter-organisational collaboration, and stakeholder engagement. Evidence gathered through stakeholder focus groups conducted within the TWIN2EXPAND project (published in Ricchiardi et al., 2024) and earlier work under the KAEBUP project (Psathiti et al., 2022) consistently points to recurring constraints. These include limited technical expertise, organisational fragmentation, insufficient policy frameworks, weak leadership commitment, and chronic resource scarcity—findings echoed in the broader literature (e.g. Conallin et al., 2022).

At the municipal level, planning departments often lack personnel with training in spatial analytics, Geographic Information Systems (GIS), and data management. Institutional silos and bureaucratic inertia further limit data sharing and inhibit cooperation between agencies. The absence of coherent policy directives and long-term evidence-based planning strategies reduces incentives to embed analytical models into urban development processes. Simultaneously, persistent underfunding constrains investments in digital infrastructure, capacity-building, and continuous training. Leadership and governance structures often operate within short-term political cycles, while stakeholder engagement—though increasingly recognised as essential—remains inconsistently implemented due to limited time, resources, and coordination (Shroff et al., 2017).

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Collectively, these conditions reveal that **data scarcity in Cyprus** is not simply a matter of **missing datasets** but a product of **institutional fragmentation, limited capacity**, and **uneven participation**. Addressing these constraints requires methods that are not only technically adaptable but also institutionally feasible, capable of aligning diverse actors and fostering more collaborative modes of evidence production and use. Within this context, the methodological framework developed in this project examines how EBDP can be operationalised under such challenging conditions, identifying pathways to strengthen institutional readiness, cross-sector collaboration, and data-informed decision-making across the island.

1.4. Report outline

This report is organised into four main parts. It begins with an introductory chapter that sets out the background to the research, presents the objectives of the project, and briefly introduces the Cypriot context as the empirical setting.

The second chapter presents the work of **Research Package 1** and examines how established EBDP methods can be adapted and applied in planning contexts with limited data availability and institutional capacity. Using Cyprus as a case study, the chapter reports on a comprehensive data audit, the development of spatial data models for EBDP, and a comparative assessment of fully automated and hybrid manually curated modelling workflows. It further tests EBDP applicability through three real-life planning case studies and introduces the EBDP Applicability Matrix as a diagnostic tool for assessing technical and institutional readiness.

The third chapter presents **Research Package 2** and focuses on reducing the data and technical barriers to EBDP adoption. It introduces the SOAR (Scalable, Open, Automated, Reproducible) framework and describes the development of lightweight spatial models based on European open data and automated workflows. The chapter demonstrates how robust evidence can be generated in data-constrained environments while ensuring transparency, scalability, and reproducibility.

The fourth chapter presents **Research Package 3** and extends the EBDP framework to explicitly integrate socio-ecological performance, going beyond the state-of-the-art. Grounded in Social-Ecological Urbanism, the chapter develops conceptual and analytical models linking urban form to ecological outcomes. It reports on an empirical study examining the relationship between urban density and biodiversity, demonstrating how ecological indicators can be embedded within EBDP spatial models and workflows.

A short summary and a dissemination box are included at the beginning of each chapter.

The report concludes with a synthesis of findings across all research packages, highlighting their methodological, empirical, and policy contributions to the advancement of EBDP, followed by a summary of the scientific and policy dissemination outputs produced during the project.

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2. Applicability of EBDP in different planning contexts and scales, specifically within the Cypriot context.

Chapter 2 presents Research Package 1 and investigates the applicability of established EBDP methods across different planning contexts and scales, using Cyprus as a case study. A comprehensive data audit (Section 2.2) reveals significant fragmentation and uneven accessibility of spatial and socio-economic datasets, shaped by institutional constraints and the island's political division. Based on this audit, the project defines a minimum data model capable of supporting core EBDP analyses focusing on socio-economic performance (Section2.3). Two street network modelling workflows, a hybrid, manually curated model, and a fully automated, open-source model, are systematically compared (Section 2.4).

Results show that while manual models remain analytically robust, automated and less data-intensive workflows can produce comparable spatial patterns for centrality and accessibility, offering a scalable alternative. The chapter presents an adaptable methodology suitable for diverse planning settings, including those with incomplete or inconsistent datasets, integrating data collection, stakeholder engagement, and spatial modelling combining hybrid and fully automated processes. Three real-life case studies at local, regional and national scales in Cyprus demonstrate the practical application (Section 2.5).

ACADEMIC DISSEMINATION OUTPUTS (full list in 5.5)	
Submitted Scientific Journal Articles	• Abdeldayem et al. (2025a), Environment and Planning B. • Charalambous et al. (2025a), Cities.
Peer-Reviewed Conference Papers	• Ricchiardi et al. (2024a)
Conference Presentations	• Abdeldayem et al. (2025b), ISUF 2025 • Abdeldayem (2025a), CUPUM 2025 • Charalambous (2024), EDMSET 2024 • Charalambous (2025), GU 2025 • Geddes et al. (2025a), UPADSD 2025 • Geddes (2024), KIOS GIS Day • Geddes et al. (2025b), ISUF 2025
Open Datasets (Zenodo)	https://doi.org/10.5281/zenodo.16411132 https://doi.org/10.5281/zenodo.16411188 https://doi.org/10.5281/zenodo.16410668 https://doi.org/10.5281/zenodo.16406543 https://doi.org/10.5281/zenodo.16409080 https://doi.org/10.5281/zenodo.16410567 https://doi.org/10.5281/zenodo.16599000 https://doi.org/10.5281/zenodo.16600733
Open Science & Preregistration	• Ricchiardi et al. (2024b), OSF, https://doi.org/10.17605/OSF.IO/9XKDV

POLICY &PRACTICE DISSEMINATION OUTPUTS (full list in 5.5.)	
Policy Briefs (D4.4)	• Charalambous et al. (2025b) • Charalambous et al. (2025c)
Evidence-Based Policy & Planning Reports	• Abdeldayem (2024a) • Abdeldayem (2024b) • Abdeldayem et al. (2025) • Geddes et al. (2024)
EBDP Applicability matrix (D 4.3)	University of Cyprus, Department of Architecture (2025).

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The EBDP Applicability Matrix (Deliverable 4.3) is introduced as a diagnostic tool to assess technical and institutional readiness (Section 2.5.4), showing that successful EBDP implementation depends on the alignment between analytical capacity and stakeholder commitment.

2.1. Aim and research design

The objective of Research Package 1 is to explore how established Evidence-Based Design and Planning (EBDP) methods and practices can be adapted and applied in planning contexts with limited data availability and institutional capacity, using Cyprus as a case study. The question is 'what are the challenges and barriers of applying established EBDP analytical methods, spatial models and tools focusing on socio-economic performance in different planning contexts (e.g., data availability and quality as well as institutional capacity)?' The research package investigates the application of established urban methodological and analytical approaches — such as Space Syntax and Place Syntax —to case studies in the Cypriot context at different spatial scales. In doing so, the project identifies the barriers and enablers of implementation, sets the minimum requirements for a comprehensive and reliable analytical spatial model that adheres to evidence-based principles, and outlines how different methods best fit specific project types, scales, and institutional conditions. The question is 'how does a less data-intensive analytical model perform in the assessment of urban interventions in comparison to a data-intensive model?' It also gives insights on how the challenges can be overcome in other data challenging or data scarce urban environments.
To reach the objective, Research Package 1 is structured in several distinct stages:

1. **Data Audit and Collection**. Gathering, assessing, comparing available datasets for Cyprus.
2. **Network data models**. Developing workflows for the creation of two network models for Cyprus for spatial analysis with different degrees of automation and data intensity:
    - Manually created model based on open-source data, following established methodologies.
    - Fully automated reproducible model (SOAR), following the methodology developed in Research Package 2 (see Chapter 3)
3. **Model Comparison based on numerical results.** Comparison of manual and fully automated model based on their analytical results for relevant spatial measures.
4. **Testing EPDB methods applicability** in real planning and design projects. Model Comparison based on applicability in projects of different scale and type.

2.2. Data audit

The Data Audit was conducted to examine the availability, completeness, quality and reliability of spatial and socio-economic datasets required for the creation of urban models appropriate for EBDP.

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The data audit also serves as a methodological step to ensure the quality and appropriateness of the urban data available for Cyprus, to address potential gaps or inconsistencies. The audit focused on spatial and socio-economic data.
We reviewed three main data sources:

1. **European databases** (e.g., *Copernicus Land Monitoring Service, European Environment Agency, Eurostat*)
2. **National databases** (e.g., *Cyprus Open Data Portal, Statistical Service, Cadastral Service*)
3. **Crowdsourced datasets** (*OpenStreetMap*)

Each dataset was **evaluated for accessibility, spatial coverage, and granularity**. Table 1 summarizes the data audit results.

Table 2. Summary of Data audit for Cyprus

Source		Data	Type	Open Source
EU databases	European Environmental agency	Urban Morphological zones	Vector	yes
	Copernicus	Impervious Built-up 2018	Raster	yes
		Impervious Density 2018		
		Urban Atlas: Land Cover/ Land use products in Functional Urban Areas (FUA)	Raster/vector grid 1km	
		Urban Atlas: Street Tree Layer		
		Urban Atlas: Population estimates per Urban Atlas polygons		
		Urban Atlas: Building height 2012		
		Tree cover density		
	Eurostat	Clusters based on Population Distribution: high density and urban clusters 2018	Raster	yes
		GEOSTAGEOSTAT 1km^2 population grid	Raster/ vector grid 1km^2	
Local Databases	Open Data Cyprus	Administrative boundaries	Vector	yes
		Postal codes boundaries		
	Official Cadastral Service	Administrative regions	Vector	yes
		urban blocks		no
		Plots		
		Building footprint		
		Building height	Attribute	

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		Building use		
		Street network- road centre line	Vector	yes
		Elevation		
		Land use and development zones	vector and attribute	
	Cyprus Statistical Office	Social and Economic statistics in 1km² granularity	Raster/ Vector grid 1km²/ CSV	yes
		Microdata in greater granularity		no
Crowdsourced Geographic databases	**OSM**	Street network	Vector	yes
		Points of interest	Vector/ Nodes	
		Regional data	Vector	
		Buildings		

Each data source offered relevant types of data based on their origin. For example, **European datasets**, such as Copernicus Land Monitoring Service provided high-quality vector and raster files derived from satellite raw data (Sentinel families), covering expansive areas. Particularly noteworthy was the Urban Atlas information, encompassing population, land cover, and land use classification for Functional Urban Areas (FUA) across 38 European countries. Eurostat service provides population densities based on a 1km² grid which is good for low granularity population density analytics.

National data sources furnished locally relevant data, including simplified road-centre-line street networks (RCL), administrative region boundaries, and postal code boundaries, available as open-source data (DLS Portal, nd). Critical data such as parcel information and building footprints were restricted to paid services provided by the cadastral services. The National Statistical Service offered census data in a 1km² grid, akin to Eurostat's data, with the additional provision of microdata for research purposes under stringent regulations.

OpenStreetMap provided a combination of data types, including street networks and building footprints, albeit with varying granularities and qualities. Notably, regions with higher centrality exhibited higher-quality OSM data, including better coverage of Points of Interest and building footprints.

The data audit highlighted several significant challenges:

- National data services lack a unified data schema that is interoperable with other schemas like OpenStreetMap (OSM), hindering seamless integration and data sharing across platforms.
- Essential research data, such as plot and building footprints, require specialized technical skills to access, rendering them largely inaccessible to the general public.
- The division of the island presents a complex situation where the occupied territories are absent from both EU and national official sources but are included in OpenStreetMap, creating discrepancies in data coverage and availability.

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- In terms of data coming from volunteer geographic information, OSM offered the most inclusive and accessible dataset even though substantial data gaps were evident, particularly outside of city cores.
- OSM remained the sole source of open-source and free POI information, as national services lacked high-granularity data on amenities.

Below we give a detailed account of data sources per theme:

Socio Economic data

Statistical measures for understanding the dynamics of cities are important in the context of the applicability of Evidence-Based Design and Planning (EBDP) methods. Statistical data enables the continuous monitoring and evaluation of a city's performance, offering insights into the trends and patterns that shape its socio-economic landscape. The Open Data Inventory (ODIN) scores can be used to draw insights on statistical data. With a score of 62, Cyprus ranks 56th globally out of 195 countries in the ODIN Global Index in 2022. This score comprises a data coverage sub-score of 50 and a 72 for data openness. Within Europe, Cyprus ranks 31st out of 45 countries, and in the European Union, it is 23rd out of 27 member states (Figure 2). The ODIN scores for Cyprus indicate the presence of significant gaps in data coverage across various assessed categories. In particular, Cyprus performs badly in categories that relate to environment statistics, including data on land use, resource use, energy, pollution, and the built environment. The country received a low score of 38 in this category. Notably, the built environment category received a score of 0 showing that insufficient data were published to meet the minimum threshold for scoring.

CYPRUS

Category Scores

Data Category	Coverage	Openness	Overall
Population & vital statistics	70	90	80
Education facilities	30	100	65
Education outcomes	30	70	50
Health facilities	30	80	55
Health outcomes	40	70	55
Reproductive health	30	80	55
Food security & nutrition	25	70	50
Gender statistics	30	60	45
Crime & justice	50	70	60
Poverty & income	60	70	65
Social Statistics subscore	**40**	**76**	**58**
National accounts	75	80	78
Labor	70	80	75
Price indexes	75	70	72
Government finance	75	70	72
Money & banking	100	70	81
International trade	50	90	75
Balance of payments	100	80	88
Economic Statistics subscore	**77**	**77**	**77**
Agriculture and land use	30	80	55
Resource use	63	70	67
Energy	50	80	69
Pollution	63	80	72
Built environment	0	0	0
Environment subscore	**38**	**62**	**51**
All Categories	**50**	**72**	**62**

Last updated: August 9, 2023

SWEDEN

Category Scores

Data Category	Coverage	Openness	Overall
Population & vital statistics	100	100	100
Education facilities	50	50	50
Education outcomes	50	50	50
Health facilities	50	70	60
Health outcomes	40	50	45
Reproductive health	90	80	85
Food security & nutrition	38	100	72
Gender statistics	60	80	70
Crime & justice	30	80	55
Poverty & income	60	100	80
Social Statistics subscore	**57**	**76**	**67**
National accounts	75	100	89
Labor	60	100	80
Price indexes	75	100	89
Government finance	100	100	100
Money & banking	100	100	100
International trade	100	100	100
Balance of payments	100	100	100
Economic Statistics subscore	**85**	**100**	**93**
Agriculture and land use	70	70	70
Resource use	63	70	67
Energy	100	100	100
Pollution	75	100	89
Built environment	100	100	100
Environment subscore	**81**	**88**	**85**
All Categories	**73**	**88**	**81**

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Figure 2. ODIN Scores for Cyprus and Sweden 2022. Source: Open Data Watch

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Similarly, Cyprus scores 40 in social statistics, covering aspects like population, education, health, gender, crime and justice, as well as poverty and income. Statistics related to the economy show better results, with an overall score of 77. This suggests that data about labour, price indexes, and banking, among other economic indicators, are more readily accessible and retrievable.

Street Network

Street networks have assumed a central role in the development of spatial models, due to their primal support for a diverse array of urban processes. Street network studies encompass explorations into various dimensions, including network structure, connectivity, centrality, typology (Berghauser Pont et al., 2019), and evolution (Kamalipour and Iranmanesh, 2021). Investigations into these aspects contribute to understanding the dynamics of urban environments, with insights and evidence on how cities function and evolve over time. Spatial models that use street segments have become common, primarily due to the widespread availability of data that can be converted into graph representations (Marshall et al., 2018). The proliferation of data sources on road-centre-lines facilitates the creation of large street networks models, allowing researchers and planners to gain insights into urban structures and behaviours by capturing city-wide and local scales (Karimi, 2023).

Street network visual assessment within the context of interest involved the examination of two different datasets: one sourced from the Public Works Department (PWD) of Cyprus and the other from the OpenStreetMap (OSM) network. Related work on comparability between the OSM data and the authoritative data from the PWD in Cyprus indicates that information delivered by OSM for the Cyprus road network is fairly accurate and these datasets are deemed appropriate for a broad scope of applications, including planning, visualization, and navigation, serving as a complementary resource to official data (Demetriou, 2016). From a geographical coverage point of view, the first dataset provides information for the southern area of the island, the territory under effective control of the Republic of Cyprus, while the OSM dataset includes also the street network of the northern occupied area of the island (Figure 3). The official dataset offers authoritative insights into the recognized territory, while OSM dataset contributes information that is crucial for Macro analysis covering the entire island. A closer analysis of the completeness and representation of data available from the Public Works Department datasets shows that the official datasets have considerable gaps, particularly in minor roads and pedestrian paths, essential elements for the construction of accurate models for the capturing of spatial configurations and connectivity patterns of urban spaces at a Micro scale of analysis. The representation of main roads in the official dataset aligns with spatial modelling recommendations, meaning that each road is represented by one line, instead of parallel lines often observed in OSM datasets for similar road types (see Figure 4).

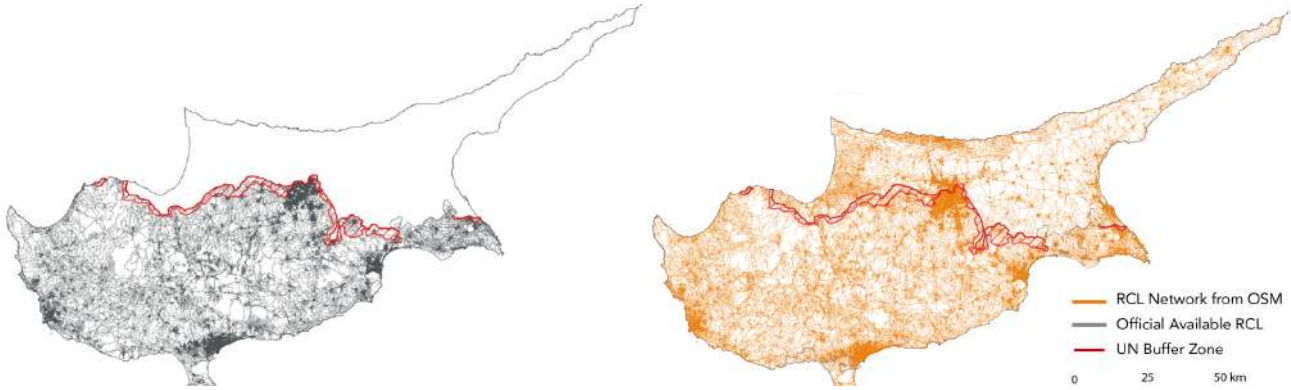

Figure 3. Street Network availability in the Island

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Figure 4. Comparison of street network datasets for the city of Nicosia

Building footprints

In the context of building footprints, the available datasets, again, encompass official data and Volunteer Geographic Information collected by OpenStreetMap (OSM). Regarding the availability of data for building footprints, the official dataset, updated until 2016, provides information, including building footprints, building types, number of floors, and other relevant details crucial for models addressing urban density dynamics and building/ urban block typology (Berghauser Pont, et al., 2019). However, access to these datasets comes at a cost, posing potential challenges, particularly for larger-scale Macro and Meso analyses, while allowing more flexibility for micro-scale interests. On the other hand, the OSM datasets, exhibit notable data gaps (see figures 5, 6). What is more, the decentralized nature of data generation by multiple users results in discrepancies, particularly in terms of information on building floors and types of buildings. A closer examination of the datasets reveals a concentration of available information in the central areas of cities, where user contributions are more accurate. Conversely, peripheral areas experience a decline in data availability and accuracy, highlighting a spatial disparity in the coverage and quality of building footprint information. This disparity presents a unique set of challenges for urban analyses, highlighting the need for careful consideration of data sources and potential strategies to address gaps and inaccuracies in the datasets.

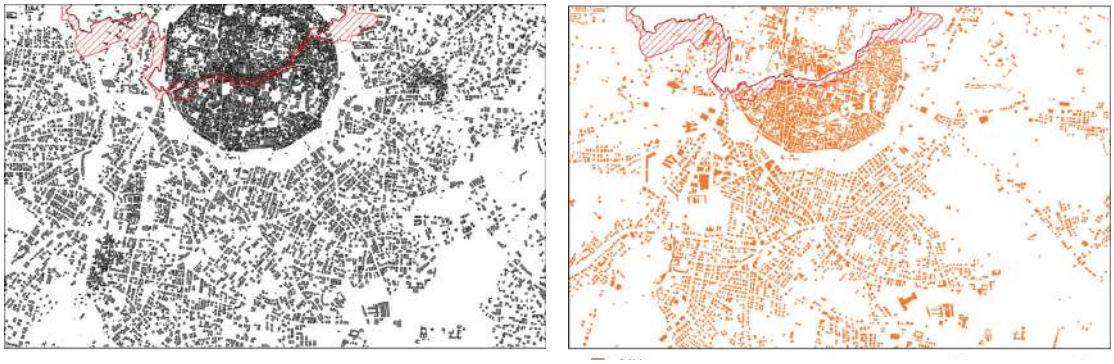

Figure 5. Building footprint datasets available for Nicosia

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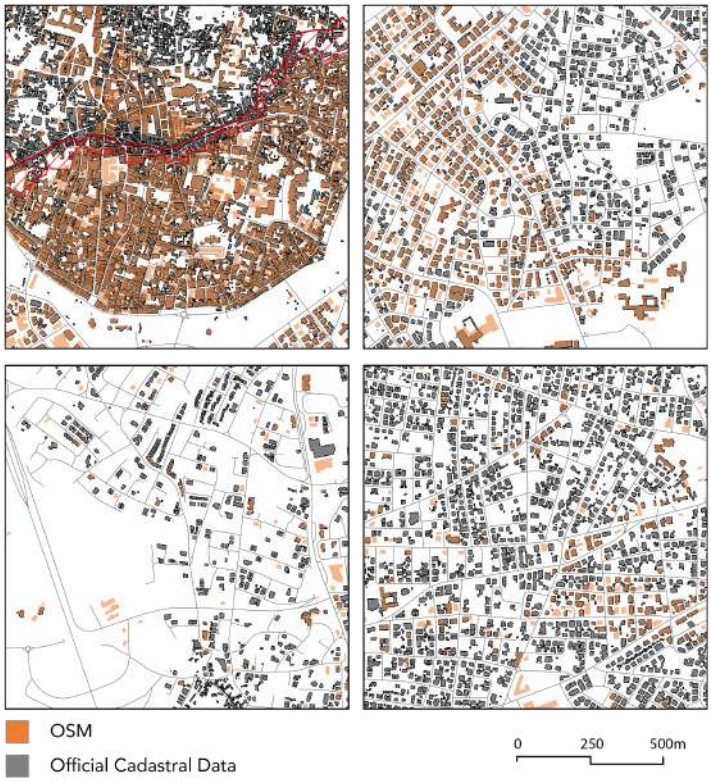

Figure 6. Comparison of datasets for building footprint available for Nicosia

Points of interest

A Point of Interest (POI) refers to a specific location that holds significance or interest for individuals. POIs encompass a diverse array of places, including businesses, landmarks, or destinations that are noteworthy since they serve as a reliable indicator of human interest and activity. Crowdsourced data on POI is commonly employed in studies focusing on urban functional use. The effectiveness of POI data in extracting urban functions from various sources has been used in previous studies (Yang and Qian, 2022, Qin et al., 2022). Two primary resources are available for POIs. The first source refers to databases that offer location-based directories, including those from national mapping agencies, open-source and business platforms. The second source involves location-based social networking data mainly focusing on business- and leisure-related POIs and specific areas (Niu and Silva, 2021).

In the case of Cyprus, Points of Interest (POI) data mainly relies on information sourced from OpenStreetMap (OSM). There is a noticeable limited coverage in peripheral areas of cities in this dataset. While catering and leisure POIs in socially active areas, such as city centres, are well-represented, information on businesses and industry may appear less complete. Establishing a taxonomy for POIs becomes crucial to define the classification of this data and assess any potential over-representation of specific categories within cities. The observed limited coverage in some cases and the potential overrepresentation of certain POI categories in others could pose challenges to conducting an accurate analysis. Such patterns might predominantly highlight commercial and

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entertainment functions in central city areas, overlooking the diversity of urban activities in peripheral zones. This emphasizes the importance of understanding the inherent biases and limitations in the available POI data and in the interpretation of urban models results.

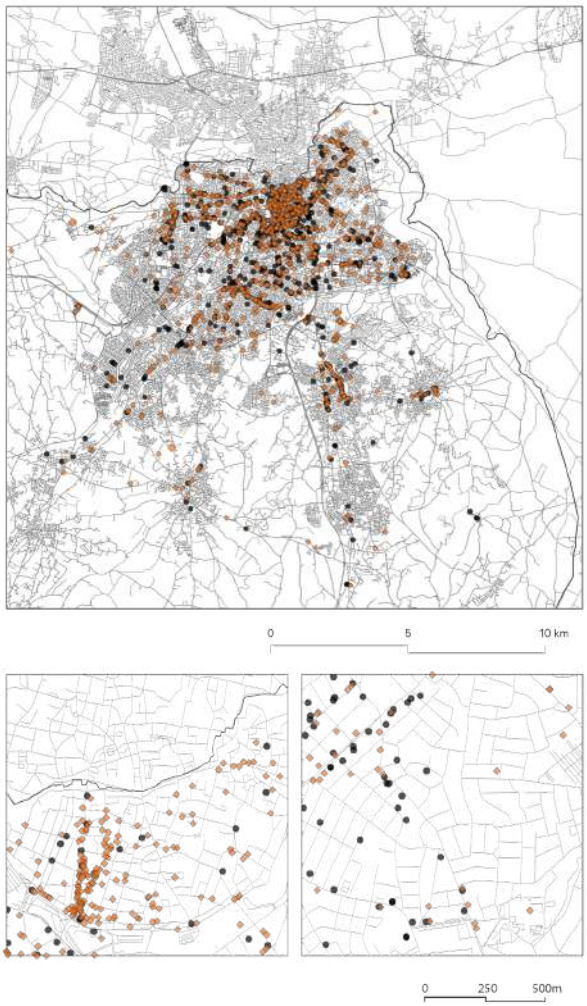

Figure 7. Points of Interest available in OSM datasets for the city of Nicosia.

In **conclusion**, the data audit revealed major inconsistencies between official and volunteered datasets, particularly between the northern and southern regions of Cyprus. No unified data schema currently exists to allow seamless integration across platforms, and critical urban data, such as detailed building footprints and land-use information, remain either incomplete (i.e. OSM) or difficult to access (i.e. official data). The island's political division further complicates data acquisition, especially for official sources that rely on national monitoring systems rather than satellite-based information. In this context, OpenStreetMap emerged as the only source providing consistent data coverage for the occupied region. Interestingly, while the Open Data Inventory (ODIN) does not classify Cyprus as a

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data-scarce country, the complex political and administrative fragmentation introduces significant gaps that limit the availability and usability of spatial data. These conditions, however, also present unique research opportunities to test the validity and reliability of open-source datasets as tools for overcoming political boundaries and enhancing data inclusivity.

Building on these findings, the data audit enables the identification of the minimum requirements for a comprehensive and reliable analytical spatial data model for Cyprus. This model will integrate the most accessible and consistent data sources available while adhering to evidence-based principles. The systematic comparison of datasets establishes the baseline for subsequent modelling work offering key insights into the structural challenges of applying EBDP in data-fragmented and politically divided urban contexts.

2.3. Compiling Data models for Cyprus

Based on the outcomes of the data audit (section 2.2.), a key next step was to determine the minimum set of spatial and statistical data layers, necessary to develop a comprehensive and reliable analytical model for Cyprus, focusing on socio-economic data. The aim was to identify which datasets are essential for applying Evidence-Based Design and Planning (EBDP) in a context marked by data fragmentation and uneven availability. Establishing this baseline enables the creation of models that are both methodologically robust and adaptable to the realities of data-scarce or politically divided environments. This work has identified the data layers that would be essential for the construction of a model that could be used for conducting spatial analysis on Connectivity, Centrality and Accessibility, Walkability, Functional mixture and Built density, all these related to established Space Syntax, Place Syntax and Spacematrix analytic methodologies. For the specific case that interest this study the model would be develop as follows:

The **foundational component of a minimum functional urban model** begins with a **street network model**, a **line-segment map**, typically sourced from national cadastral services or OpenStreetMap. Subsequently, the model should integrate information about **potential attractions and origins/destinations** to highlight patterns of movement based on these points of interest. **Administrative boundaries**, such as regional, communal, or postal code boundaries, and **land use** designations, should be incorporated to provide a complete understanding of the urban landscape. Further granularity would be achieved through the inclusion of **population statistics**, distribution and access to **amenities**. **Urban blocks and plot data** would enhance the model by detailing block and plot size dynamics, as well as population and amenity densities.

Additional layers would include **detailed building information** such as footprints, occupancy, height, number of floors, **land use classifications** and **construction dates**. High-resolution population data at smaller scales or by specific urban blocks or plots further enriches the model. Finally, a comprehensive urban model, suitable for Evidence-Based Design and Planning (EBDP) applications, should integrate data on **green street coverage** with detailed foliage information. This might be particularly relevant in regions like Cyprus and the Mediterranean, where street shade and microclimatic conditions highly influence walkability.

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The minimum data layers were defined by assessing three main criteria: a. availability — whether the data exist in open or accessible form; b. coverage — whether the dataset spans the whole island, including both the Republic of Cyprus and the occupied north; and b. analytical relevance — whether the dataset supports core EBDP analytical tasks such as spatial configuration, density assessment, accessibility analysis, and land-use classification. The selected layers thus represent the minimum threshold required to construct a functional and comparable model that adheres to EBDP principles while remaining applicable across varying data contexts.

The **five core categories** of data layers are summarised below:

1. Street Network, motorised and non-motorised
2. Building Footprints
3. Land Use / Land Cover
4. Population Distribution and Demographics
5. Points of Interest (POIs)

The inclusion of street networks, building footprints, and land use ensures a morphological understanding of the urban system, while population and POI data provide socio-economic context. While this list represents an ongoing research effort, it stresses the importance of data quality in defining a valid urban spatial model. Close attention must be paid to the accuracy, currency and coverage of the data layers to minimize blind spots and ensure the model's efficacy as an EBDP tool.

These five data layers form the minimum analytical structure for implementing an EBDP-compatible spatial model in Cyprus. Together, they enable the construction of both a **complete data model** and a **less data-intensive, 'lightweight' model**. Importantly, this combination balances data accessibility and analytical relevance, allowing for meaningful evidence-based evaluation even in regions where detailed cadastral or socio-economic datasets are unavailable. By establishing this minimum dataset, the research creates a replicable template for applying EBDP in data-limited and institutionally diverse contexts, providing a methodological foundation for future comparative studies and for scaling up the approach to other regions. Table 3 summarizes the data selected for the development of a spatial model for Cyprus.

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Table 3 Data selected for the development of a complete data model for Cyprus related to the relevant analysis for the model to be tested with

	Analysis	Data requirements	Data source
Connectivity Analysis	Intersection density/ Street network connectivity	street network	OSM
Centrality and Accessibility analysis	Integration measurements/ To- movements	street network unweighted/ POI weighted	OSM
	Choice measurements/ Through- movements Distance to nearest Attraction reach	street network unweighted/ POI weighted street network unweighted/ POI weighted	
Walkability analysis	Isochrones analysis	street network/ travel distance or time	OSM
	Catchment area	street network/ POI	
Functional mixture analysis	Population Density	urban blocks/ population estimates	Urban Atlas
	Functional Density	urban blocks/POI	
	Density of Public Spaces	land use/land cover, urban block	
Built density analysis	Floor Space Index FSI	parcel/ footprint/ urban block/ building height	OSM / Urban Atlas / Official Cadastral Service
	Ground Space Index GSI	parcel/ footprint/ urban block/ building height	

2.4. Street Network model. Manual and automated workflows.

As already discussed, urban spatial models have emerged as indispensable tools for understanding, planning, and managing urban areas across scales and disciplines (Miller, 2018), by providing a scientific tool for analysing and predicting urban complexity, including the impact of physical infrastructure changes (Røe et al., 2022). Among these, street network modelling and analysis are fundamental, as they describe the morphology and spatial systems of cities. They enable researchers and practitioners to understand movement patterns, evaluate accessibility, and inform urban design decisions. Theoretical frameworks such as space syntax and graph theory underpin many of the tools used in this domain, offering valuable insights into the functionality and structure of urban form.

Despite their potential, in the past, acquiring comprehensive and accurate datasets, essential for accurately representing and simulating urban environments, was often constrained by data availability and quality, making urban models data-intensive, complicated and riddled with technical challenges

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(Lee, 1973, 1994). Furthermore, manual workflows for preprocessing – fetching, cleaning, and preparing data for spatial analysis – are still often time-intensive, labour-intensive, and prone to subjectivity (Fleischmann et al., 2025), particularly when applied to large-scale analyses; these are limitations that hinder reproducibility and scalability, which are essential for robust urban modelling. For these reasons, strategies to address data sparsity, quality and consistency have gained traction, including the use of open-source geographic data platforms, remote sensing, participatory mapping, and machine learning-based data imputation techniques.

Automated workflows, particularly those leveraging open-source tools and data, present a promising alternative to overcome these challenges. By reducing the time and effort required for preprocessing, automation can enhance the efficiency, reproducibility, and scalability of street network modelling (Fleischmann et al., 2025; Krenz, 2017). As cities continue to grow in complexity and size, the adoption of automated workflows will be essential for providing timely, reliable, and comprehensive insights that support evidence-based urban planning and design (Batty, 2017; Longley, 2015). However, the question arises about whether such models produce valid results regarding identifying spatial patterns and measuring specific spatial characteristics, such as centrality measurements, as well as accessibility to points of interest (POIs), especially in contexts where even open-source data may not be of optimal quality. To assess this, automated models must be compared with manually edited models, which, despite being susceptible to subjectivity, have long provided valid results for the above metrics (Hillier, W., 2016; Yamu et al., 2021).

To address these questions, we developed two street network models for the city of Nicosia, using two different workflows:

- one **hybrid** workflow combining limited automation with extensive manual processing
- one **fully automated** workflow

Both workflows used OSM as the source dataset. The resulting network models, are line-segment maps, following Space Syntax methodology for network analysis. Each workflow produced two network models:

- Motorised network, including streets and routes accessible to vehicles.
- Non-motorised network, including all streets, paths and spaces accessible to pedestrians.

Using Cyprus as a case study, our objective is to investigate the effectiveness of open-source automated workflows, focusing on how preprocessing techniques, such as network cleaning, influence the results of centrality and accessibility analyses. The aim is to assess if the output produced by such workflows can be used to respond to relevant planning and urban design questions. This evaluation is performed for the case of Nicosia, Cyprus, where the data challenges, such as a lack of open-access data of international standards for the built environment from official sources, were previously identified (see section 2.2., published in Ricchiardi et al., 2024). By comparing the hybrid and fully automated network model, we aim to test their feasibility, accuracy, and analytical performance, particularly in terms of preprocessing and subsequent network analysis. The central research question

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guiding this comparison is: How does a less data-intensive analytical model perform in the assessment of urban interventions compared to a data- and labour-intensive model? The aim is to evaluate the trade-offs between data completeness, analytical precision, and operational efficiency.

2.4.1. Space Syntax network modelling

Prior to presenting the network models, it is important to describe the representational principles that underpin them and follow the Space Syntax tradition of network modelling.

Space syntax provides a framework to analyse how urban spatial configurations influence movement, making it useful for measuring connectivity and predicting human behaviour (Koohsari et al., 2019; Stavroulaki, I., 2022). Its models support evidence-based design by translating spatial relationships into measurable data linked to socio-economic patterns. This allows designers to assess current conditions, explore alternatives, and forecast outcomes, turning urban design into a data-driven, performance-oriented process (Maretto et al., 2023). And it represents an alternative method to model the street network by seeing it as aggregated street segments (Marshall et al., 2018).

Early space syntax relied on manually drawn axial maps, minimal straight lines covering public space to represent sight and direction, but this approach was subjective, time-consuming, and poorly suited to curved streets. To overcome these limits, the field shifted to segment maps, which use GIS-based road-centre-line (RCL) data to automate and finely detail street networks (Turner, Alasdair, 2007). Segment maps enable Angular Segment Analysis (ASA), which quantifies directional changes at junctions and introduces parametric flexibility: by adjusting angular thresholds, researchers can explore different cognitive and spatial interpretations from the same base network (Maretto et al., 2023; Omer et al., 2017; Stavroulaki, G. et al., 2017; Turner, A., 2000; Turner, Alasdair, 2007).

Raw road-centre-line (RCL) maps often suffer from over-fragmentation due to excessive vertices and minor angular shifts, making them inconsistent with axial maps (Dhanani et al., 2012). Kolovou (Kolovou et al., 2017) showed that simplifying geometry with the Douglas-Peucker algorithm and manually modelling complex features improves accuracy at both city and local scales by better reflecting human spatial cognition. Stavroulaki (Stavroulaki, G. et al., 2017) similarly, addressed over-segmentation, proposing angular merging (e.g., below 15°) to reduce noise and align maps with perceptual continuity. Krenz (Krenz, 2017) introduced the SIMP workflow to clean and simplify OpenStreetMap data for Angular Segment Analysis, resolving topological issues and achieving high correlation analysis results based on axial maps ($R^2 = 0.98$), while drastically reducing segment count and processing time. Together, these approaches highlight that effective segment mapping relies on cognitively informed simplification, offering scalable, accurate alternatives to manual axial methods. Based on these studies, the main goal is to reduce complexity by removing redundancies, such as minor curves and excessive nodes, and to optimise angular relationships between street segments. The key principles are angular and intersection simplifications.

However, existing space syntax tools (e.g., Space Syntax Toolkit) that work with the preprocessing of RCL from OSM data often still require significant manual intervention, such as intersection consolidation or correction of over-segmentation, which limits their scalability for large-scale analysis.

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In contrast, network Python packages (e.g. Cityseer) provide an open-source workflow that robustly cleans and simplifies RCL data while supporting angular segment analysis. Given this, we aim to test whether such packages can produce analytical outcomes comparable to those of conventional space syntax modelling, while offering a more automated, scalable solution.

2.4.2. Hybrid Workflow for network modelling

The **hybrid workflow** represents the conventional, space-syntax–aligned approach to building a high-quality street network model through **a combination of automated GIS tools and expert manual editing.** For the Nicosia case, the process began with the retrieval of road-centre-line data from OpenStreetMap (via https://www.geofabrik.de/). This served as the base dataset, which was then cleaned and simplified through a two-stage procedure, following space syntax methodology.

First, **automated preprocessing** was performed using the **Space Syntax Toolkit** within QGIS (https://plugins.qgis.org/plugins/esstoolkit/). This step applied standardised routines to remove duplicated edges, consolidate intersections, correct topological errors, and perform an initial simplification of the network.

Second, the resulting network underwent **manual editing**, conducted by one researcher and cross-reviewed by another to ensure consistency and accuracy. This **manual stage** involved:

- Removing duplicated or isolated lines that incorrectly appeared as part of the network.
- Snapping and reconnecting misaligned segments**,** ensuring topological correctness.
- Cleaning and generalising geometry, including eliminating unnecessary over-segmentation.
- Adding missing lines where OSM coverage was incomplete.
- Removing features that do not represent publicly accessible movement corridors.
- Ensuring representational consistency**,** so that:
    - All roads, irrespective of number of lanes, are represented as a single line, where they function as one perceived space.
    - Adjacent pedestrian or cycling paths are merged with parallel streets when they form a unified movement corridor.
    - Footpaths are included where they meaningfully contribute to pedestrian accessibility.
    - Roundabouts and intersections accurately reflect navigable geometry.

The hybrid workflow results in a **clean, generalised, cognitively coherent representation** of the street network, closely aligned with established Space Syntax modelling principles. It typically produces longer segments, fewer nodes, and smoother geometries than raw OSM data. While this workflow produces high-quality analytical networks, it remains **labour-intensive, slow, and difficult to scale**, especially in large study areas or multi-city comparative research. Its strengths make it ideal as a **reference model** against which automated methods can be critically assessed.

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2.4.3. Automated Workflow for network modelling

The **fully automated workflow** was designed to maximise reproducibility, scalability, and efficiency by relying entirely on open-source tools and scripted routines. This workflow was implemented using the **Cityseer Python package**[1] **(v4.17.0)**. Cityseer is a collection of computational tools for street network and land use analysis (Simons, 2023). This Python package is for generating fine-grained, pedestrian-scale street networks, advancing network tools like NetworkX and OSMnx through robust topological cleaning of volunteered geographic data. It supports a wide range of spatial analyses, including metric and angular centrality measures, as well as Euclidean and angular routing (Simons, 2023). This makes it a powerful and flexible toolkit for urban network modelling and accessibility studies

Cityseer automatically retrieves road-centre-line data from OpenStreetMap and applies a robust set of preprocessing operations. For this study, the chosen configuration included:

- Automatic geometric simplification using a default distance threshold of 6–12 metres (default), consolidating small bends and reducing unnecessary segmentation.
- Removal of disconnected components with fewer than 100 nodes, ensuring the network remained connected
- Retention of cycleways, recognising their importance as connectors in both motorised and non-motorised networks[2].
- Standardised node and edge cleaning, including automated snapping, merging, and intersection consolidation.

These automated rules produced a network with much finer spatial resolution than the hybrid workflow, typically characterised by more segments (often 2–3 times more), significantly shorter segment lengths, senser node distributions and additional paths representing small connectors, service routes, parking-lot circulation paths, and inter-building passages. Importantly, these additional paths reflect not errors but the high geometric sensitivity of the automated workflow, which captures a more detailed representation of available movement space—sometimes even identifying informal or minor routes that manual modelling tends to omit.

The fully automated workflow therefore creates a **comprehensive, highly detailed pedestrian-scale network, well suited for reproducible, large-scale, or cross-city comparisons**. Its main limitations lie in the trend for **over-segmentation, excessive node density,** and the inclusion of **very fine-grained paths, which may introduce local distortions in angular network analyses or accessibility calculations**. For these reasons, comparisons with the hybrid workflow are essential to assess analytical validity.

[1] https://github.com/benchmark-urbanism/cityseer-api/
[2] https://benchmark-urbanism.github.io/cityseer-examples/recipes/networks/network_simplification.html

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2.4.4. Comparison of manual vs automated workflows.

The comparison investigates the effectiveness of open-source automated workflows, focusing on how preprocessing techniques, such as network cleaning, influence the results of centrality and accessibility analyses. The research question is 'How does a less data-intensive analytical model perform in the assessment of urban interventions compared to a data- and labour-intensive model?'

This study examined two key aspects of street network measurements in space syntax analysis: centrality and reach calculations. These methods apply to various street network types and serve the needs of both researchers and practitioners. While different tools can generate and analyse street network models, this analysis was conducted using the Place Syntax Tool, an open-source plugin in QGIS (https://github.com/SMoG-Chalmers/PST). This tool integrates all necessary analyses in a single environment and functions as an independent platform to evaluate the two street models.

2.4.4.1. Method

Spatial Analysis
For **centrality** measurements, we employed Angular Integration (i.e. closeness centrality) and Angular Betweenness centrality, which calculate the angular distance from each street segment to all others (i.e. total degrees turned) in the network along the shortest paths. To account for varying segment lengths, we weighted the analysis by segment length, ensuring longer segments contributed proportionally more to integration and betweenness values. This adjustment reduces bias by incorporating real-world distances rather than treating all segments equally. The analysis was conducted using multiple radii for different street network models.

- Non-motorised network: 400, 800, 1200, and 2000 meters.
- Motorised network: 2000 and 5000 meters (Hillier, B. & Iida, 2005).

The study focuses on the Urban Morphological Zone (UMZ) of Nicosia. A buffer of 20 km around it was created to avoid the edge effect (Gil, 2017). Areas in the UN buffer zone were excluded.

For **reach** measurements, we employed two attraction-based methods: Attraction Distance (AD) and Attraction Reach (AR). AD calculates the minimum walking distance from each origin point (buildings) to the nearest destination (points of interest), providing a basic accessibility metric (Stavroulaki et al. 2024). Both of building and points of interest datasets were constant and used across all measures and across both models. AR extends this concept by summing the attraction values of all reachable destinations within a given radius, offering a cumulative measure of accessibility. Both methods utilised metric distance to maintain consistency across analyses. The study examined multiple thresholds (400, 600, 800, 1000, 1200, 1500, and 2000 meters) using only the non-motorised network model, with buildings serving as origins and six different types of points of interest as destinations. This multi-radius approach allowed for a comprehensive evaluation of pedestrian accessibility patterns at different spatial scales.

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Apart from the street network models, two more datasets were used for the analysis. Firstly, the buildings' footprints were retrieved from official sources [3]. Secondly, a set of points of interest (POIs) that were created manually within QGIS, by georeferencing and curating datasets from official sources[4], except for one. These POIs contain six categories: bus stops (1509 points), entrances to green areas (501 points from OSM), pre-primary/kindergarten schools (197 points), primary schools (137 points), secondary schools (49 Points), and Citizen Service Centres (22 points).

Evaluation method

The analysis generated two distinct types of outputs from the centrality measurements. For each street network model (automated and hybrid), we obtained integration and betweenness values in the different analysis radii for every segment.

Since the models represented space differently (i.e. the number and exact location of segments), we implemented an **aggregation** approach to enable meaningful comparison as shown in Figure 8. We overlaid the study area with a grid of 100m × 100m hexagonal cells, each capturing values from both models. All hexagon neighbours are equidistant, and each cell has six neighbours, avoiding the unequal adjacency of square grids. Aggregating to hexes of this size balances granularity with statistical stability; it averages out very local anomalies while still retaining neighbourhood-scale variation (Longley, 2015). The 100-meter grid cell size was chosen because it corresponds to the upper bound of the interquartile range of street segment lengths in the hybrid model. This scale reflects a typical local spatial unit in the network and ensures that aggregation captures a representative number of segments per cell without excessive generalisation or fragmentation. **Aggregation** was performed using two methods: (1) calculating mean values of all segments within each cell, and (2) selecting the maximum value among the segments in each cell. Using both mean and max centrality values together provides a comprehensive view of network structure, capturing both the typical accessibility (mean) and the presence of key, high-impact segments (max). This dual approach allows for assessing whether centrality is evenly distributed or concentrated in specific locations, offering deeper insight into spatial hierarchy and performance.

To **statistically compare** the **models' spatial rankings**, we conducted a **Spearman correlation** test on the grid cells' centrality rankings, independent of absolute values, to account for differences in the number of street segments between models, which can affect the absolute centrality values. That enables a normalised and scale-independent comparison of spatial importance.

[3] The Cyprus Department of Land and Surveys.
[4] Cyrus Post, Cyprus Ministry of Education, Sport and Youth, and Public Works Department.

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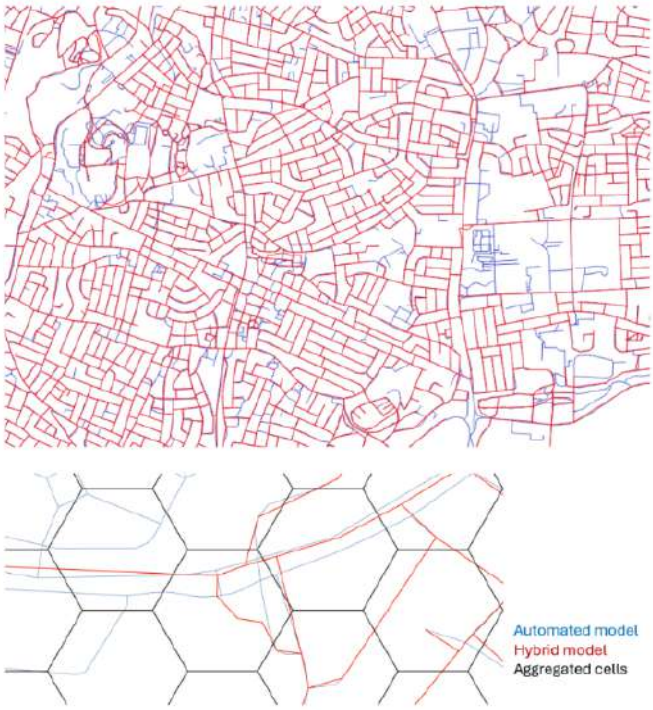

Figure 8. Differentiation in spatial coverage between the two models and the aggregated cells.

The **accessibility measurements** produced absolute values, including distances and destination counts, enabling direct comparison between models. To assess agreement between these measurements, we performed a **Bland-Altman analysis**, which quantifies the mean difference between models while accounting for measurement variability. Additionally, we generated **kernel density estimate (KDE) plots** to visualise the distribution of inter-model differences across the study area. This combination of statistical and graphical approaches provided comprehensive insights into the spatial agreement patterns between the two network representations.

Our initial observations revealed significant **representational differences** between the two network models. To systematically investigate the causes behind the variations in centrality and accessibility results, we conducted additional spatial analyses. Firstly, to specifically test **whether the automated model's additional connections affected results**, we performed a **sensitivity analysis**: we recalculated all the centrality measures for the automated model while retaining only those paths that overlapped (within a 25m buffer) with the hybrid model's network, as shown in Figure 9 (calling it the buffered model). This approach allowed us to isolate the impact of connectivity differences between the models. Furthermore, we reviewed the change in the correlation values compared to the whole model. Secondly, we employed **Moran's Index** to examine whether the observed differences exhibited spatial clustering, which could indicate localised factors disproportionately influencing the results.

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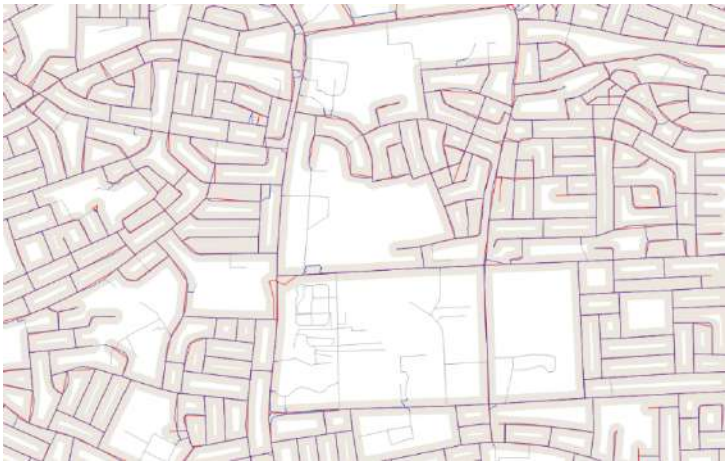

Figure 9. For the sensitivity analysis, we selected the automated model (blue lines) that only falls within a 25 m buffer from the hybrid model (red lines), creating a buffered model. (Grey lines are the ignored lines from the automated model)

Lastly, and given the models' **inherent geometric discrepancies**, particularly the automated model's more extensive spatial coverage (it covers more areas in the same UMZ) compared to the hybrid model, we analysed **how geometric variations between the two models correlated with their differences in ranking centrality**. Using the same hexagon cells from previous analyses, we aggregated multiple geometric properties/metrics: segment counts, total and mean segment lengths, node counts, and mean/maximum angular changes at nodes. We refer to the node here as a point where two or more segments meet. To calculate the angular change per hexagon cell, we went through a preparation process using Python within QGIS. This process involved three stages:

- First, it identified street segments intersecting the hexagon and decomposes them into elementary two-point segment. For each elementary segment, it calculated the directional angle (0-360°) using inverse tangent functions.
- Second, it systematically compared all segment pairs within the hexagon, detecting geometric connections where segments share start/end points.
- Third, for each connected pair, it computed the smallest angular difference (0-180°) between their direction vectors using circular difference calculations.

The generated points layer represented a street intersection characterised by the angular relationship between its connecting segments within discrete hexagonal analysis units. Then we aggregated the mean/maximum value for each cell. Finally, we applied **Spearman's correlation** test to identify significant relationships between these geometric properties and variations in ranking centrality.

Table 1 summarises the equations used and comparison methods for each measurement. Figure 10 summarises the centrality assessment workflow for this process.

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Table 4. Summary of equations used and comparison methods for each measurement (symbol explanation in Appendix B)

Measurements	Equations	Comparison Method
Centrality measurements		
Angular Integration	$AI_H(x) = \frac{N^2}{1 + \sum_{i \neq x} D(x,i)}$	Spearman's rank
Angular Integration weighted	$AI_H(x) = \frac{(\sum_{i \neq x} l(i))^2}{1 + \sum_{i \neq x} D(x,i) \cdot l(i)}$	Spearman's rank
Angular Betweenness	$B(x) = \sum_{s \neq x \neq t} \frac{\sigma_{st}(x)}{\sigma_{st}}$	Spearman's rank
Angular Betweenness weighted	$B(x) = \sum_{s \neq x \neq t} \frac{\sigma_{st}(x)}{\sigma_{st}}$	Spearman's rank
Centrality's spatial discrepancies	$I = \frac{N}{W} \cdot \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij}(x_i - \bar{x})(x_j - \bar{x})}{\sum_{i=1}^{N}(x_i - \bar{x})^2}$	Moran's I
Accessibility measurements		
Attraction Distance	$AD(o) = \min_{a \in A} D(o,a)$	KDE analysis & Bland-Altman analysis
Attraction Reach	$AR(o) = \sum_{a \in A} f(a) w(D(o,a))$	KDE analysis & Bland-Altman analysis
Metric measurements		
Number of segments	$S = \lvert E \rvert$	Bar plot
Segments length	$L = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$	Box plot
Density of nodes /cell	$N_i = \sum_{j=1}^{m} \delta(n_j \in c_i)$	Box plot
Density of segments /cell	$S_i = \lvert E_i \rvert$	Box plot
Density of total segment length /cell	$L_i^{total} = \sum_{e_k \in E_i} L_k$	Box plot
Density of mean segment length /cell	$\bar{L_i} = \frac{1}{S_i} \sum_{e_k \in E_i} L_k$	Box plot
Density of max angle change /cell	$\Delta\theta_i^{max} = \max_{e_k, e_{k+1} \in E_i} \lvert \theta_{k+1} - \theta_k \rvert$	Box plot
Density of mean angle change /cell	$\overline{\Delta\theta_i} = \frac{1}{\lvert E_i' \rvert} \sum_{e_k, e_{k+1} \in E_i'} \lvert \theta_{k+1} - \theta_k \rvert$	Box plot
Relating the difference in centrality to the difference in metric measurements		
Correlation matrix	$\rho_s(X,Y) = 1 - \frac{6 \sum_{i=1}^{n} (R_{X_i} - R_{Y_i})^2}{n(n^2 - 1)}$	Spearman's rank

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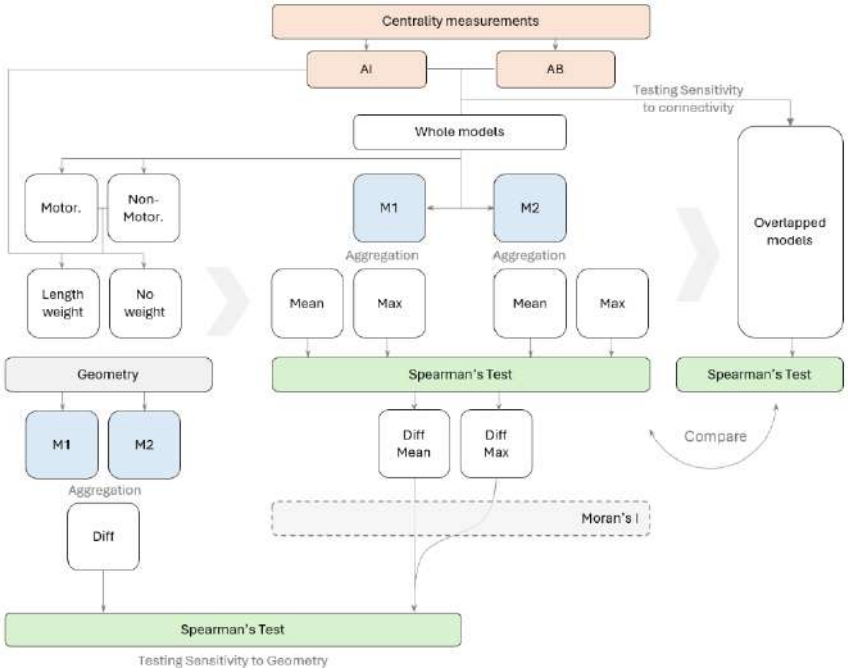

Figure 10. Centrality assessment framework

2.4.4.2. Comparison results

Geometric characteristics

The comparative analysis of street network metrics reveals distinct structural differences between hybrid and auto-derived models for both non-motorised and motorised networks. We investigated the total measurements of both models, and in terms of density, comparing aggregation to the 100 m cells. Firstly, characteristics related to the study area: In terms of total street length, the non-motorised automated network records the highest coverage at approximately 11,000 km, followed by the non-motorised hybrid at 9,500 km, while motorised hybrid and motorised automated networks cover around 6,500 km and 7,500 km, respectively. And as shown in Figure 11, the average segment length in the automated model is 36 meters, while the hybrid has an average of 88 meters. Segment length distribution in the box plots further highlights divergence between the modelling approaches: hybrid models exhibit broader ranges and higher medians, with non-motorized hybrid segments extending from roughly 20 m to over 200 m and a median around 90 m, while auto-derived segments (both motorized and non-motorized) are notably shorter, clustered between 20 m and 50 m, with medians closer to 35 m. The Node count disparities reinforce this pattern. The non-motorised automated model includes nearly three times more nodes than the hybrid model (280,000 and 90,000, respectively). Similarly, the motorised network that the automated model generates has around 180,000 nodes, while the hybrid model generates less than 50,000 nodes for the same area. When normalising the node count by the total network length, the automated model also exhibits higher node densities, with both motorised and non-motorised. The automated model reaches 25 nodes per kilometre, whereas the hybrid model remains below 10 nodes per kilometre. The automated model is characterised by shorter segments and many nodes. These are due to the finer spatial resolution provided by the automated

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model following the street geometry or centreline. Figure 12 shows examples from the study area where the difference between the two models could be spotted, especially in roundabouts and curved streets.

Analysis of the buffered model further supports these findings. Although its total street length is nearly equivalent to that of the hybrid model for the same spatial extent, the number of segments remains approximately three times higher, matching the count in the automated model. This clearly reflects the extent of over-segmentation introduced by the automated process within the same area. This pattern is also evident in the ratio of total node count to total street length, which remains consistent with that of the automated model across both motorised and non-motorised networks. Moreover, simple calculations show that approximately 80% of the automated model's nodes and total segment length are contained within the buffered model. This suggests that the majority of the increased node count in the automated model is due to finer segmentation of existing network elements, while only about 20% results from the inclusion of additional connections not captured in the hybrid model.

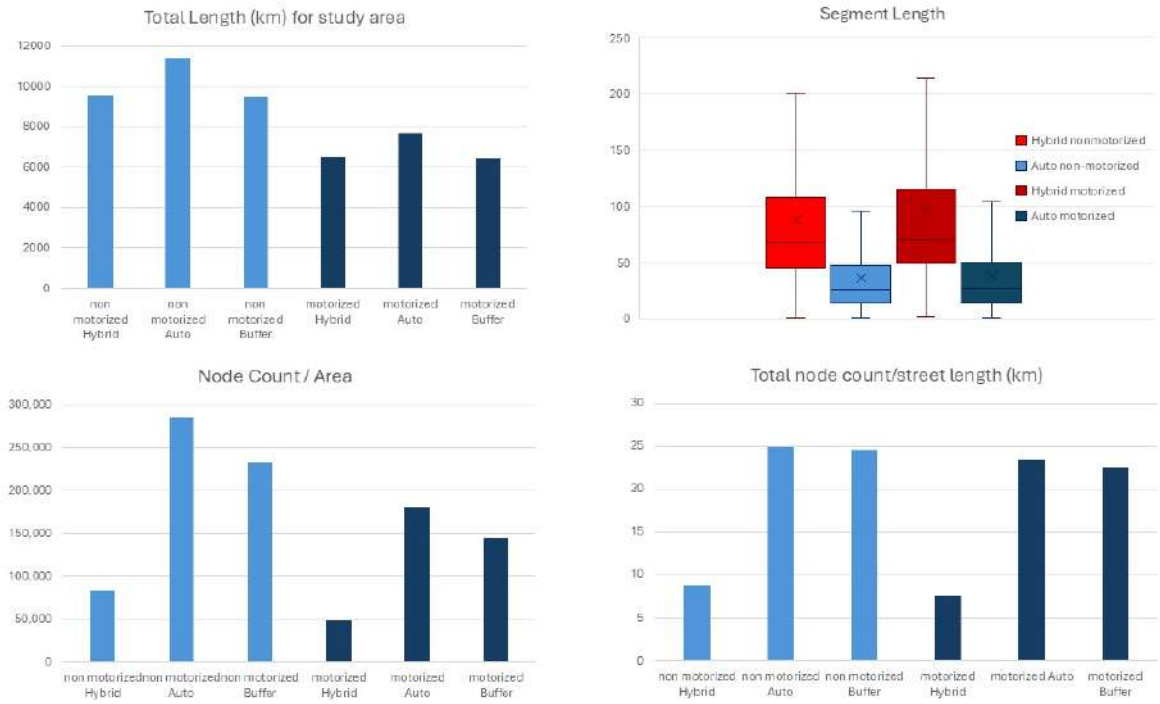

Figure 11. Comparison between the geometrical characteristics of models covering the study area

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Figure 12. Difference in representation (segments & nodes) between the two models, the upper images represent the non-motorised, and the lower images represent the motorised

Secondly, we investigated a localised cell-based analysis that reveals density differences between the two. The hybrid models show higher median total street lengths per grid cell for the motorised and non-motorised (~250–500 m and ~200-400m, respectively), with maximum values reaching over 800 m, suggesting more continuous and less fragmented segments. In contrast, the automated networks display shorter median lengths (~150–300 m for motorised and non-motorised), but with significantly higher segment counts per cell, up to 15 segments in non-motorised auto, compared to just 3–5 in hybrids. This pattern reflects the auto models' tendency to produce smaller, more frequent segments, confirmed by the lower mean segment lengths per cell (~30–80 m for motorised and non-motorised) compared to 60–140 m in hybrids. Most notably, node count per cell is substantially higher in automated models, with non-motorised reaching medians around 6 and maximums near 25 nodes per cell. In comparison, hybrid models stay below 5 nodes, as shown in Figure 13 after discounting the outliers. This analysis shows that the hybrid model implies a simplified, smoothed representation, while the automated model enhances the resolution of the network.

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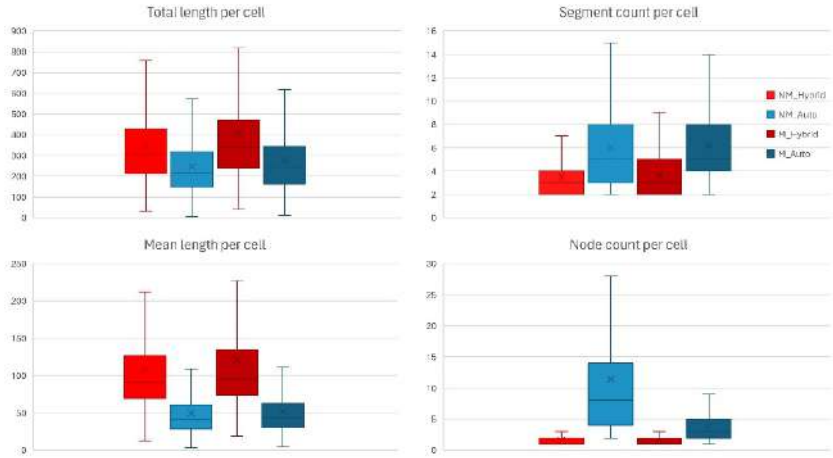

Figure 13. Comparing geometric density per 100m spatial cell across models

An in-depth examination of a key source of divergence between the automated and hybrid network models stems from differences in network granularity and coverage. Specifically, the automated model includes a greater number of line segments, often representing fine-scale paths such as those within parking lots or interstitial spaces between buildings. These segments are typically generated from high-resolution imagery and offer a more detailed, albeit sometimes functionally ambiguous, representation of pedestrian movement potential. In contrast, the hybrid model, being manually curated, tends to omit such segments, especially when they are deemed non-essential or non-navigable in practical terms.

Centrality measurements

The ranking of the aggregated cells between the two models varied across scales (radii), type of network model, and weighting by segment length. Overall, the correlation values are consistently high for motorised and non-motorised networks, indicating a strong monotonic agreement between the rankings produced by the two models, especially at larger spatial scales. Across all forms of Angular Integration (AI_Max, AI_Mean and their length-weighted versions), the correlation between models strengthens steadily as the spatial radius increases. For instance, AI_Mean improves from 0.71 at 400m to 0.98 at 5000m, while its weighted version (AI_Mean_W) mirrors this trend with slightly higher consistency (from 0.78 at 400m to 0.98 at 5000m). This suggests that both models produce increasingly similar rankings of street segments concerning integration as the analysis radius widens. At smaller radii (400m), discrepancies are more apparent ($\rho \approx 0.71–0.78$), but convergence is almost perfect by 5000m ($\rho \geq 0.96$), implying that differences between models become negligible at broader spatial scales.

Angular Betweenness values also show increasing agreement with spatial scale, though they exhibit weaker correlation overall compared to integration metrics. For instance, AB_Max rises from 0.75 at 400m to 0.89 at 5000m, and its length-weighted version (AB_Max_W) reaches 0.93 at the same latter scale. AB_Mean and AB_Mean_W follow similar patterns but start from lower baseline correlations at

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smaller radii ($\rho \approx 0.73–0.79$). These results indicate that while the models broadly agree on the betweenness ranking of segments at larger scales, there is greater divergence in how they capture through-movement potential, especially at local scales. Length-weighted versions of both AI and AB tend to yield higher Spearman correlations than their unweighted counterparts at nearly all scales. This suggests that when segment length is considered, the models' outputs align more closely in terms of how they rank segments as the length normalisation reduces sensitivity to small-scale structural or geometric differences. Figure 14 shows an example of the differences in correlation strength among scales, model type, and weighting by length.

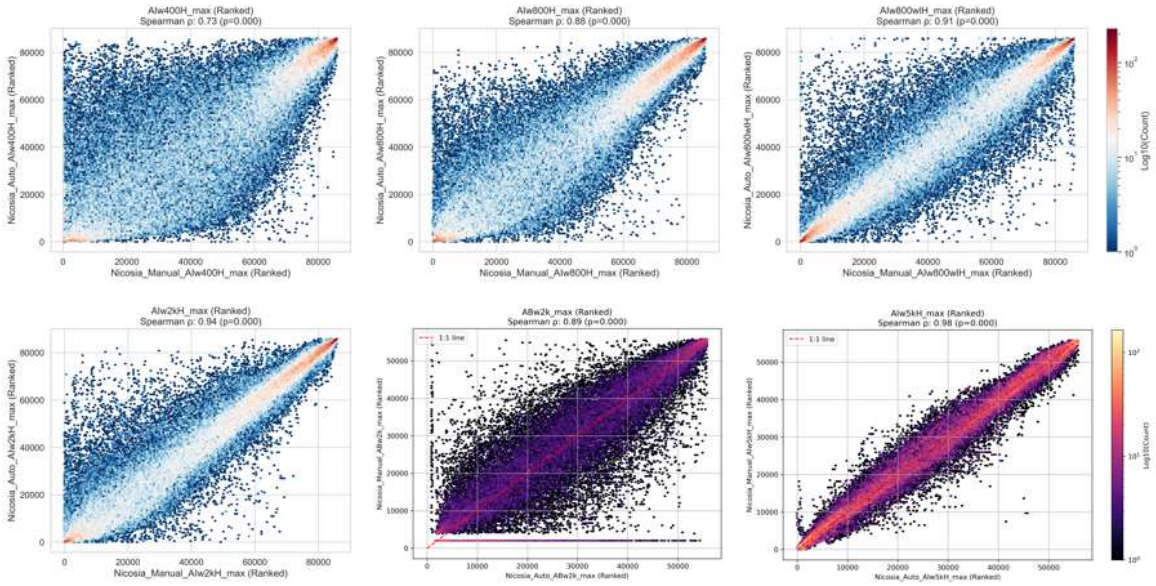

Figure 14. Correlation strength among scales, analysis, networks, and weighting by length (dark magma graphs are for motorised network)

To further investigate how the connected spaces/paths (testing of the sensitivity of connectivity) by the automated model influence this correlation, Figure 15 shows the difference in Spearman correlation values after combining the two models to the same paths (_B refers to the buffered network). The results reveal minimal differences between each pair of metrics, underscoring a high degree of robustness in centrality rank structures despite the geometric modifications introduced by precise overlapping. For Angular Integration (AI) metrics, the differences between base and overlapped models are marginal across all scales. For instance, at 400 m, AI_Max and AI_Max_B show a strong correlation of 0.73 and 0.74, respectively, increasing in near lockstep to 0.98 by 5000 m. This pattern repeats across the mean and weighted variants, where improvements in correlation from the automated to the buffered version are minor (typically in the range of 0.01–0.02), suggesting that the integration metric is largely unaffected by uncovered/unconnected spaces. In the case of Angular Betweenness (AB) metrics, similar trends are observed, with slightly more noticeable gains in correlation when comparing the two models. For example, the correlation of the Angular betweenness (Max) increases from 0.75 to 0.80 at 400 m when considering the buffered model, and this difference becomes more stable and minor (about 0.03–0.04) at larger scales. Weighted variants like Angular Betweenness (Max), weighted by length in the buffered model, show a clear pattern of consistent

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improvement, e.g., 0.79 to 0.85 at 400 m and 0.96 to 0.98 at 5000 m. Notably, the highest differences are concentrated in the smaller radii (400–800 m), where the network's granularity has a stronger influence, while at larger radii (2000 m and above), the original and the buffered versions converge, reflecting the dominance of global structure over local variation. Overall, these comparisons confirm that while connecting to broader spaces/paths introduces some local changes, especially for betweenness measures, the overall rank structure remains highly preserved, particularly at broader spatial scales.

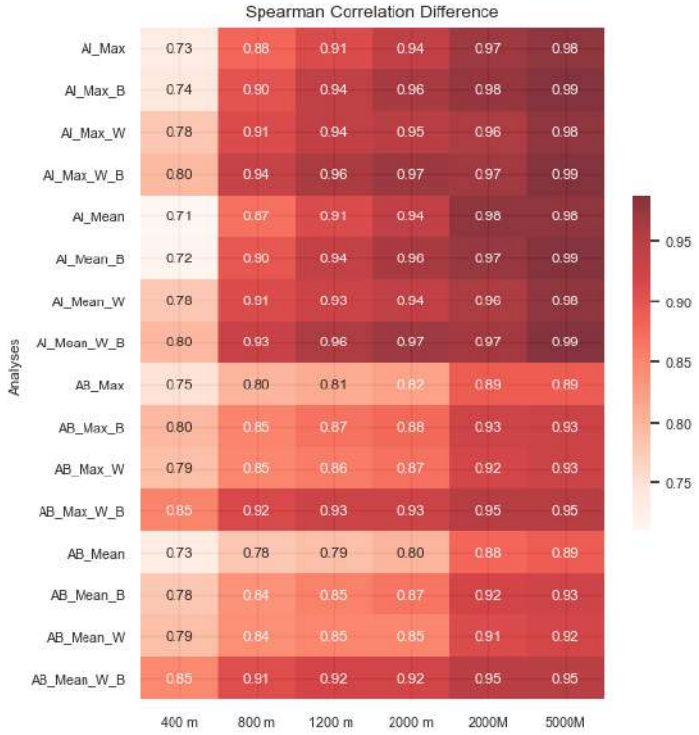

Figure 15. Spearman correlation values between centrality measurement, weighing by length (ending_W), and overlapped model (ending_B), (2000M and 5000M are for the motorised network)

Spatial autocorrelation

To understand more about the cause of this difference in ranking, especially at the smaller scale (e.g., 400 meters), by seeing if there is a spatial correlation between the difference in ranking of the cells between the two models, we performed Global Moran's Index measures for spatial autocorrelation based on both feature locations and feature values simultaneously (Dubé & Legros, 2014). With all p-values almost close to zero, it indicates a statistically significant spatial autocorrelation in the differences of ranked values between the two models across all tested variables and spatial scales. These variables represent the spatial distribution of rank differences in Angular Integration (AI) and Angular Betweenness (AB) measures aggregated within spatial cells. The high Moran's I values observed for AI-related differences (ranging from 0.74 to 0.89) reveal that those areas where the models diverge in their integration rankings are not randomly scattered but tend to cluster spatially. This pattern holds consistently across multiple scales, from local (400m) to more extensive urban

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extents (5000m), with slightly reduced values when accounting for segment length (AI_Mean_W and AI_Max_W). In contrast, differences in AB rankings (AB_Mean and AB_Max) display moderate spatial autocorrelation at smaller scales (400–1200m), but this clustering weakens significantly at the motorized scales (2000m and 5000m), especially when weighted by length (e.g., AB_Max_W dropping to 0.42 at 5000m) as shown in Figure 16.

Figure 16. Moran's Index values for the difference in ranking per centrality measurement for motorised and non-motorised

These results suggest that spatial discrepancies between the two models are more persistent and spatially structured in the case of integration-based measures than for betweenness-based ones. It suggests that the two models systematically disagree in certain geographic areas, rather than at random.

For integration analysis across different scales, the analysis shows clusters outside urban/rural areas, especially at the roads that connect rural areas or rural areas with urban areas in the non-motorised network. These roads tend to have longer segments with fewer nodes in the hybrid model compared to the automated model. Figure 17 shows a map of the location of the clustered area at 400m, while Figure 18 shows a close-up of one of these areas to showcase. On the other hand, betweenness and across scales, the biggest difference in ranking was spotted more within urban/rural areas in places where the hybrid model considered it a dead end, while the automated model has a more connected network due to the existence of informal roads/paths or less simplified dead ends with more pseudo nodes (see Figure 19). Weighting by length helps in reducing the clustering effects across all analyses and scales.

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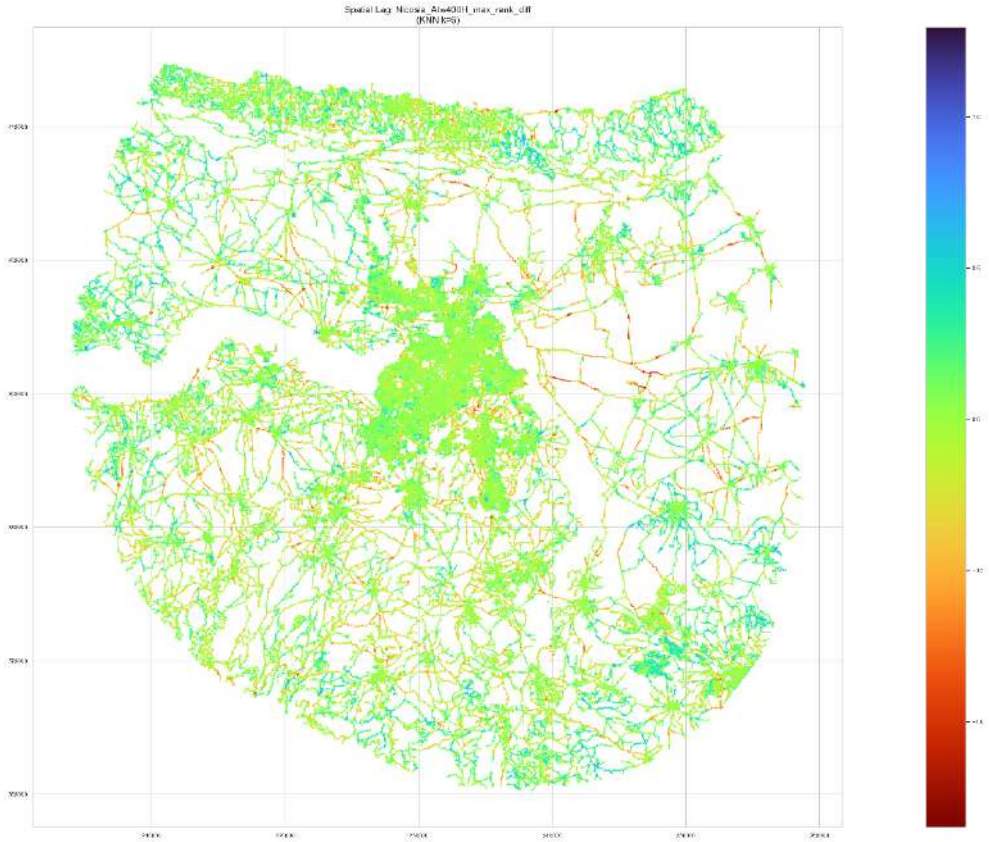

Figure 17. Mapping areas with the most rank difference between the two models at a 400m non-motorised network (clustered outside urban/rural areas).

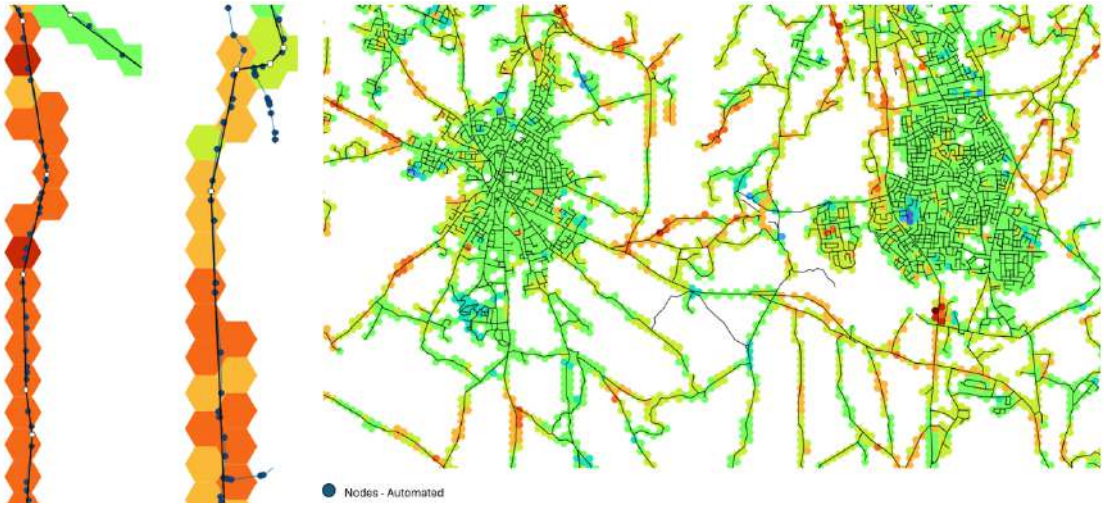

Figure 18. Close-up of the areas with the largest differences in ranking, highlighting roads between rural/urban areas, the largest differences in segment length and node counts

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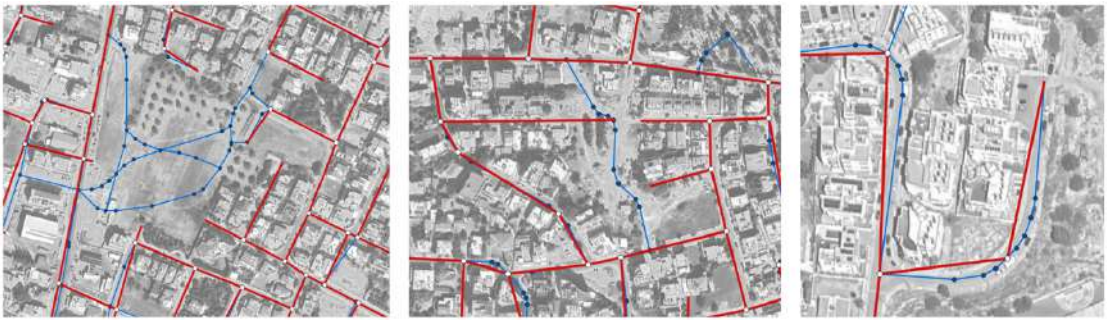

Figure 19. Areas clustered the highest in ranking difference in betweenness at 400 m, where the hybrid model (red) had a dead-end, while the automated model (blue) found connections

For the motorised network, although the radius is bigger in this analysis, the clustering seems to follow the same pattern as in the non-motorised network. integration clusters are located outside the urban areas. And for the betweenness still falls into the dead-end scheme. These patterns imply that underlying spatial or geometric features may be driving the divergent rankings between the models in those areas. Consequently, further analysis of the geometry metrics across the two models is discussed in the following sections.

To further investigate the potential influence of geometric divergence on the difference in spatial centrality outcomes between the automated and the hybrid model, a Spearman rank correlation analysis was conducted between geometric difference and centrality rank difference across various radii and weighing schemes. In all different calculations, we subtracted the automated model from the Hybrid (e.g. Δ Rank = Rank Hybrid – Rank Automated) to address the directional shift in how models rank centrality based on geometry. Figures (20, 21) represent the correlation matrix for the non-motorised and the motorised models, respectively.

In the non-motorised network, segment count exhibited the strongest positive correlation with differences in betweenness centrality rankings, particularly at smaller spatial scales. Spearman's ρ values were 0.57, 0.51, 0.46, and 0.40 for radii of 400m, 800m, 1200m, and 2km, respectively. When centrality was weighted by length, the strength of the correlation decreased, with ρ values of 0.33, 0.28, 0.23, and 0.18, respectively. A similar pattern was observed for integration (closeness centrality), although with generally lower correlation values than those found for betweenness. These findings highlight the importance of segment count differences between models, particularly in shaping angular betweenness outcomes at finer pedestrian scales.

The second most influential variable was mean segment length, which showed a strong negative correlation with centrality rank differences, again strongest at smaller radii. This indicates that cells where the Hybrid model had longer average segments tended to be ranked lower in centrality than in the Automated model. As with segment count, correlations were reduced when using length-weighted centrality. Interestingly, in the case of integration, applying length-weighting reversed the direction of the correlation from negative to positive. This suggests that weighting by length introduces a structural shift in how centrality values respond to geometry, particularly for closeness-based measures.

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Other variables, such as node count and total length (length sum), showed moderate to weak correlations, but followed the same directional pattern: node count was positively correlated, like segment count, while length sum followed the negative correlation trend of mean length. Finally, differences in angle had the weakest correlations overall, typically close to zero, though they loosely mirrored the trend observed in length-based metrics.

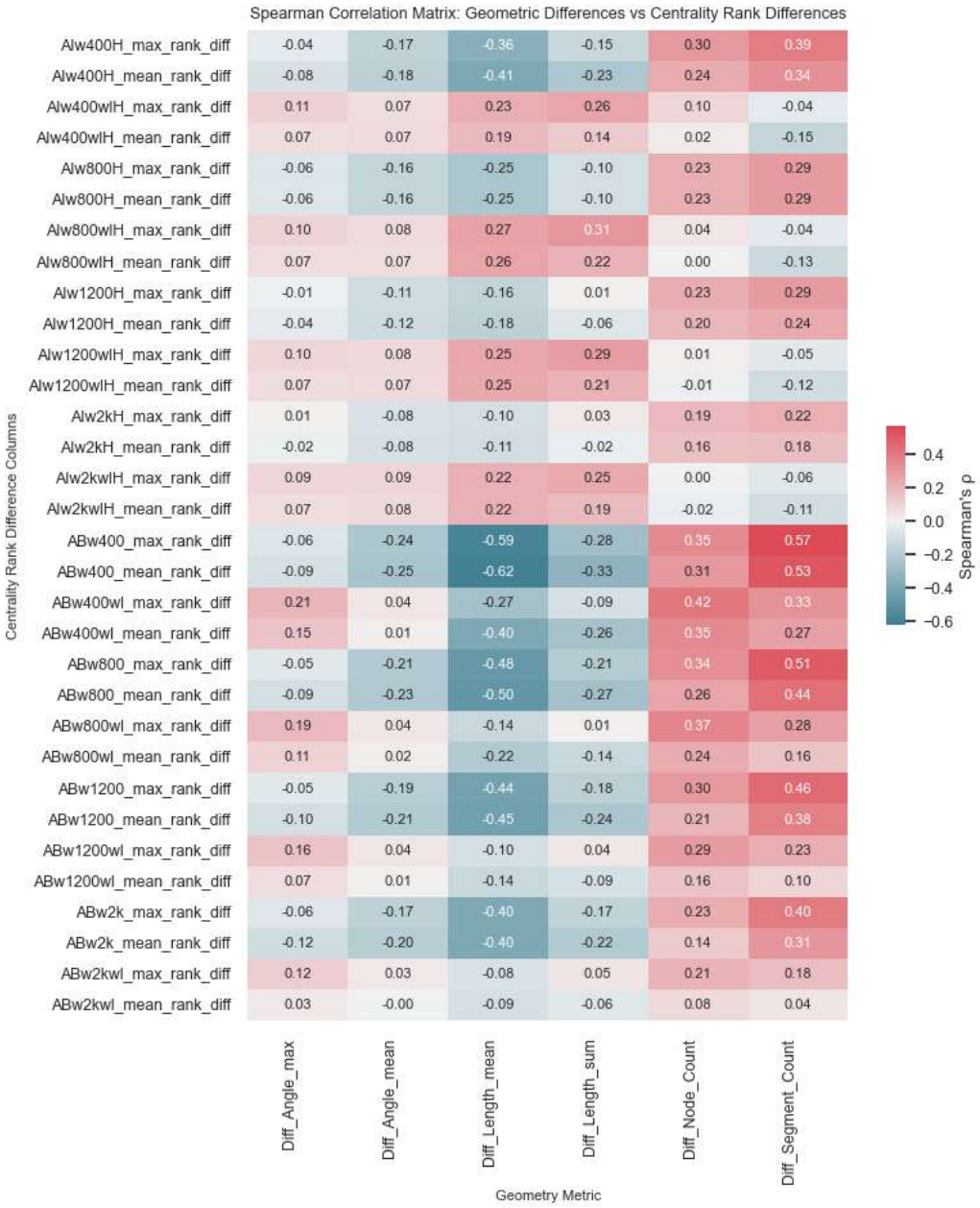

Figure20. Correlation matrix between the geometric difference and centrality ranking for the non-motorised networks

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In the motorised network, the correlation values between geometry differences and centrality rank differences are generally lower compared to those observed in the non-motorised network. The highest correlation coefficients were observed at the smallest scale (2K), with segment count showing a moderate positive correlation ($\rho = +0.36$) and mean segment length exhibiting a moderate negative correlation ($\rho = -0.37$). The overall correlation patterns across variables remain consistent with those found in the non-motorised analysis. However, a key distinction in the motorised network is that node count correlations are more closely aligned in magnitude with segment count, unlike in the non-motorised case, where segment count dominates.

Figure 21. Correlation matrix between the geometric difference and centrality ranking for the motorised networks

Accessibility measurements

Figure 23 (top figures) presents a matrix of mean difference values derived from a Bland-Altman test, assessing the level of agreement between the two models in estimating Attraction Reach to various destination types across multiple spatial scales. Each cell reflects the average difference in values between the models (Hybrid – Automated). Negative values indicate a systematic bias in favour of the automated model, meaning that more destinations are reached when the automated network is used. The results reveal a clear trend in which model agreement diminishes with increasing reach distance. This effect is particularly pronounced for bus stops, which show the largest discrepancies at larger scales (e.g., a mean difference of -0.98 at 2000 meters), suggesting divergent representations of

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connectivity in extended networks. In addition to other measured destinations, the findings suggest that the two models are consistent at capturing short-range accessibility patterns but diverge considerably in longer-range contexts.

For the attraction distance, the values represent the average disparity in estimated travel distances, capturing how differently each model quantifies the spatial extent required to reach specific destinations. The results highlight that as the spatial scale increases, so does the divergence in Attraction Distance, following the same pattern spotted for the Attraction Reach. The pattern found across these analyses was not only subject to the average value of the mean difference. We also looked into the upper and lower levels of agreements across tests, destinations, and scales. The same pattern is still to be found, meaning and disparity increase as the scale increases. Figure 22 shows an example of this test for Attraction Reach and Distance for the bus stops.

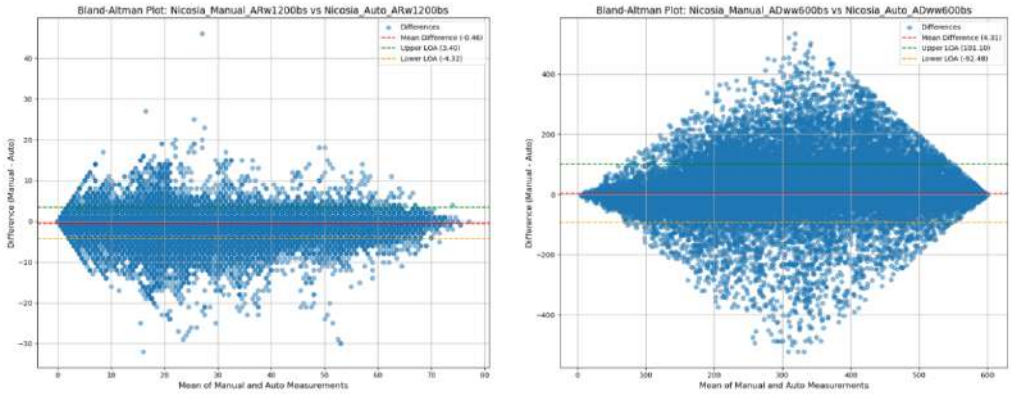

Figure 22. Example of a Bland-Altman plot for different scales showing the distribution of values across the mean for Bus stops (Attraction Reach 1200m (left), Attraction Distance 600m (right))

Furthermore, to see how the differentiation between the two models is distributed across the dataset. Figure 23 (bottom) presents a series of Kernel Density Estimation (KDE) plots that illustrate the distribution of differences in attraction reach values between two street network models, across varying spatial thresholds (ranging from 400 to 2000 meters). Across all thresholds, the KDE curves exhibit a prominent central peak around a value slightly above 1, indicating that the two models generally produce similar accessibility estimates. As distance increases, certain destination categories, such as bus stops and green entrances, show broader, flatter distributions, reflecting increased variability in model outputs. Interestingly, these wider distributions do not necessarily indicate larger mean differences; instead, they suggest a greater spread of values while still centring around relatively small differences. In other words, even though the variation increases with scale, the average difference between models remains modest for many destinations, implying a form of loose agreement at larger distances. These KDE plots complement the Bland-Altman analysis by revealing that model agreement not only has a small mean difference but also is consistent in its distributional pattern.

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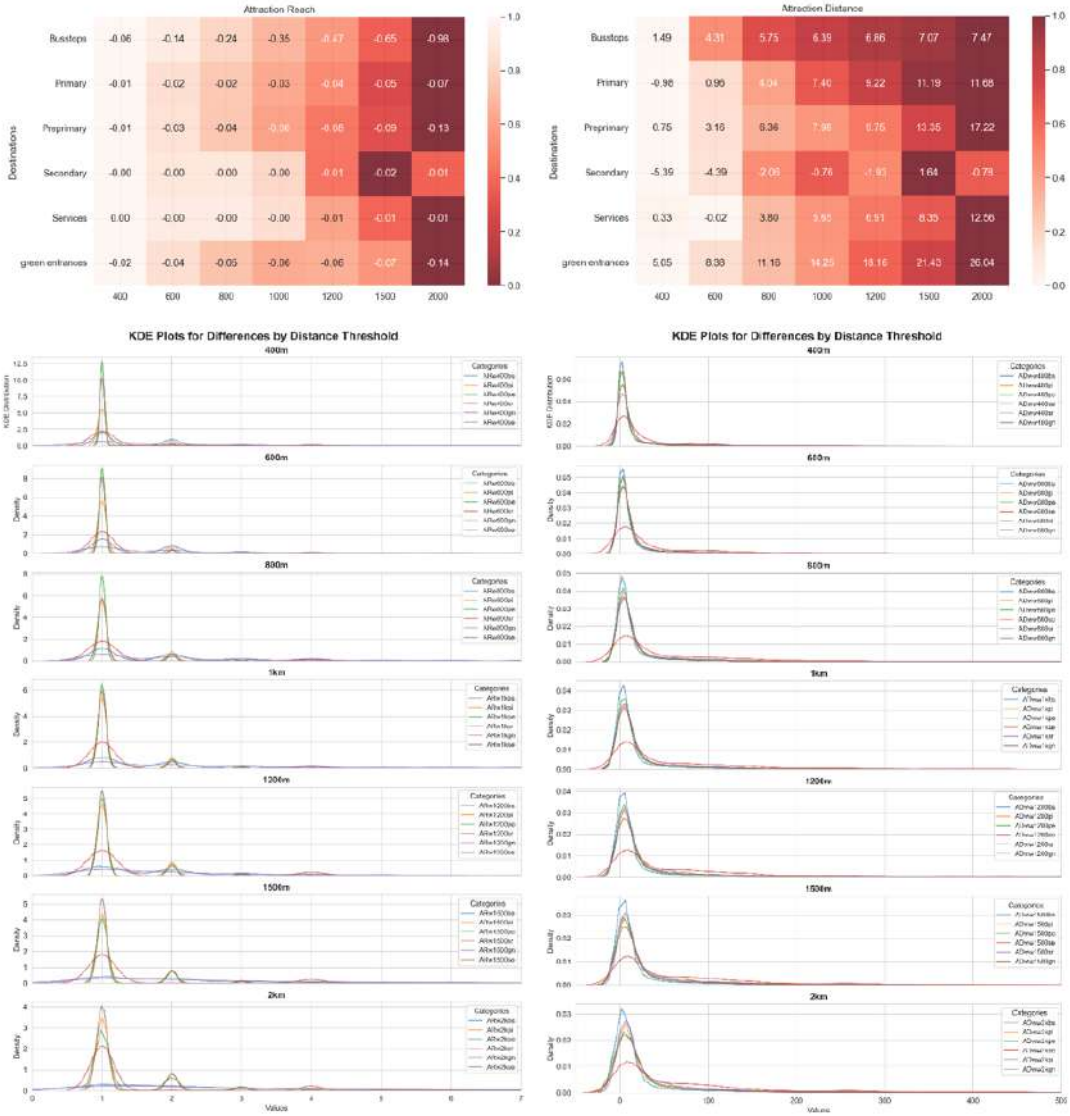

Figure 23. Matrices and KDE plots for attraction reach and distance differences

2.4.4.3. Discussion

The generally higher correlation values observed in integration (closeness) compared to betweenness can be explained by the underlying mechanics of these metrics. Angular betweenness (choice) is sensitive to least-angle paths, meaning that even small angular deviations or zigzags introduced by an automated model can significantly affect route counts. In contrast, angular integration (closeness) is less sensitive to such local variations, as it is based on the aggregate angular depth to all other nodes. As a result, the addition of a few extra nodes or bends only marginally alters the average path length.

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This illustrates that integration is more robust to small geometric noise, whereas betweenness is more vulnerable to fine-scale topological shifts.

This interpretation aligns with the observed strong correlations between centrality discrepancies and local geometric characteristics, particularly node count and segment length, which had the most influence on centrality differences between models. It also supports established principles in space syntax theory, where integration reflects broader spatial accessibility and remains stable despite minor geometric alterations, while choice (betweenness) emphasises route specificity, making it highly sensitive to each additional turn.

Furthermore, examining the length-weighted versions of centrality reveals that, although the automated model produces more (but shorter) segments, it still aligns well with the hybrid model in terms of spatial logic, especially regarding major streets and movement corridors. The stronger correlations in the weighted centrality metrics suggest that the observed differences are primarily the result of geometric and topological artefacts, rather than fundamental changes to the spatial structure itself.

The trend of increasing correlation with scale also reinforces this understanding. At smaller spatial scales, the automated model's denser segmentation introduces more angular deviations and topological complexity, amplifying discrepancies in both integration and betweenness. However, as the radius of analysis increases, the influence of these local variations diminishes, and the analysis becomes governed more by the broader, macro-scale structure, which is more consistently represented in both models.

Importantly, most of the additional connections introduced by the automated model occur in peripheral or background areas that were excluded from the hybrid model, rather than in key foreground routes. In other words, the hybrid model did not omit major movement corridors or significant urban spaces that would meaningfully impact centrality results. This is especially evident in the buffered model, where the effect of these added connections was minimal. Altogether, this supports the conclusion that the automated model primarily adds local refinement without disrupting the core spatial structure captured by the hybrid model.

This disparity also introduces important functional differences in accessibility computations. For instance, in cases where a building or origin point is located adjacent to such fine-grained segments present only in the automated model, the analysis algorithm identifies the closest available segment and initiates distance calculations from that point (see Figure 24). As a result, the automated model can systematically underestimate access distances compared to the hybrid model, which may lack such proximate connections. This mechanism effectively introduces a bias in favour of the automated model in reach estimations, particularly in densely built environments or areas with complex internal circulation networks. Additionally, another observed scenario highlights how these extra segments in the automated model can lead to an overestimation of reach. In some cases, the presence of more adjacent connections enables a particular origin (such as a building) to be connected to a destination within the threshold distance defined by the reach algorithm. However, in the hybrid model, where such connecting segments are absent, the same origin remains beyond the reach threshold and is therefore

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excluded from the set of accessible origins. This results in a situation where the automated model includes destinations or buildings as reachable that the hybrid model excludes, thereby inflating reach values in the automated representation.

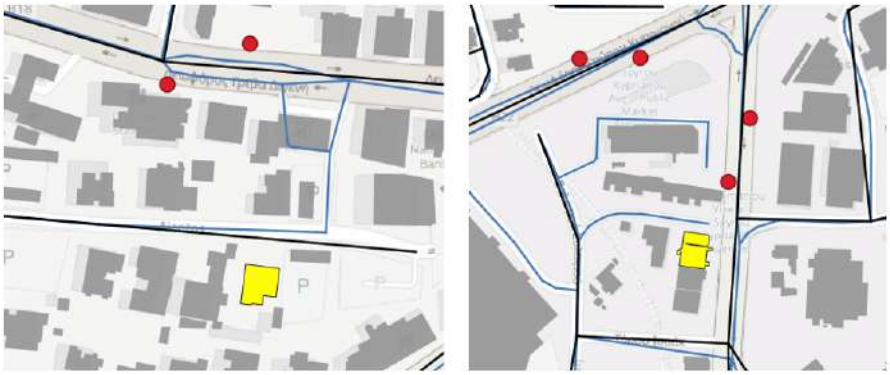

Figure24. Cases where the automated model (blue lines) over- and underestimates values (the hybrid are black lines)

Crucially, both effects are scale dependent. At smaller radii, only a limited number of such discrepancies influence the results. However, as the analysis radius expands, a larger number of these detailed segments fall within the threshold, compounding their influence on model outputs. This cumulative effect explains the increasing divergence in reach values observed between the two models at broader spatial scales. Ultimately, the inclusion or exclusion of fine-scale paths not only affects local accessibility outcomes but also contributes substantially to systematic model variance in large-scale reach assessments.

2.4.5. Conclusion

The automated model demonstrates strong capability in capturing both angular and metric dimensions of centrality and accessibility. Its reliability becomes increasingly evident at broader spatial scales and when applied to motorised networks, where it closely aligns with expected centrality patterns. When compared to the space syntax-based hybrid model, the automated approach effectively represents the overall spatial structure of the network. Its performance is further enhanced through length-weighted analyses, which mitigate the effects of over-segmentation and allow for a more accurate representation of the hierarchical importance of longer, continuous street segments.

Concerning local connectivity, the results indicate that although the correlation with the hybrid model appears weaker when compared to broader, city-scale radii, the statistical correlation values remain high in absolute terms. This suggests that the automated model remains a valid and reliable option, particularly in data-scarce urban contexts, where it can serve as a robust foundation for space syntax centrality analyses. However, the observed discrepancies at smaller scales can largely be attributed to issues inherent in the automation process, most notably, the collinearity of segments and the merging

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of nodes, which affect the accuracy of local spatial relationships. These limitations highlight the need for further manual refinement of the automated models, especially in scenarios where local-scale spatial precision is critical.

In the context of reach measurements, the automated network model demonstrates a high degree of reliability. The observed differences in outcomes between the models are not primarily attributable to geometric inaccuracies or spatial errors, but rather to the automated model's inclusion of a more extensive and detailed set of paths. This expanded coverage results from the automation process capturing additional micro-scale segments, such as internal circulation routes, inter-building connectors, or peripheral access ways, that are often omitted in manually curated models. Consequently, the automated model offers a more comprehensive and high-resolution representation of accessible space. From this perspective, the automated model is not only methodologically sound but also practically applicable, particularly in analyses where fine-grained connectivity plays a critical role in determining reach or accessibility metrics.

In practice, validating automated networks by computing centrality or reach on both raw and curated networks in sample areas is advised. If significant outliers appear, one needs to inspect the street representation for fragmentation and simplify the geometry by applying segment-merging or angle-threshold rules to OSM data before analysis to remove spurious nodes (as suggested by (Xing & Guo, 2022) and (Kolovou et al., 2017)). Then, hybrid editing can be used, combining automated extraction with manual correction of main routes and complex junctions, especially in projects where local accuracy is critical. Finally, the metrics need to match the scale of analysis by favouring integration (closeness) for large-scale planning, and reserving betweenness or detailed reach analyses for contexts where the network has been carefully validated.

2.5. Assessing the applicability of EBDP spatial models in real life projects

The research project employs a case study strategy spanning multiple planning scales - national, territorial, urban, and project-specific, to address challenges encountered in the EBDP process. Three detailed case studies were selected to reflect these scales and to test the framework under different planning challenges. Each case study was designed to answer context-specific research questions, while collectively providing comparative insights into the adaptability of EBDP methods. The aim was to evaluate both the capability of existing analytical models and the availability of data to address a specific research question across different spatial scales. Together, the three case studies are specifically selected to test the applicability of the EBDP framework across different spatial scales (regional, urban, and project), institutional settings (national authorities, inter-municipal partnerships, and private consultants), and stakeholder configurations, thereby demonstrating the framework's adaptability to diverse planning challenges and governance contexts.

The analysis delves into the process of acquiring and utilizing datasets, highlighting the pivotal role of open-source platforms in facilitating data access and integration. It also investigates how the network models that were developed (see section 2.4) were used, emphasizing the contributions of open and automated frameworks in enhancing efficiency and reproducibility, particularly useful for studies on a

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territorial or national scale. Additionally, the report outlines the stakeholder engagement process, shedding light on how collaboration and inclusivity were fostered throughout the decision-making process. Finally, it evaluates the outcomes of each case study, assessing whether the results effectively address the research questions and meet the needs of stakeholders. By doing so, we aim to give a comprehensive understanding of the interplay between data, technology, and stakeholder involvement in a data-challenging environment.

The case studies are:

- Case study 1: Assessing citizen services provision across urban and rural areas
- Case study 2: Assessing Accessibility of amenities from and within Pedieos Linear Park (existing and Masterplan)
- Case study 3: Assessing Urban Accessibility: Evaluating Connectivity and Spatial Reach in the 'Land of Tomorrow' Master Plan

2.5.1. **Case study 1.** Assessing citizen services provision across urban and rural areas

This study was commissioned by the Cyprus Ministry of Transport, Communication and Works and developed in partnership with the Cyprus Post administration, which operates Citizens' Centers within selected post offices. The study evaluates the locations of citizen services to optimize accessibility for populations across varying distances, to foster sustainable development and equitable service distribution through evidence-based planning. Using spatial analysis, the study examines existing and potential new locations for Citizens' Service Centers (KEPs) and Citizens' Centers (KEPOs), assessing the proportion of the population that can access these services from their homes at three scales. The study area encompasses two major cities in the Republic of Cyprus (Nicosia and Larnaca) and is defined geographically as a 20 km buffer zone around the urban morphological zones (UMZ) of both cities, as shown in Figure 25. Within this territory, our primary interest lies in the rural areas, that is, the spaces located outside the UMZ boundaries of Nicosia and Larnaca. The central question is how many residents living in rural areas can reach these services from their homes using the existing public transportation system. By examining this issue, the study aims to provide evidence-based strategies for sustainable development, particularly in relation to the effectiveness of current service locations and the degree to which the public transport network supports accessibility and equity.

New potential locations (proposed by the Cyprus post administration) were tested in the study to evaluate their accessibility for local populations, with additional locations assessed where relevant to explore alternative or supplementary options. At the national and rural cluster scales, accessibility was assessed at distances of 10 km, 12 km, and 15 km, as well as access by public transport (rural routes). For the urban scale, shorter distances like 400 m, 1,200 m, 2 km, and 5 km were evaluated to reflect accessibility by walking, cycling, driving, and public transport (urban routes). Following the national-scale analysis, the study identifies priority underserved non-urban areas and assesses potential new

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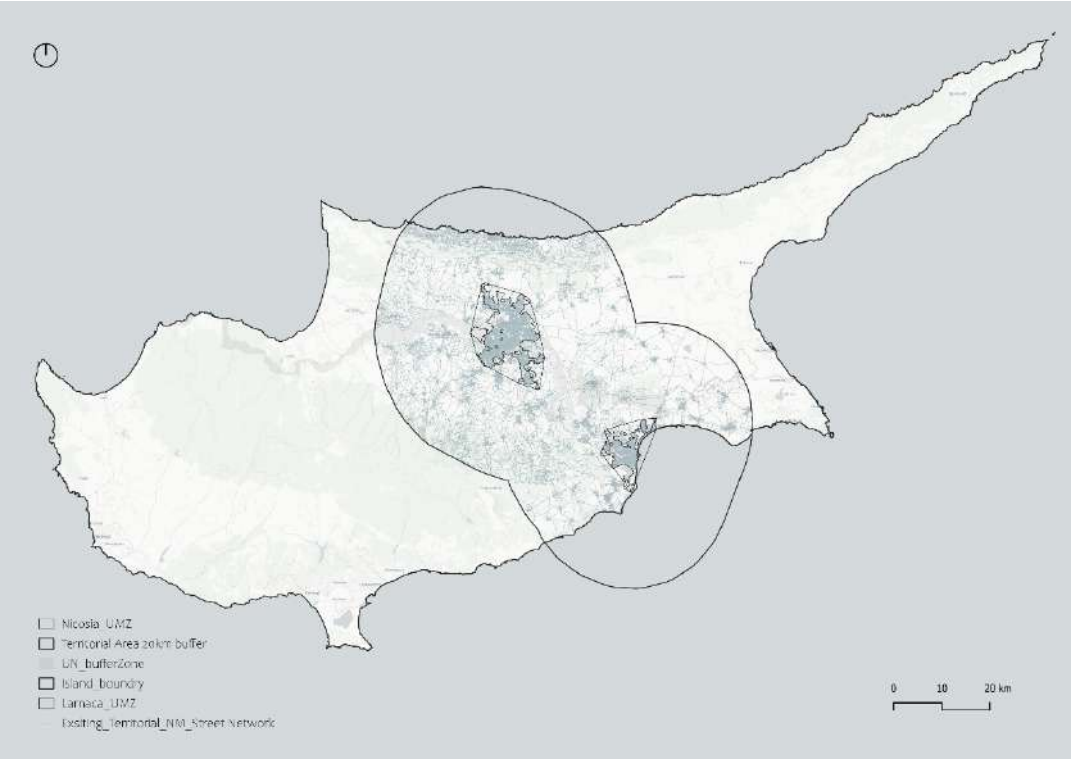

Figure 25: The territorial area covers 20km from the two major cities: Nicosia and Larnaca

KEPO locations to determine their effectiveness in serving these populations. For locations deemed effective, a qualitative assessment is provided regarding proximity to other services, which can enhance overall accessibility.

This study was designed to evaluate both the capability of existing analytical models and the availability of data to address a specific research question across different spatial scales. Through this approach, the study establishes a robust framework for understanding how well the current public transport system supports accessibility to essential services, especially in rural territories where reliance on efficient connections is most critical. By linking spatial data with accessibility outcomes, the analysis provides evidence that can guide more sustainable, equitable, and people-centered planning decisions.

2.5.1.1. Methodology

The project employed a **mixed-method approach** that included qualitative data collection through focus groups and quantitative spatial analysis to evaluate accessibility. **Stakeholder participation** involved representatives from the Ministry of Transport, Communications and Works and the Cyprus Post administration. Here, discussions in the focus groups focused on policy alignment and the operational feasibility of alternative service-centre locations. Stakeholders contributed data, validated accessibility assumptions, and reviewed analytical scenarios to ensure compatibility with existing administrative frameworks and service delivery goals.

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The methodology of **spatial analysis** includes steps to identify the locations of service centers, process population data, and running spatial analysis using open software within Geographic Information Systems (GIS). A comprehensive geo-database of service centres, population, the road network, bus routes and bus stops, and buildings have been created. These were curated to enable analysis and visualization of the results. The following datasets are included in the database:

- Citizens' service centers (KEPs), citizens' centers (KEPOs) and post offices. These were obtained as a list from citizen services and post office websites, structured manually in a dataset into GIS with coordinates identified through Google Maps.

- Population data from the Eurostat website. These data are derived from the 2021 census and are the official data from the Cyprus Statistical Service submitted to the EU in a standardized format. The raw geodata describes population density as 1Km-by-1Km cells. To achieve the most accurate results, the data was interpolated to construct a finer scale of 100m-by-100m within GIS.

- Bus routes and bus stops were retrieved from data.gov.cy in the GTFS data standard, which includes a series of text files, that include information such as routes, stops, and stop times with longitude and latitude coordinates when appropriate. The data was incorporated into Excel datasheets and organized appropriately. A secondary curation with the use of Python and data analysis tools was performed to directly link bus stops to routes and vice versa, for the dataset to be usable within a geospatial model.

- The buildings dataset was retrieved from the Cyprus cadastral service from the Inspire portal and it was organized per administrative region. The dataset was then created into a single database with administrative regional information as well as information related to the building itself such as building height (number of floors) which is used to calculate how much built density (e.g. floor space) is reached by the service centers at different scales.

- Appropriate network models created using the methods described in section 2.4. depending on the scale of the analysis. For the urban scale analysis focusing on Nicosia, the hybrid network model was used (see section 2.4.2) to ensure high accuracy for the accessibility analysis. For the national scale, covering the entire island, the priority was to prepare a comprehensive street network for analysis, hence the fully automated model was used (see section 2.4.3). Furthermore, the motorized network model is used for analysis at the scale of the clusters (10 km and above); the non-motorized models are used for analysis at the scale of the urban area (up to 5 km).

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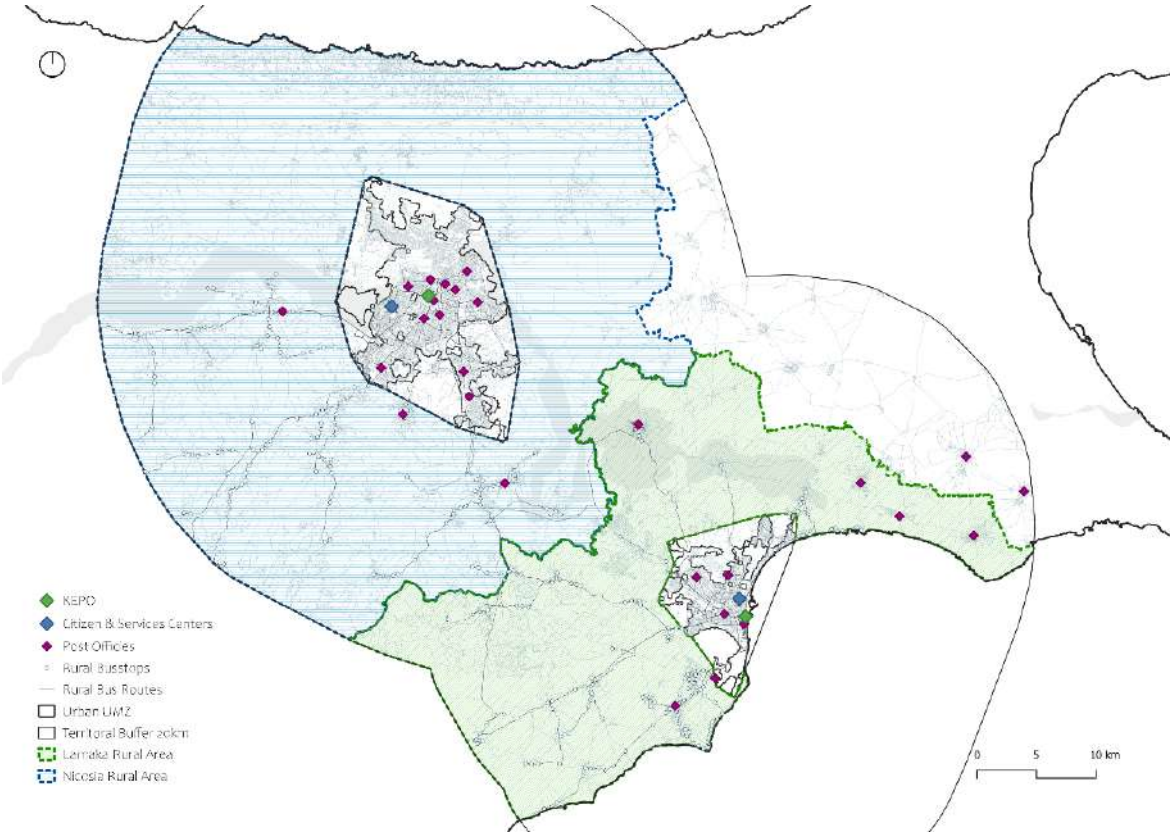

Figure 26. The targeted areas for analysis within the territorial area.

The management of datasets, spatial analysis, and map visualisation was carried out in QGIS. To measure population accessibility to each service location, the study applied the Place Syntax Tool (PST), an open-source QGIS plugin (https://github.com/SMoG-Chalmers/PST). Specifically, we used the Attraction Reach method, which calculates how many potential destinations (in this case, population cells) can be reached from a given location within a specified distance along the road network (Stavroulaki et al. 2024). Importantly, the distance is not an abstract radius but reflects real distances along the street network, ensuring realistic results. For each service location, PST summarised the population living within walking distance thresholds (250 m and 400 m) of a bus stop connected to that service.

2.5.1.2. Results

Citizens' Service Centres (KEPs)

Within the territorial area defined for this study, one Citizens' Service Centre (KEP) is located in each of the two urban areas, Nicosia and Larnaca. In Nicosia, the analysis shows that the KEP is not connected to any nearby bus stop, meaning that the service cannot be accessed by public transport. This limitation applies not only to residents of rural areas but also to residents of the city itself, resulting in a reached population of zero. In Larnaca, the situation is slightly different, as the local KEP is linked to a single bus route serving rural areas. However, the impact remains minimal: only 72 people in rural areas can access the service within 250 meters walking distance from a bus stop, and 193 people within

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400 meters. While this provides some level of accessibility, the numbers are negligible compared to the total rural population, amounting to almost zero % at the territorial level.

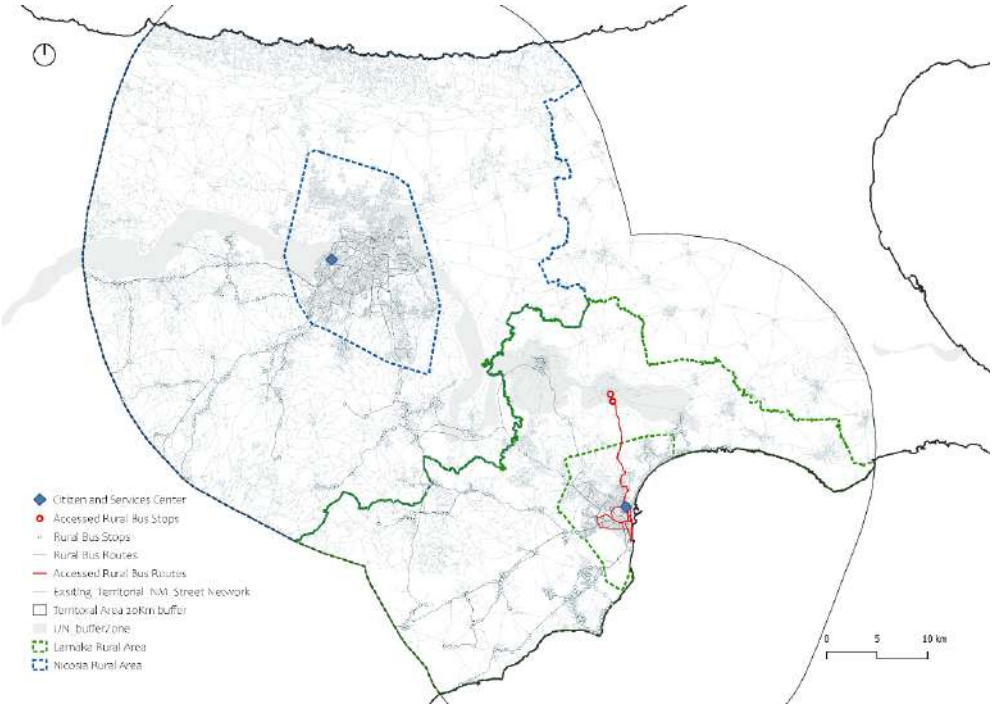

Figure 27. Accessibility to citizens' and service centres by public transport in the rural area

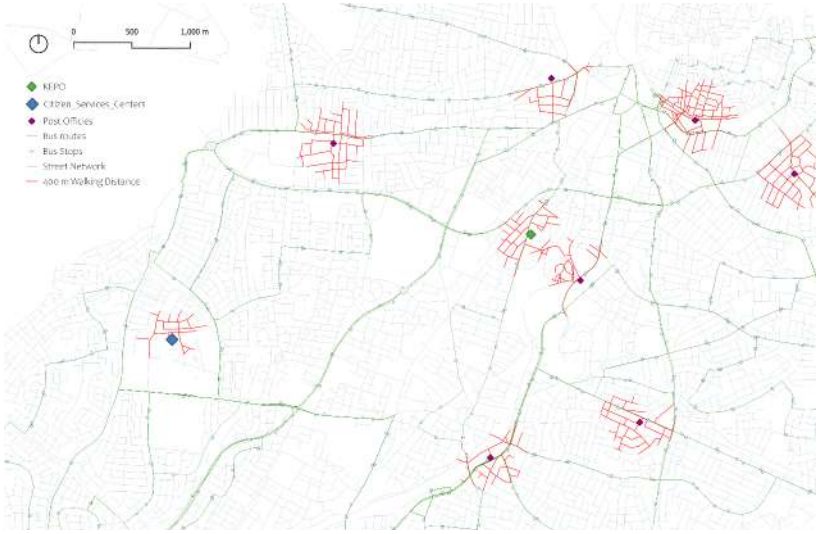

Figure 28. 400m walking distance from the service's locations in Nicosia overlapped with the existing bus routes.

Citizens' Centres (KEPOs)

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Accessibility improves somewhat in the case of Citizens' Centres (KEPOs). In Nicosia, one KEPO is located within the city and benefits from a bus stop that connects to rural bus routes. The analysis reveals that 628 people in rural areas can access the service within 250 meters walking distance from a bus stop, while 1,657 people can do so within 400 meters. Even so, this represents only about two percent of the rural population in the territory, indicating that the centre remains difficult to reach using public transport. In Larnaca, the situation is more favourable. The KEPO is located in the city centre, an area well connected by bus routes that pass through the urban core. This results in significantly higher accessibility, with 5,417 rural residents able to reach the service within 250 meters walking distance and 14,519 residents within 400 meters. In percentage terms, this corresponds to roughly 25 % of the rural population in the Larnaca territory, making the KEPO there one of the most accessible services studied.

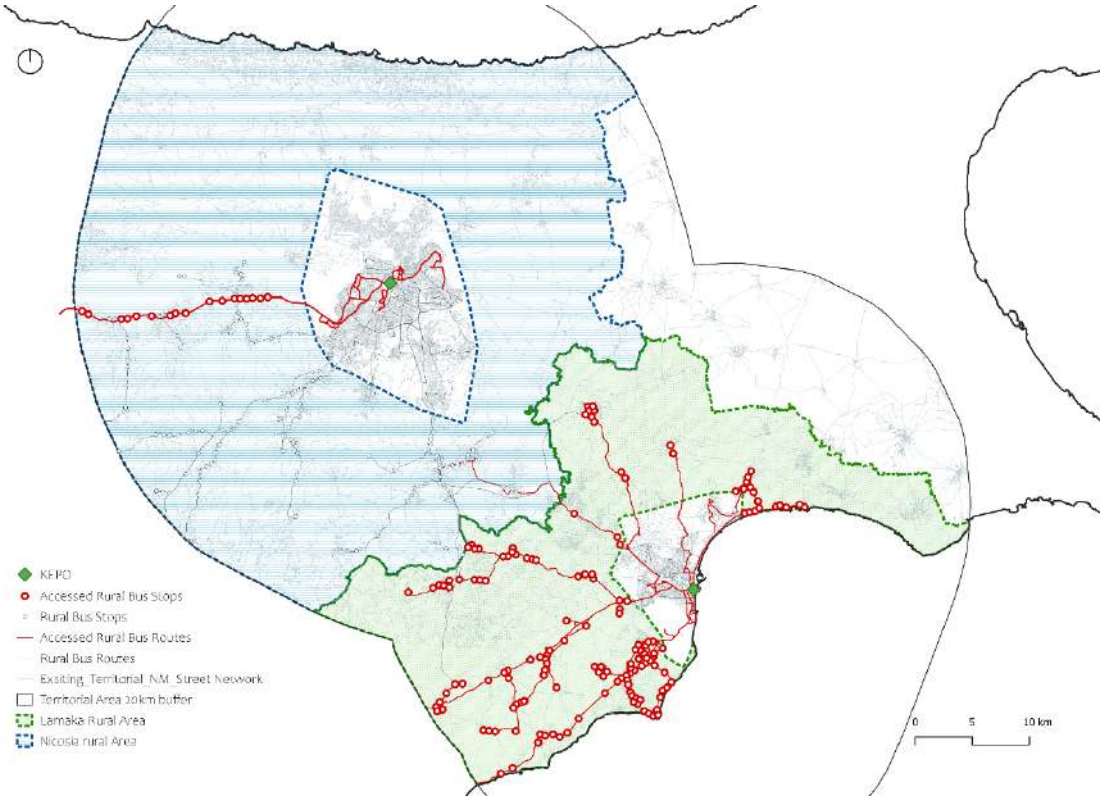

Figure29. Accessible bus stops and routes within the rural area to the Citizens' Centre (KEPO).

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Post Offices

Post offices are more numerous than either KEPs or KEPOs, which generally improves their accessibility. In total, 16 post offices were identified in Nicosia and 11 in Larnaca within the defined study territory. In Nicosia, public transport provides access to 10 of the 16 offices, or 62 %. These accessible offices serve 2,777 rural residents within 250 meters of a bus stop and 7,575 residents within 400 meters, equivalent to around 10 % of the rural population in this area. In Larnaca, public transport provides access to six of the 11 post offices, or 55 %. Because two of these offices are located in the city centre, they benefit from the same extensive bus connectivity observed in the case of the KEPO. This means that 5,417 rural residents can reach a post office within 250 meters walking distance and 14,519 residents within 400 meters, again representing about 25 percent of the rural population.

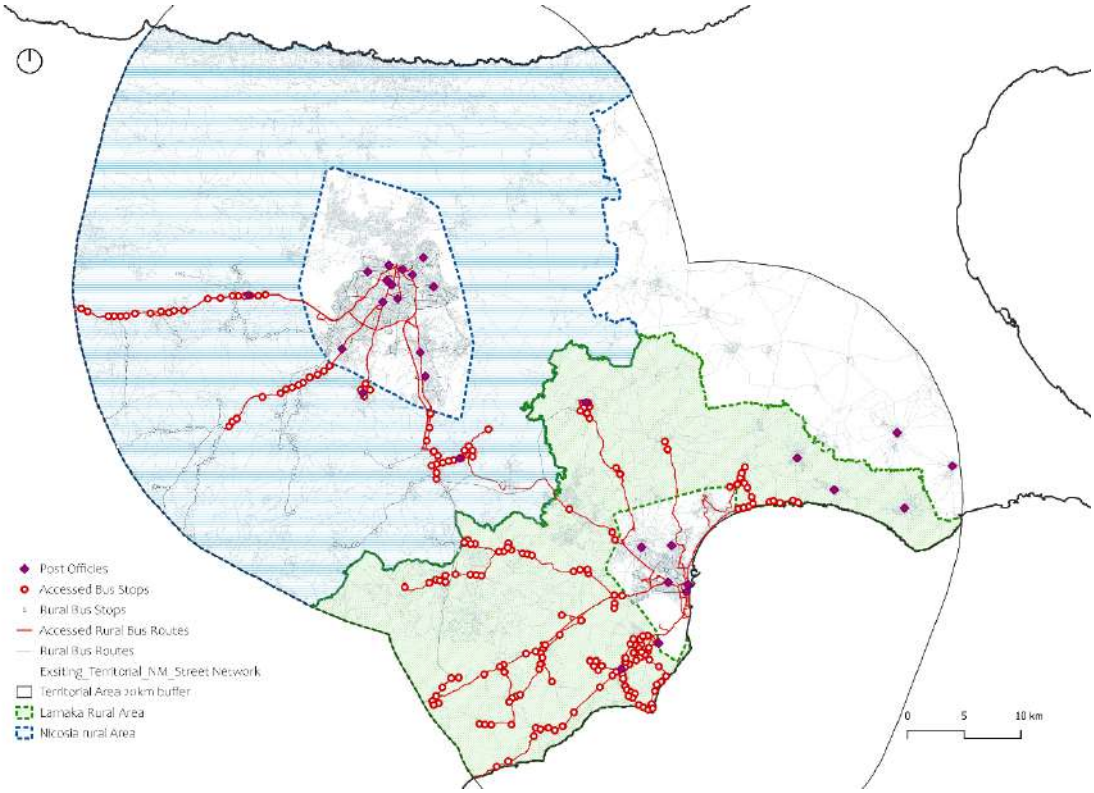

Figure 30. Accessible bus stops and routes within the rural area to the post offices.

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2.5.1.3. Conclusion

These findings highlight a clear gap between Nicosia and Larnaca in terms of rural accessibility to public services. In Nicosia, the absence of a bus stop near the KEP and the limited coverage of KEPOs and post offices result in only small fractions of the rural population being served. By contrast, the concentration of services in central Larnaca, combined with stronger bus route connectivity, allows up to a quarter of the rural population to access KEPOs and post offices. Nevertheless, even in Larnaca, the overall share of rural residents with access to essential services remains modest, underscoring persistent challenges in ensuring equitable service provision through the existing public transport network.

Table 5. Summary of results

City	Type of services	Number of Services		Population Reach		
		Existing	Reached	240 m	400 m	Percentage 400M
Nicosia	KEP	1	0	0	0	0%
	KEPO	1	1	628	1657	2%
	Post Office	16	10	2777	7575	10%
Larnaca	KEP	1	1	72	193	0%
	KEPO	1	1	5417	14519	25%
	Post Office	11	6	5417	14519	25%

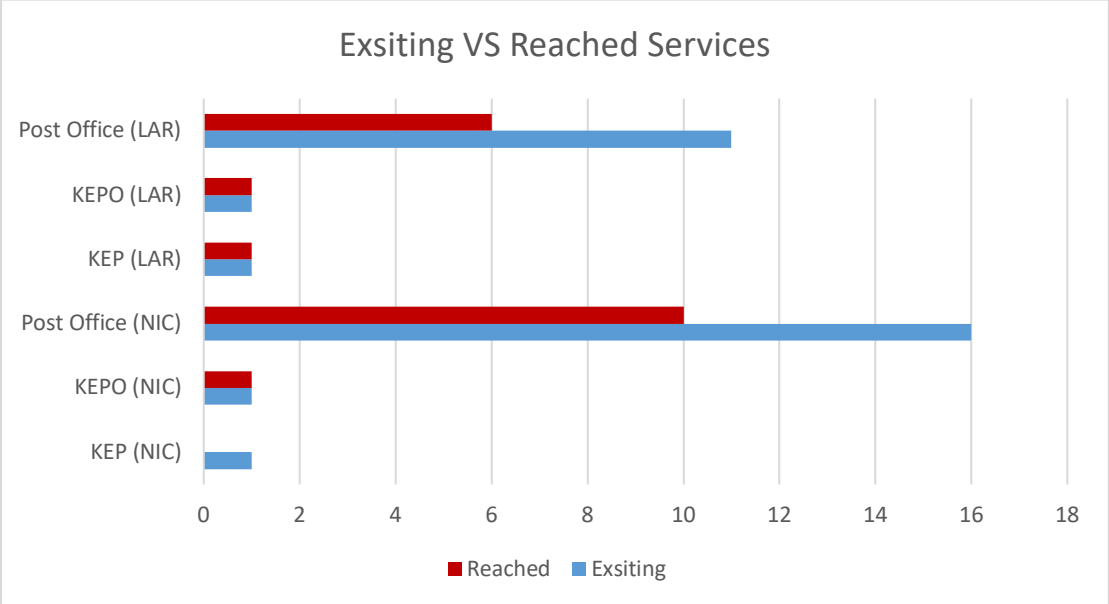

Figure 31. Comparing the existing number of services versus the ones that could be reached by public transport from rural areas.

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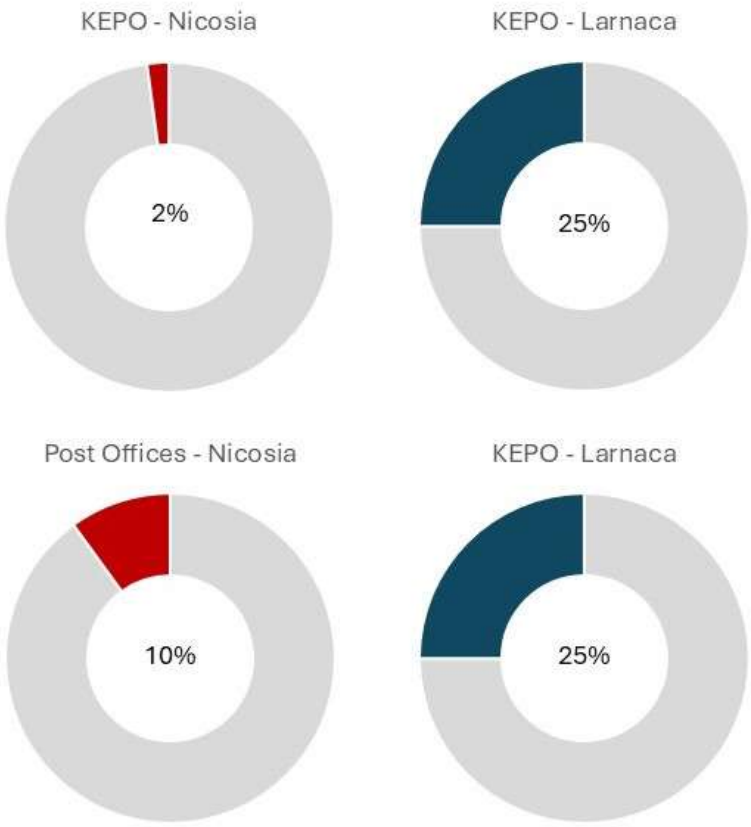

Figure 32. The percentage of the population that could reach services by public transportation from rural areas.

2.5.1.4. Recommendations

The findings of this study highlight the urgent need to improve the alignment between public service provision and public transport connectivity in Cyprus, particularly for rural populations. A first priority is to strengthen public transport connections to essential services. This can be achieved by introducing new bus routes or rerouting existing ones to directly serve Citizens' Service Centres (KEPs) and Citizens' Centres (KEPOs), with a particular emphasis on Nicosia where accessibility gaps are most severe. Beyond route adjustments, improvements in bus frequency and reliability are also essential for ensuring that rural residents can depend on public transport as a viable means of accessing services.

Equally important is the strategic placement of services. The evidence suggests that current locations, particularly for KEPs, are poorly integrated with the public transport network. Relocating certain services or introducing new service points in areas already well connected by bus routes would significantly increase accessibility. Spatial accessibility tools, such as those applied in this study, can serve as practical decision-support instruments for determining optimal locations for future services, ensuring that the largest possible share of the population can be reached.

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There is also a clear need to integrate service provision with broader mobility planning. Service accessibility should not be considered in isolation but rather as part of a wider framework for sustainable mobility and territorial equity. Strengthening multimodal connections, including walking and cycling access to bus stops, would complement public transport improvements and enhance overall accessibility. In this respect, municipalities should coordinate more closely with transport authorities to ensure that service location strategies and transport investments reinforce one another.

Finally, data quality and monitoring represent an essential component of evidence-based planning. At present, the lack of detailed public transport data, particularly regarding timetable frequencies and transfers, limits the accuracy of accessibility assessments. Developing richer datasets would enable more refined analysis and more robust planning decisions. At the same time, establishing mechanisms for the regular monitoring of accessibility to essential services would allow authorities to track progress, identify gaps, and adapt strategies over time.

Taken together, these recommendations emphasise the importance of a more integrated and evidence-based approach to public service provision and mobility planning in Cyprus. Addressing the accessibility disparities identified in this study would not only improve the daily lives of rural residents but also contribute directly to the country's broader sustainability, inclusivity, and balanced territorial development goals.

2.5.2. **Case study 2:** Accessibility of amenities from and within Pedieos Linear Park (existing and Masterplan)

The Pedieos Linear Park in Nicosia serves as a crucial urban green corridor, stretching over 9.5 km. It plays a vital role in enhancing urban connectivity, promoting environmental sustainability, and improving residents' quality of life. Despite this relatively high level of accessibility, the distribution of these amenities remains uneven across different sections of the park, leading to disparities in the quality of experience for visitors. Within the park itself, there are multiple categories of facilities, including social, sports, animal, commercial, and general amenities, with varying degrees of accessibility and distribution. The existing situation indicates that while the park is a well-utilized green space, it requires further enhancements to address accessibility gaps, improve safety, and better integrate public services. The study evaluates the park's current state and assesses the impact of a proposed masterplan designed to optimize urban connectivity, expand population reach, and ensure equitable distribution of amenities. The initiative emerged from participatory focus groups, where community stakeholders emphasized the need for a well-connected, environmentally sustainable, and inclusive public space. Key priorities included improving pedestrian pathways, integrating safety measures, expanding amenities, and fostering community engagement through cultural and recreational activities.

The masterplan assessment highlights several proposed improvements aimed at increasing accessibility, enhancing connectivity, and making the park more inclusive for different user groups. The masterplan suggests increasing the number of entrances by 20%, improving pedestrian and cycling infrastructure, and ensuring better connectivity with public transportation. Additionally, the

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masterplan incorporates the expansion of social, ecological, and cultural facilities. It adopts strategies that are crucial in reducing dependency on private vehicles, minimizing environmental impact and promoting sustainable urban mobility.

In this report, **we focus on the spatial analysis and the models' capability to answer related questions to assess the proposed masterplan in relation to the existing situation.**

2.5.2.1. Method

The project employed a **mixed-method approach** that included qualitative data collection through focus groups and quantitative spatial analysis to evaluate accessibility and connectivity.

A series of **workshops** were conducted to engage the local community in discussions about improvements needed in the park. The discussions generated 43 ideas, which were refined through a structured voting process. Participants emphasized the need for smooth pedestrian pathways, ramps for people with disabilities, and additional entrances. Infrastructure expansion and maintenance were key topics, with calls to widen pedestrian paths and fix uneven surfaces. There was also significant support for zoning different usage areas, such as designated lanes for pedestrians and cyclists, and the addition of essential services like rest areas, water stations, and parking spaces.

The **spatial analysis** involved assessing the park's current accessibility based on population reach and proximity to key amenities from and within the linear park. Data was collected on population reach within different accessibility radii, including 400, 800, and 1200 meters. In addition, accessibility to amenities from the park was evaluated, with healthcare, educational, sports, and cultural facilities analyzed for their proximity, within the park, social, sports, animal, commercial, and general amenities were mapped out to determine service distribution and accessibility.

In addition to the data sets use in Case study 1 (section 2.5.1.1) mentioned previously, this case included:

1. Existing entrances and amenities with the linear park. This data was obtained manually through field visits and using GPS tracking. The amenities were categorized based on the visual observation on the field visit and taking into consideration the categorization used in the masterplan proposal to make it easy to compare. Afterwards, it was processed into the GIS database.
2. Proposed entrances and amenities within the masterplan were processed manually in the GIS environment based on the official document sources provided by the development planners.
3. Proposed pedestrian bridges, pathways, and streets over the linear park were edited manually to the existing street network model.
4. The points of interest related to healthcare, sport, culture, and educational facilities outside the linear park were obtained from OSM.

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A comparison between the existing situation and the proposed masterplan was conducted to evaluate improvements in accessibility, connectivity, and public transport reach. The effectiveness of new entrances, bridges, and public transportation access was examined to determine their impact on connectivity and user experience. For the spatial analysis, Place Syntax Tool, open-source plugin in QGIS (https://github.com/SMoG-Chalmers/PST) was used. PST provides a systematic understanding of spatial accessibility and connectivity within the urban fabric, objectively measuring ease of access and identifying bottlenecks.

2.5.2.2. Results. Analysis of Existing Situation

Pedieos Linear Park is currently characterised by its significant spatial reach and its potential to serve as a key element of urban connectivity in Nicosia. The park extends for 9.5 kilometres, covering an area of approximately 1.3 km², and is accessed through 67 entrances that provide multiple points of integration with the surrounding neighbourhoods. This network of entrances allows for broad accessibility and positions the park as a vital urban corridor, yet its reach varies depending on distance thresholds. An analysis of the population living within different radii from the park indicates that 13,793 residents fell within 400 meters, 20,504 residents within 800 meters, and 49,019 residents, representing 19 % of Nicosia's total population, within 1,200 meters. While Figure 33 demonstrates the park's extensive coverage, it also highlights that more than four-fifths of the city's population lives beyond the immediate catchment, leaving room for improvement in extending accessibility and ensuring that the benefits of the park are distributed more widely across the city.

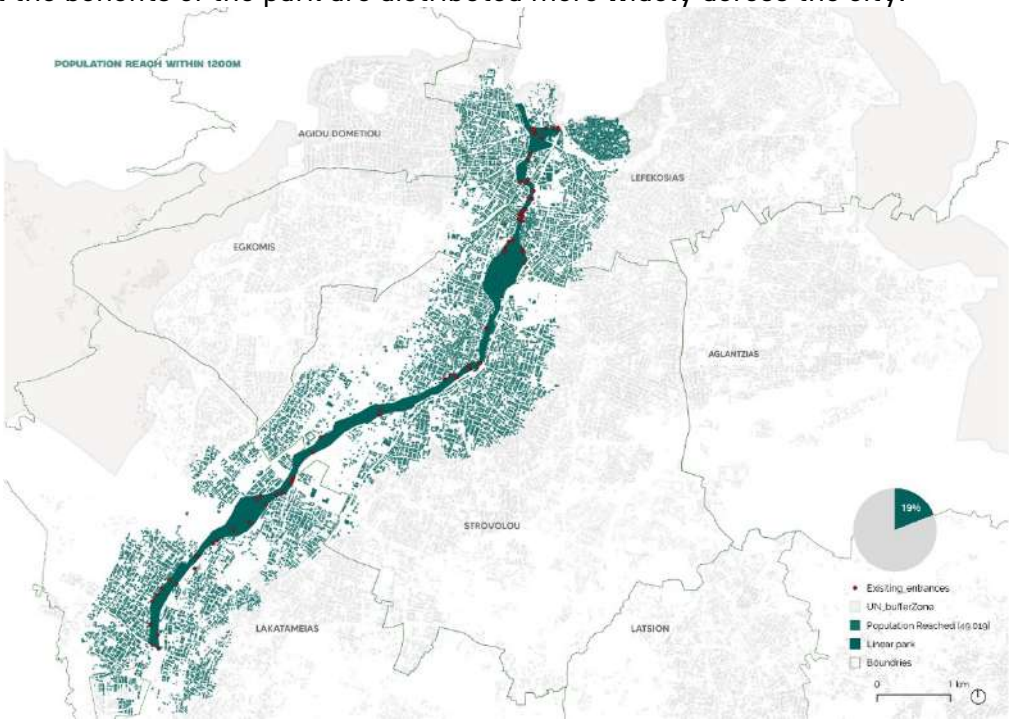

Figure33.The population reach within 1200m around the Linear Park

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Accessibility to Amenities from the Park

In terms of its connectivity to the city, Pedieos Linear Park provides relatively strong access to essential services and amenities within walking distance, though disparities in distribution remain evident. From the official entrances of the park, residents can reach a wide range of urban facilities within a 1,200-meter walking distance. These include 64 healthcare facilities, 43 educational facilities, 59 sports facilities, and 31 cultural facilities, underscoring the park's strategic location and its potential to serve as a hub of daily activity, as shown in Figure 34. This level of accessibility suggests that the park is well-integrated into a broader urban system, allowing users to combine recreational use of green space with access to important services. However, the accessibility is not uniform across the entire length of the park. Certain sections are better connected than others, which creates imbalances in the way different communities experience and benefit from the park. This uneven accessibility points to the need for targeted interventions to achieve greater equity in how the park interacts with its urban surroundings.

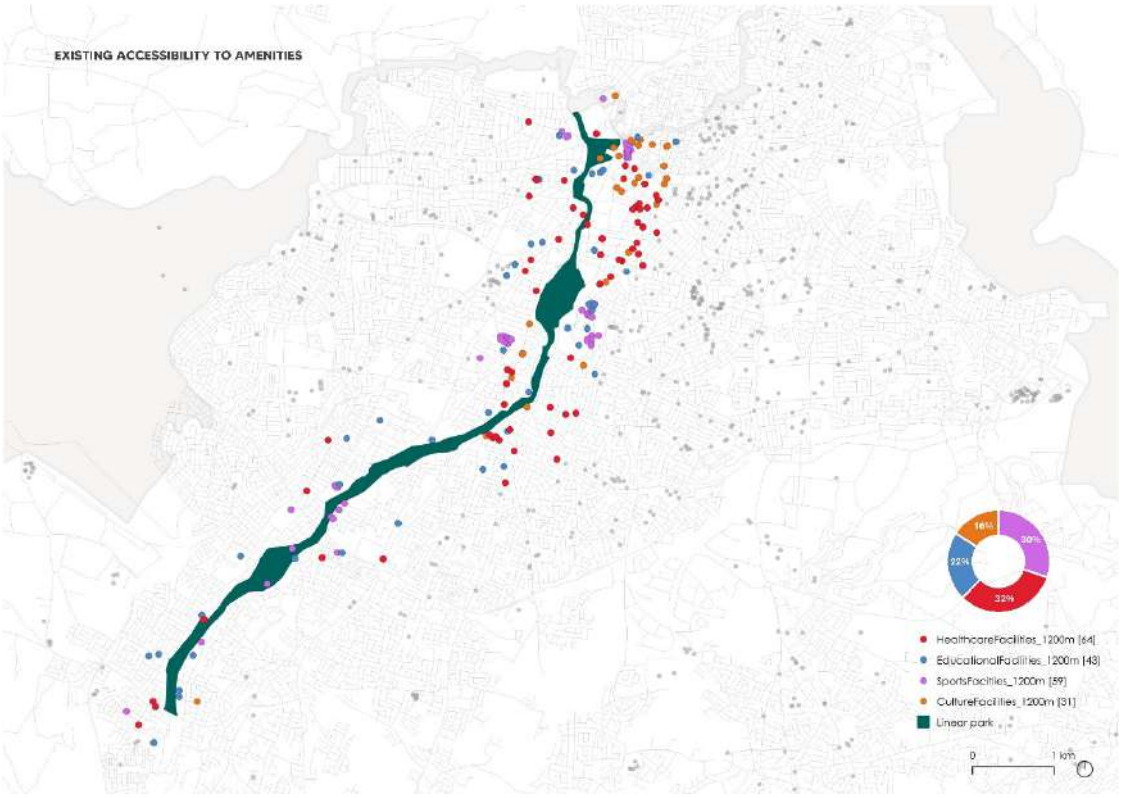

Figure 34. Accessibility to existing amenities from the Linear Park

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Amenities within the Park

Within its boundaries, the Pedieos Linear Park offers a diverse range of facilities that reflect its multifunctional character, supporting recreation, social interaction, and basic services for visitors. Amenities are categorised into five main groups. Social facilities form the largest category, with 32 spaces including seating areas, children's playgrounds, plazas, and fountain seating that encourage relaxation and community gatherings. Sports facilities are also well represented, with 11 spaces such as playgrounds, a dog park, a skate park, and outdoor gyms catering to active users. Animal facilities add a unique dimension to the park, with 7 areas dedicated to bird cages, kitten shelters, and other forms of animal care, while 5 commercial facilities, including cafés and restaurants, provide opportunities for leisure and socialisation. In addition, 18 general amenities, such as restrooms, drinking water stations, and elevators, support the comfort and usability of the park, as shown in Figure 35. Despite this wide variety, there are notable disparities in the distribution of these facilities across the park's length. Some areas, particularly the middle sections, are underserved, while others are more concentrated with services. This uneven provision suggests that while the park already functions as a key multifunctional urban asset, further improvements in the balance and placement of amenities are necessary to ensure that all users can benefit equally, regardless of where they access the park.

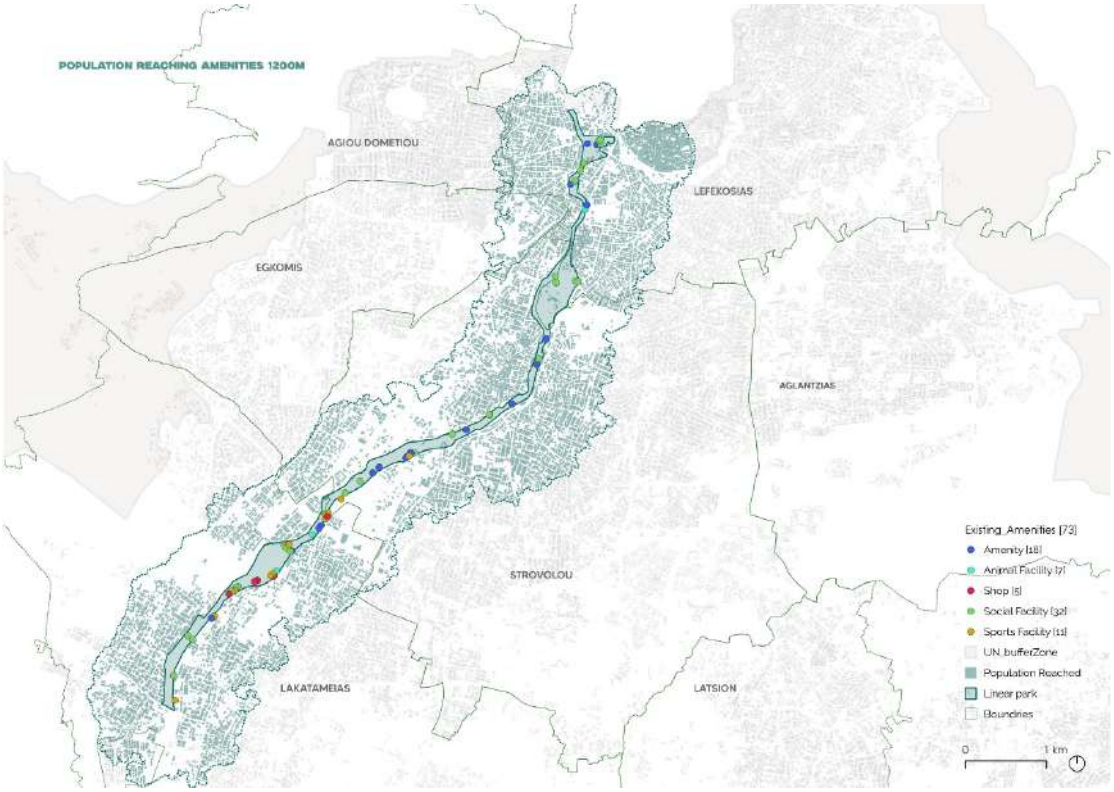

Figure 35. Reach area within 1200m to existing amenities within the Linear Park

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2.5.2.3. Results. Masterplan Assessment

Population Reach

The proposed masterplan for Pedieos Linear Park introduces several interventions designed to extend accessibility and broaden the park's catchment area. A key outcome of these changes is a modest increase in the proportion of the population living within walking distance of the park. Under the existing conditions, 49,019 residents, or approximately 19 % of the city's population, are located within 1,200 meters of an entrance. With the implementation of the masterplan, this number rises to 51,236 residents, representing about 20 % of the population, as shown in Figure 36. Although this 1 % increase may appear marginal, it reflects the impact of new connections and entrances that expand the park's reach, particularly in peripheral neighbourhoods. The master plan also introduces a 20 % increase in the number of entrances, which enhances continuity and allows the park to become more permeable within the city's street network (see figures 38 and 39). While these changes do not significantly alter the overall population reach, they demonstrate incremental progress in strengthening connectivity and creating opportunities for more residents to engage with the park. When comparing population density and accessibility between the linear park and the masterplan (see Figure 37), the increase in accessible areas is quite small and affects only a limited population. Additionally, the areas with the highest population density show the least improvement in accessibility.

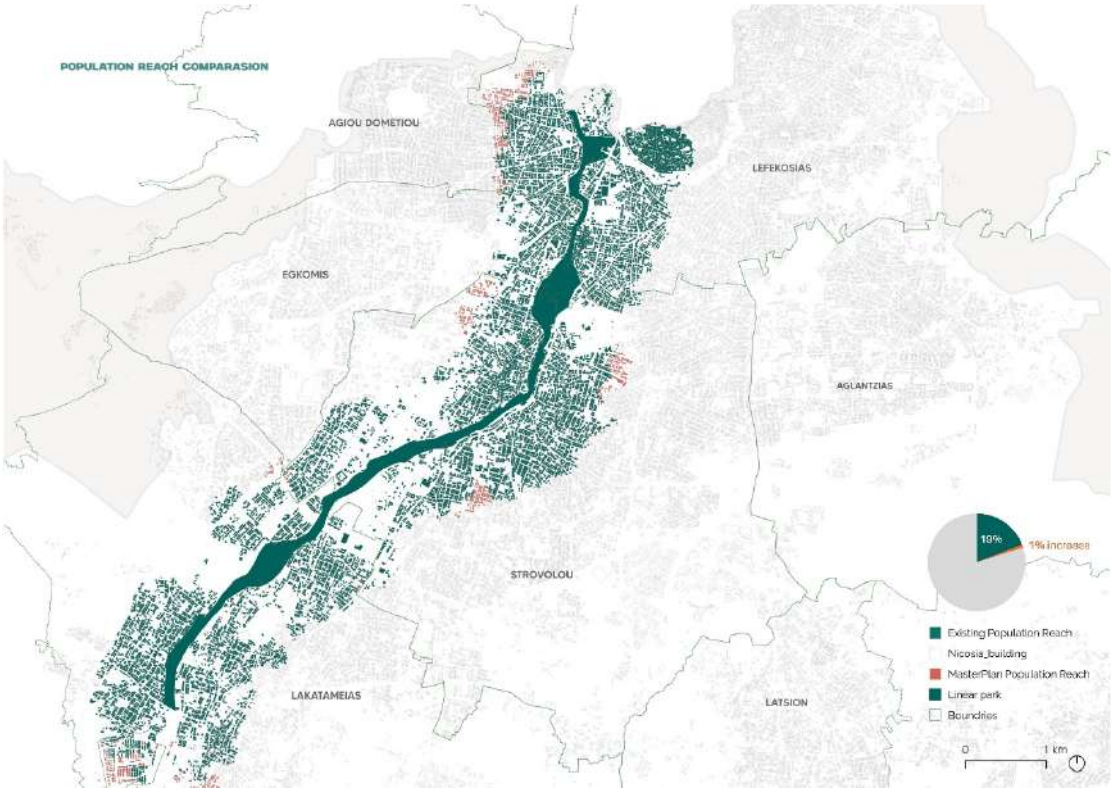

Figure 36. Comparing the population reach by the masterplan to the existing

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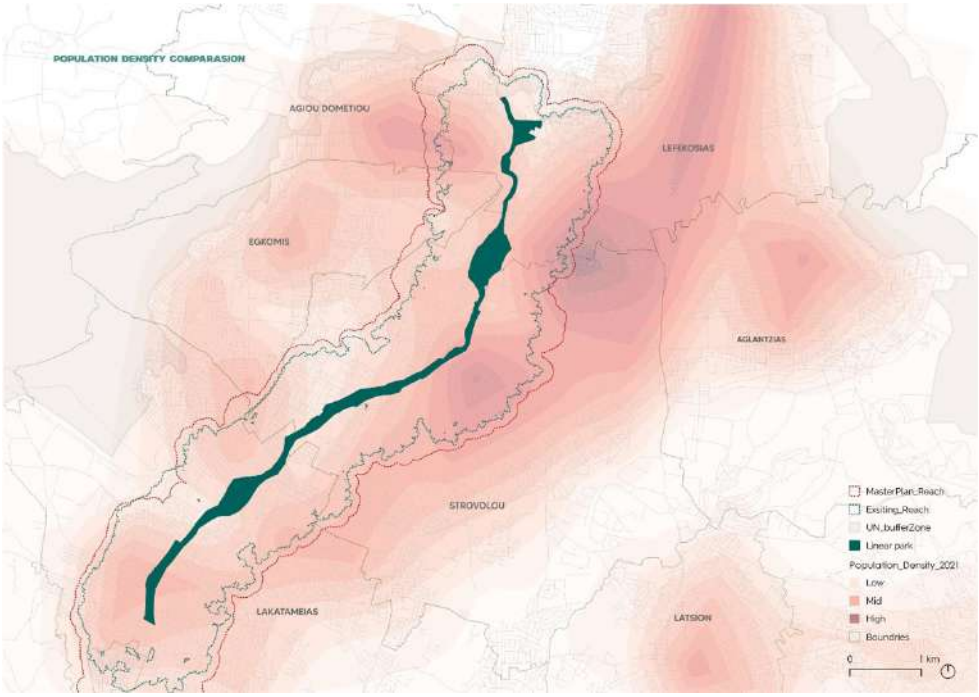

Figure 37. Comparing the reach provided in each case, overlapping the population density.

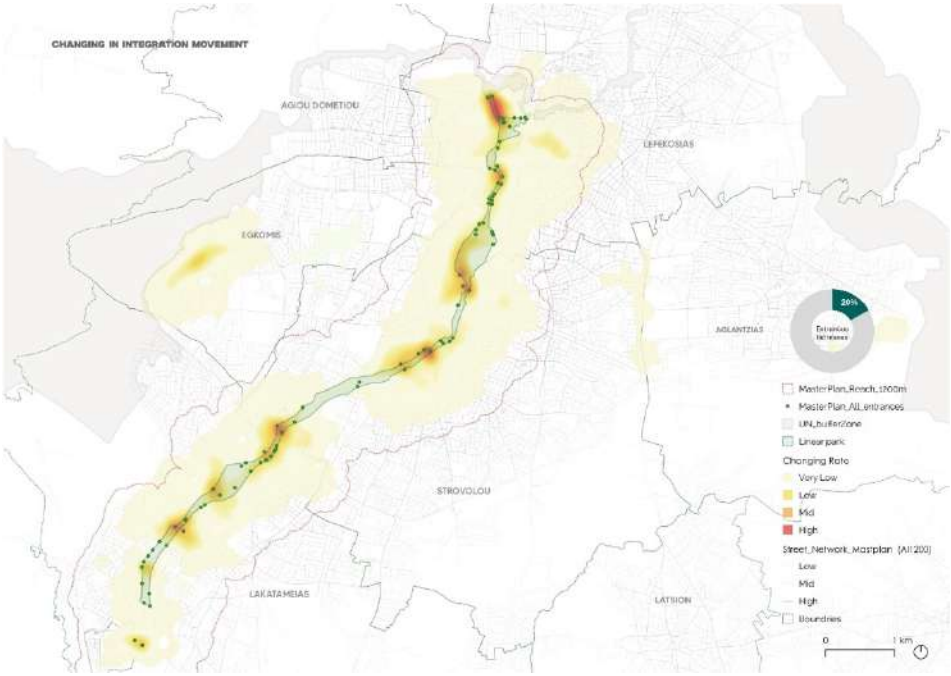

Figure 38. Change in the Integration of the network at 1200m after adding the new bridges by the masterplan.

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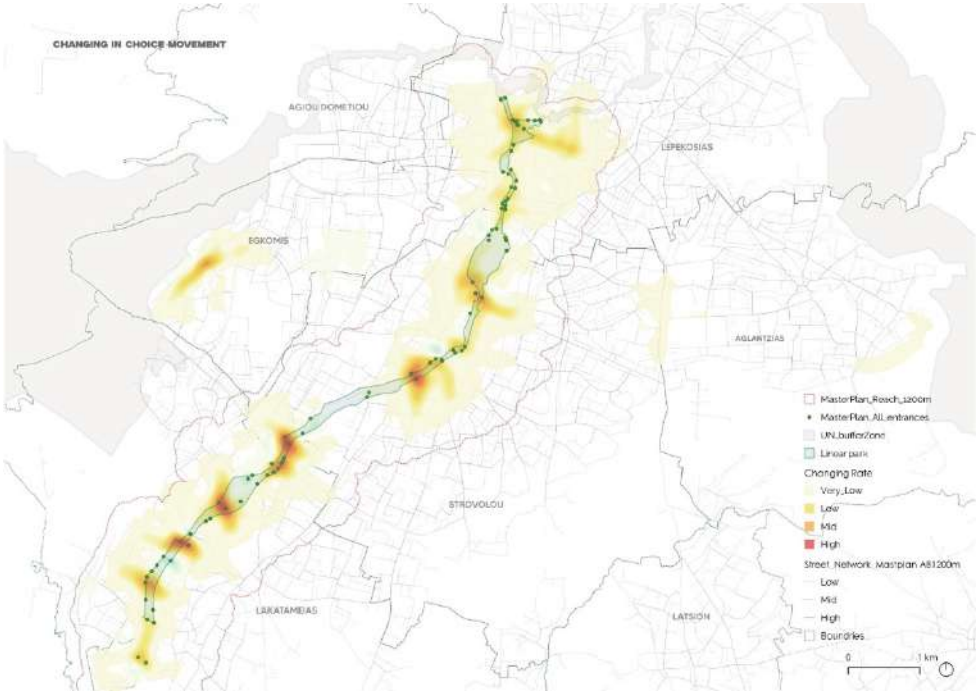

Figure39. Change in the Choice of the network at 1200m after adding the new bridges by the masterplan.

Public Transport Connectivity

Another major aspect of the master plan is its effort to align the park more effectively with the city's public transportation system. Accessibility by bus is particularly important in ensuring that the park can be reached not only by those living nearby but also by residents from other parts of the city. The plan identifies 70 bus stops within 500 meters of park entrances, significantly improving the potential for integration with the broader mobility network. In addition, it is estimated that approximately 80,797 people, or 31 % of the city's population (Figure 40), can reach the park by first accessing a bus stop within 200 meters of their residence and then walking an additional 500 meters from another stop to an entrance. This demonstrates that the masterplan increases the park's functional accessibility well beyond the immediate walking catchment and enhances its role as a metropolitan-level green space that is closely tied to sustainable modes of transport.

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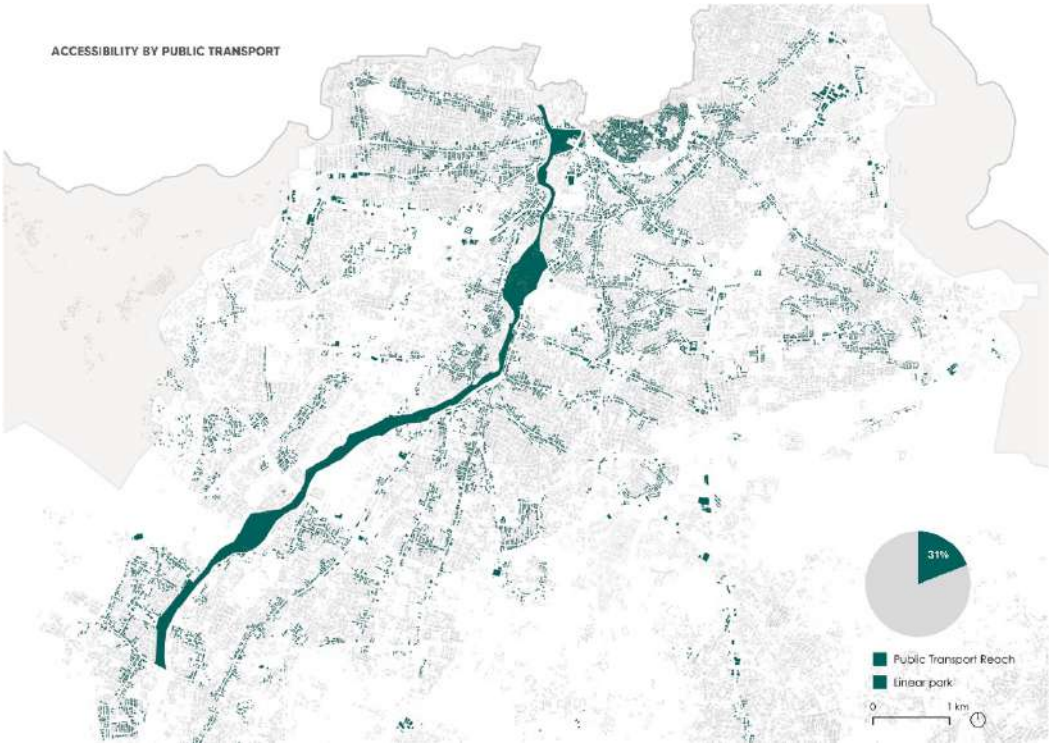

Figure 40. Accessibility by public transport using entrances added by the masterplan

Accessibility to Amenities from the Park

The master plan also improves the extent to which Pedieos Linear Park connects essential services and facilities in the city, further strengthening its role as a central urban corridor. From official entrances, the number of accessible healthcare facilities rose from 64 to 80, educational facilities increased from 43 to 56, sports facilities grew from 59 to 76, and cultural facilities rose from 31 to 34. These improvements demonstrate a clear improvement in accessibility to amenities, reflecting the strategic placement of new entrances and pathways that bring the park into closer proximity with surrounding services. While the relative gains vary across facility types, the increases collectively underscore the park's potential to act not only as a recreational landscape but also as an integral part of the daily routines of residents who rely on nearby schools, healthcare centres, and other urban functions, as shown in Figure 41.

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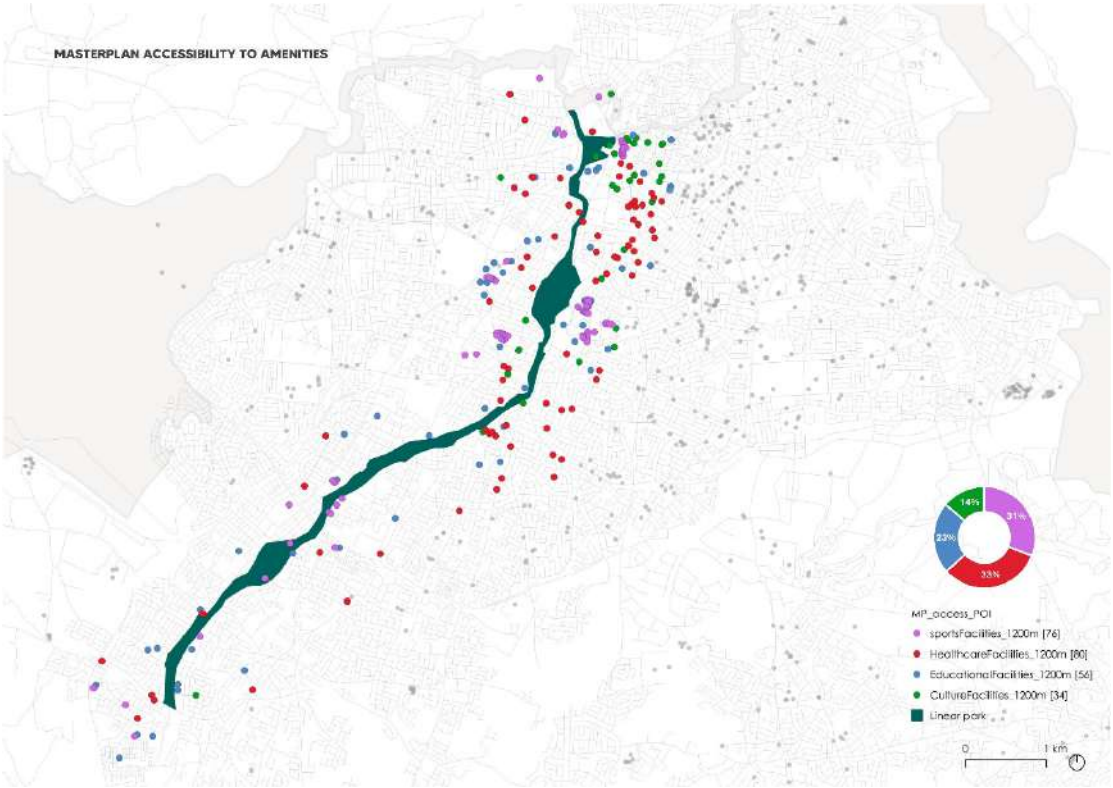

Figure 41. Accessibility to amenities in the masterplan case

Distribution of Facilities within the Park

Within its boundaries, the masterplan introduces a revised distribution of amenities, seeking to fill existing gaps and expand opportunities for diverse user experiences. However, while ecological facilities are well-distributed across the park and considered a strong addition, other facility types reveal uneven coverage. Social facilities, for example, are concentrated in the northern and southern sections, leaving the central area noticeably underserved. Similarly, cultural facilities are limited, with only a few located in the northern and southern zones and an overserved cluster in the south, while the middle portion of the park remains without such features despite its proximity to streets with high betweenness centrality. Animal facilities are somewhat better distributed, with balanced coverage in the northern and southern zones, though some middle sections of the park fall outside the 1,200-meter accessibility range. In contrast, ecological amenities, such as biodiversity zones, therapeutic gardens, and environmental education centres, are well-placed across the park, ensuring their accessibility to most entrances and users. These findings highlight that while the masterplan introduces meaningful improvements, particularly in terms of ecological value, significant disparities remain in the provision of social, cultural, and animal-related amenities, with the central areas continuing to be underserved (see Figures 42, 43, 44, and 45).

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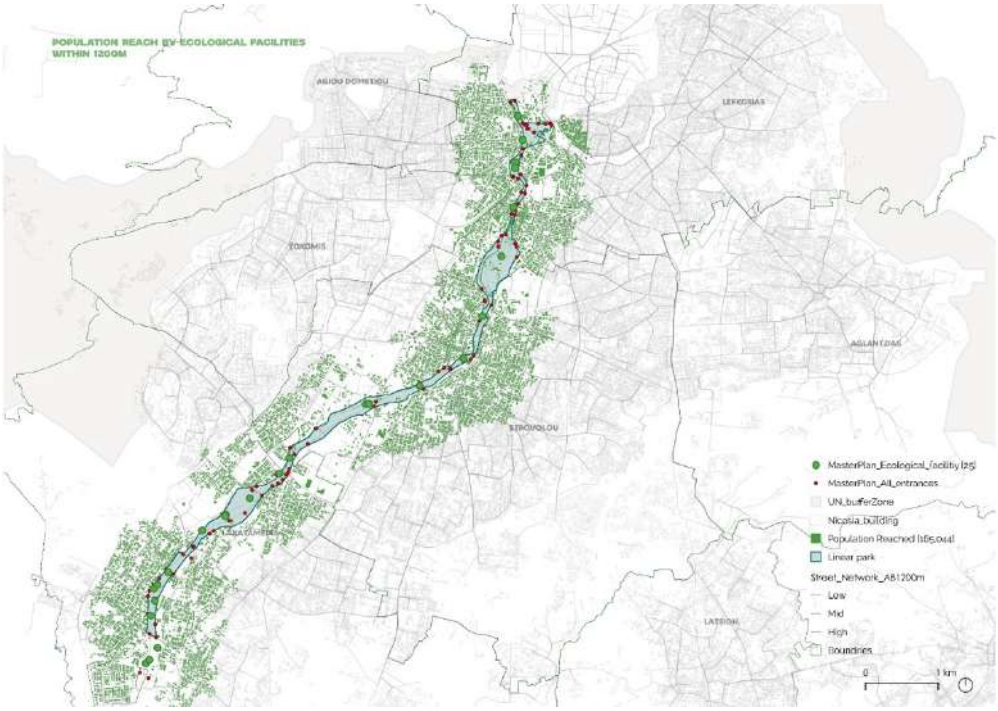

Figure 42. The population reach ecological activities within the linear park.

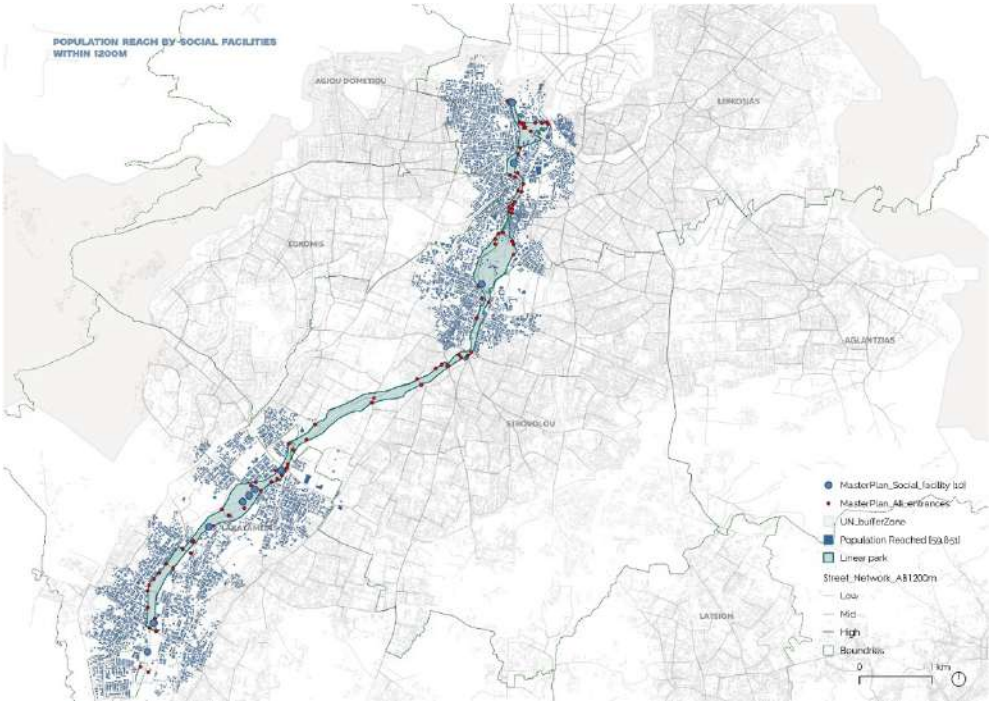

Figure 43. The population reach social activities within the linear park.

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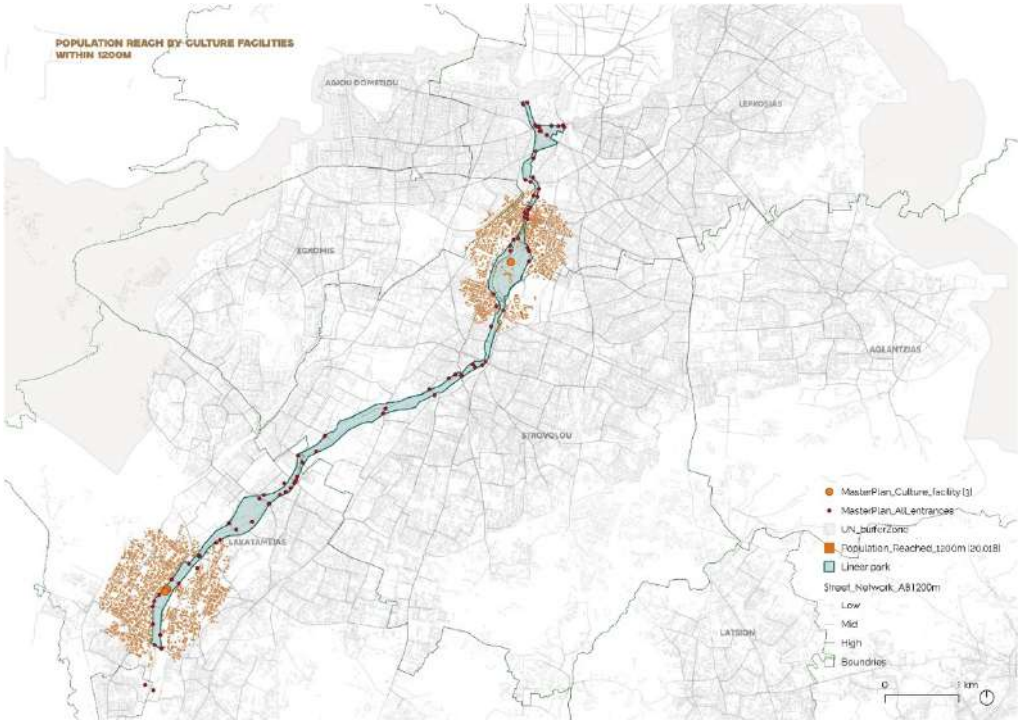

Figure 44. The population reach cultural activities within the linear park.

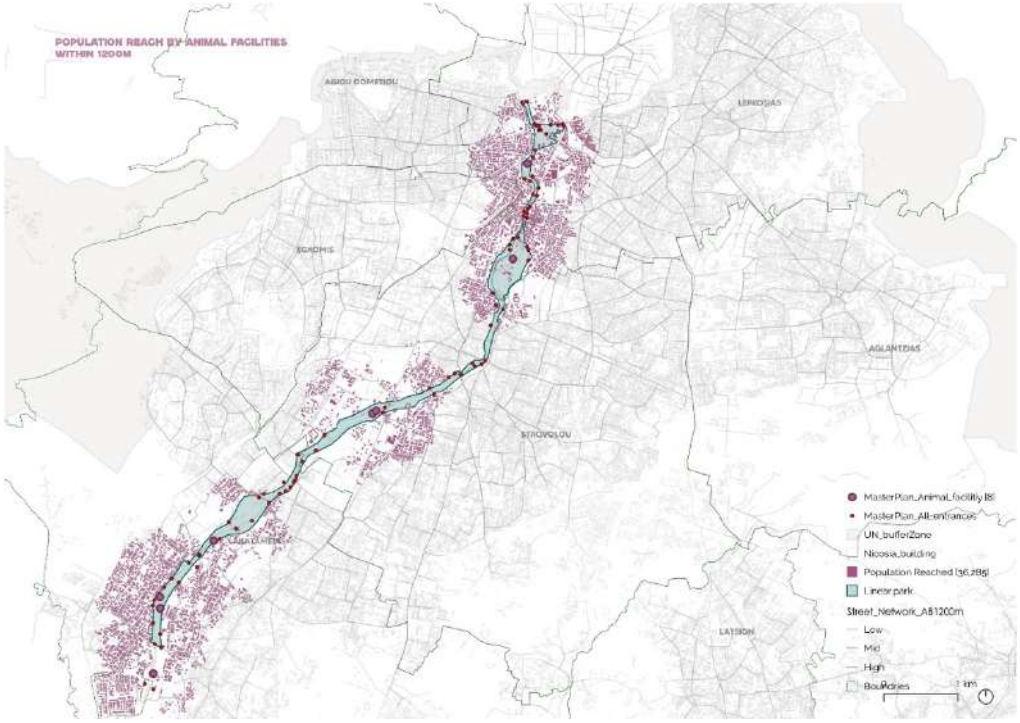

Figure 45. The population reach animal facilities within the linear park.

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2.5.2.4. Strengths, Challenges, and Prioritisation

Existing Strengths

Pedieos Linear Park already demonstrates several significant strengths that position it as a cornerstone of urban life in Nicosia. Its linear configuration allows it to function as a green corridor, enhancing accessibility across multiple neighbourhoods while offering ecological, social, and recreational value. With 67 entrances distributed along its 9.5-kilometre length, the park is highly permeable and integrated into the city's street network, allowing thousands of residents to benefit from its presence. The diversity of amenities it currently provides, spanning social, sports, animal, commercial, and general service facilities, underscores its multifunctional role and capacity to support a wide range of users. Moreover, its ecological character contributes to sustainability by offering residents a natural retreat in the urban core, thereby improving overall quality of life. These strengths make the park an invaluable public asset and a platform upon which future interventions can be built.

Improvements Introduced by the Masterplan

The proposed master plan introduces several improvements that build upon the park's existing strengths. Most notably, the plan enhances connectivity by increasing the number of entrances by 20 %, making the park easier to access from surrounding neighbourhoods. The population living within 1,200 meters of the park grows from 19 % to 20 %, representing a modest but measurable expansion of its catchment area. Integration with public transport is also strengthened, with 70 bus stops located within 500 meters of park entrances and 31 % of the city's population able to combine bus access with a short walk to reach the park. Accessibility to urban services also improves, with more healthcare, educational, sports, and cultural facilities located within walking distance of park entrances. Within the park itself, new ecological facilities are introduced, providing opportunities to promote biodiversity, environmental education, and sustainable practices. Together, these improvements enhance the park's function as both a local and citywide amenity, demonstrating the masterplan's potential to elevate Pedieos Linear Park into a more central component of Nicosia's urban landscape.

Challenges and Gaps

Despite the progress achieved, the masterplan faces several challenges that limit its overall impact. The most critical issue is that the increase in accessibility is relatively minor, raising population reach by only one percentage point. While new entrances and connections improve continuity, the benefits are not distributed evenly across the urban population. In particular, the areas of the city with the highest population densities experience the least improvement in accessibility, suggesting that the interventions are not sufficiently targeted to serve those communities most in need. Furthermore, the distribution of facilities within the park remains uneven. The central sections continue to be underserved, with notable gaps in social, cultural, and animal-related amenities, despite their proximity to high-betweenness streets that could otherwise support greater footfall and activity. These disparities risk reinforcing inequalities in access to the park's benefits and highlight the need for more deliberate planning to ensure inclusivity across the entire linear corridor.

Prioritisation Needs

To address these challenges, clear priorities must guide future development. Environmental and biodiversity considerations emerge as a top priority, as the ecological facilities introduced in the

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masterplan represent one of its strongest contributions and should be expanded further to maximise their value. Social and animal facilities, while present, require redistribution to ensure that underserved sections of the park, particularly the middle areas, receive adequate provision. Public spaces for activities and amenities that cater to different age groups also require targeted investment to increase inclusivity and encourage more consistent use throughout the park. Finally, cultural facilities, although considered a lower priority compared to ecological and social interventions, should not be overlooked, as they remain unevenly distributed and hold significant potential to transform the park into a destination as well as a transit corridor. By prioritising biodiversity, redistributing existing facilities, and addressing accessibility gaps, Pedieos Linear Park can evolve into a more balanced, equitable, and resilient urban space.

2.5.2.5. Conclusion

The assessment of Pedieos Linear Park and its proposed masterplan highlights both the progress already made and the opportunities that remain for creating a more inclusive, accessible, and sustainable urban space in Nicosia. The park stands out as a vital green corridor, offering ecological, recreational, and social benefits while connecting multiple neighbourhoods through its extensive network of entrances and diverse amenities.

The masterplan introduces several positive changes, including new entrances, better integration with public transport, and an expansion of ecological, healthcare, educational, and sports facilities. These interventions represent meaningful steps toward strengthening the park's role as both a local and metropolitan-level public asset. However, the improvements are incremental, with only a modest increase in population reach and significant disparities in accessibility across high-density areas and the park's central sections. Uneven distribution of social, cultural, and animal facilities remains a key challenge, limiting the ability of the park to serve all residents equitably. Moving forward, the success of Pedieos Linear Park depends on addressing these gaps by prioritising biodiversity, redistributing amenities to underserved areas, and ensuring that connectivity improvements directly benefit those communities with the greatest need. By refining its approach, the masterplan can transform the park from a partially accessible corridor into a fully integrated urban landmark that promotes sustainability, inclusivity, and well-being for all residents of Nicosia.

Recommendations

Based on the findings of the existing situation analysis and the masterplan assessment, several key recommendations emerge to guide the future development of Pedieos Linear Park. **First**, connectivity should be strengthened by optimising the location of entrances and linking them more effectively to streets with high betweenness centrality, ensuring that residents from densely populated areas gain improved access to the park. **Second**, efforts should be made to address disparities in accessibility by redistributing amenities more evenly across the park, particularly in the underserved central sections that currently lack adequate social, cultural, and animal facilities. Introducing additional social spaces, such as playgrounds, seating areas, and community plazas, would help encourage daily use and foster interaction among diverse groups, while expanding cultural facilities, including amphitheatres, exhibition spaces, or outdoor museums, would transform the park into a destination for cultural exchange as well as recreation. **Third**, ecological interventions should continue to be prioritised, as the new biodiversity-focused facilities represent one of the strongest contributions of the masterplan.

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Expanding these interventions and integrating them with educational programs could further promote sustainability and environmental awareness among residents. **Finally**, the design and implementation of new facilities should emphasise inclusivity by considering the needs of different age groups, people with disabilities, and vulnerable populations, ensuring that the park functions as a truly accessible and equitable public space. Together, these recommendations aim to transform Pedieos Linear Park into a well-connected, multifunctional, and resilient urban corridor that balances ecological preservation with social vibrancy and community well-being.

2.5.3. **Case study 3**: Assessing Urban Accessibility. Evaluating Connectivity and Spatial Reach in the 'Land of Tomorrow' Master Plan

As populations grow and urban landscapes evolve, ensuring equitable access to spaces, services, and amenities becomes a critical challenge. The Land of Tomorrow masterplan, a strategic development initiative located within a waterfront context of Larnaca, exemplifies such a transformative project. Its ambition lies not only in introducing new programs and infrastructures but also in fostering integrated, accessible, and multimodal patterns of urban movement. The study provides a structured evaluation of the spatial qualities of the masterplan, aiming to offer a comprehensive understanding of how the proposed urban fabric might function once realised. The assessment focuses on two core dimensions: Accessibility, which determines how easily residents can navigate and utilize urban spaces, and Reach, which assesses connectivity to essential Points of Interest (POIs) such as transit hubs, cycling lanes, and community facilities. By integrating advanced spatial analysis techniques, the project aims to identify strengths and gaps in the proposed urban design, ensuring it aligns with broader goals of sustainability, inclusivity, and resilience.

2.5.3.1. Method

The project employed a **mixed-method approach** that included qualitative data collection through focus groups and quantitative spatial analysis to evaluate accessibility, connectivity and spatial reach.

A series of **focus groups** with architects and design consultants were used to co-define research questions, interpret spatial analysis outputs, and assess alternative design scenarios. Practitioner input proved critical in refining spatial indicators, particularly those relating to walkability and connectivity, and in contextualising analytical results within broader design intentions and sustainability objectives.

Spatial analysis.
To systematically assess accessibility, we employed two primary centrality measurements: angular integration and angular betweenness centrality. The assessment was carried out at three spatial scales: the local (400m pedestrian level), local area region (1200m for cycling and public transport), and city region (2000m). Additionally, the project assessed accessibility (reach) to points of interest (POIs) to evaluate whether the proposed POIs enhance spatial equity. The analysis examines how well these POIs integrate with the existing urban structure, how effectively people can reach destinations, and their catchment area within different scales and with different mobility modes:

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a. **Public Transport Reach:**
600 m walking catchments around bus stops.
Additional 200 m catchments to assess population proximity.
b. **Cycling Infrastructure Reach**
200 m catchment around the proposed cycling lane.
c. **Points of Interest (POIs) Reach**
POI accessibility at 500 m and 1200 m network distances.

The analysis was applied across four distinct planning scenarios:

- **The existing urban situation** which serves as a baseline for comparison.
- **The proposed masterplan**, introduced independently of surrounding developments.
- **The masterplan integrated with the comprehensive area plan**, which reflects a more coordinated spatial strategy for the broader district.
- **The masterplan combined with a planning scenario**, incorporating projected enhancements such as improved marina connections or infrastructure upgrades.

This layered approach made it possible to trace the incremental spatial effects of each development stage and assess how connectivity evolves across conditions.

The **data sources** used as well as the modelling approaches were the same as in Case study 2. (section 2.5.2.1). Place Syntax Tool (PST), the open-source plugin to QGIS was used for the analyses as in Case study 1 and 2 (Stavroulaki et al. 2024).

2.5.3.2. Results

Across all scenarios, the **angular integration** and **betweenness centrality**[5] analyses show that the masterplan delivers strong improvements at the local scale but has limited impact on wider city-regional movement patterns. At 400 metres, the addition of new pedestrian links, finer-grained blocks, and continuous internal routes substantially boosts both integration (Figure 46), indicating improved overall accessibility, and betweenness (Figure 47), reflecting stronger local through-movement potential. These effects diminish at 1200 metres, where gains are more modest and largely shaped by the broader low-density context, with only specific corridors, such as the waterfront path, emerging as meaningful connectors. At the 2000-metre scale, neither integration nor betweenness changes significantly: the masterplan remains constrained by the surrounding urban fabric and the absence of larger structural connections. Overall, the results highlight a plan that performs well in creating a coherent, walkable internal network, but whose influence on city-scale connectivity depends heavily on integration with wider area plans and future infrastructural investment.

[5] For the short description of the measures and formulas used in PST, see PST Documentation (Stavroulaki et al. 2024)

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Figure 46. Angular integration in 400m across all scenarios

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Figure 47. Angular betweenness in 400m across all scenarios

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The **accessibility (reach) analysis** shows that the masterplan performs reasonably well in terms of proximity to key mobility infrastructures but remains limited by the low density and incomplete programmatic structure of the surrounding area. Most of the site falls within 600 metres of existing bus stops, and many residential locations lie within 200 metres, suggesting good baseline walk-access to public transport (Figures 48, 49); however, true effectiveness ultimately depends on service quality, which falls outside the scope of the plan. Cycling reach is far weaker: only a single external cycling lane is accessible within 200 metres (Figure 50), and the lack of continuous internal cycling infrastructure restricts cycling from becoming a viable everyday mode. Access to Points of Interest (POIs) shows a similarly constrained pattern, within 500 metres, POI supply is sparse due to extensive vacant land, while the 1200-metre catchment expands opportunities but still reveals fragmented amenities and weak integration with movement corridors (Figure 51). Overall, the reach analysis underscores that while the masterplan introduces a spatial logic supportive of walkability and accessibility, the limited density of services, discontinuity of cycling infrastructure, and dependence on external transport systems restrict its capacity to support a fully functional, multimodal urban environment without coordinated development beyond the site boundary.

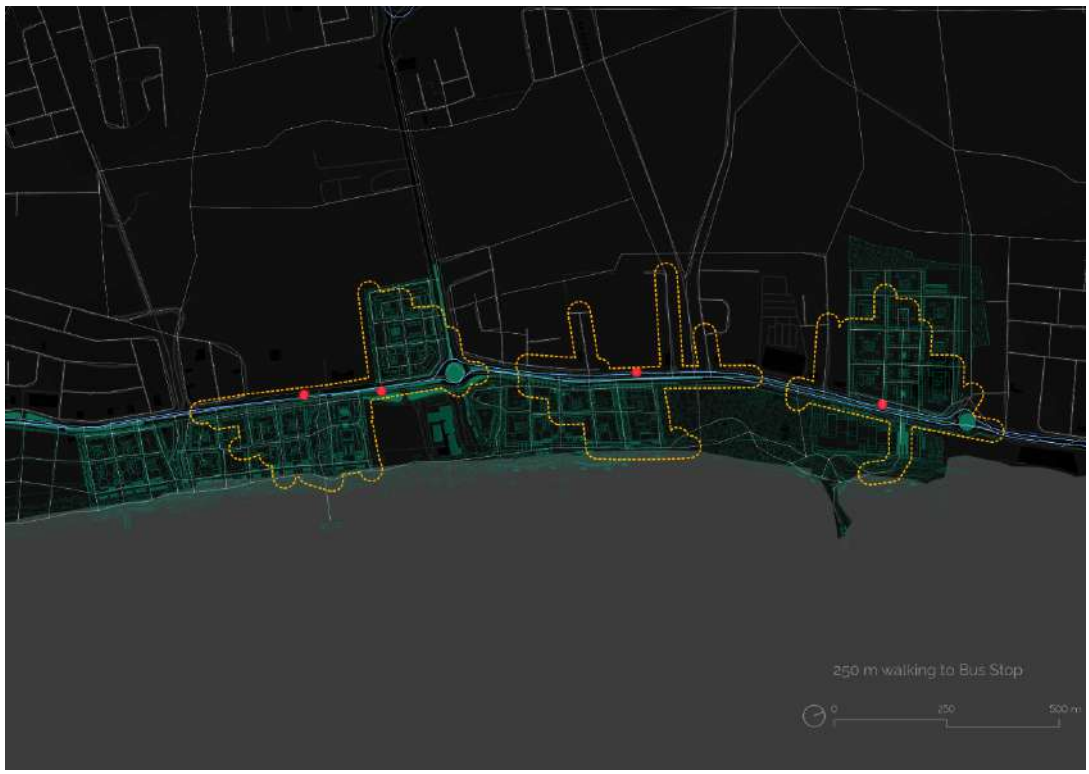

Figure 48. 250-meter walking distance from the bus stops

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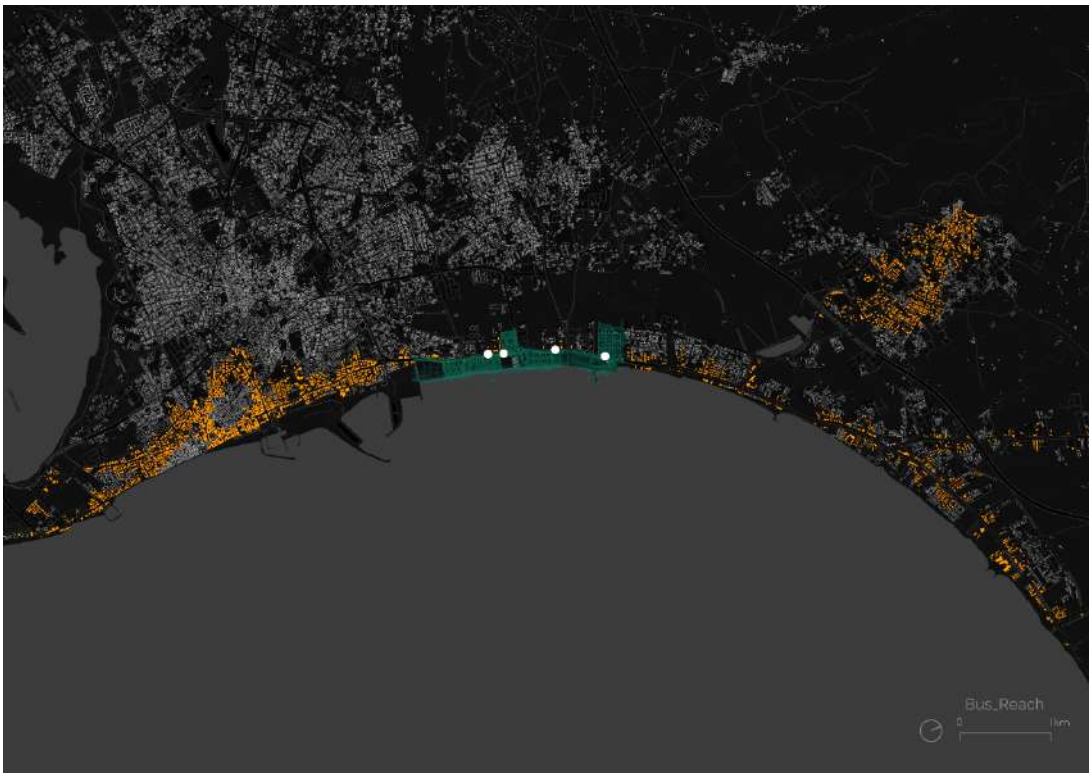

Figure 49. Population reaches within 200 meters from each bus stops connected to the bus line

Figure 50. 200 meters of reach from the biking lane using the street network

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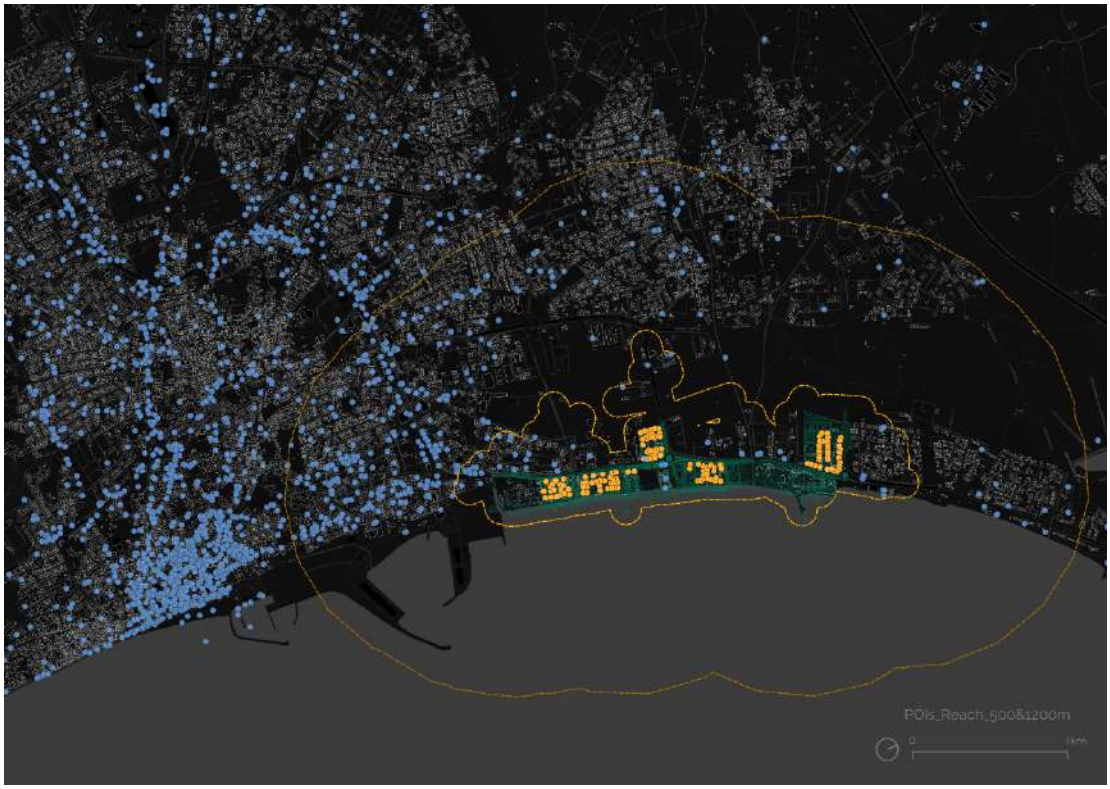

Figure 51. Position and Reach distance by the POIs offered by the masterplan compared to the existing within 500 and 1200 meters

The **high-resolution modelling of the masterplan** demonstrates that fine-grained pedestrian details play a decisive role in shaping local accessibility and movement patterns. By incorporating elements such as internal paths, service alleys, pedestrian crossings, and short connecting links, the detailed models capture micro-scale permeability that is invisible in more generalized street networks. These additional pedestrian-level connections substantially increase the density of possible routes, creating shorter path options, improving local integration, and supporting stronger through-movement across the site (Figure 52). This effect is especially pronounced within the masterplan area, where newly introduced passages significantly reconfigure the internal movement logic, producing more direct and accessible walking routes. The comparison between baseline and detailed models highlights how even small adjustments, such as stitching together adjacent blocks or adding a mid-block crossing, can meaningfully shift centrality distributions and improve access to key destinations. Overall, the inclusion of pedestrian-scale detail reinforces the finding that micro-scale design interventions are critical drivers of walkability, and that capturing these features is essential for producing realistic, evidence-based assessments of urban performance.

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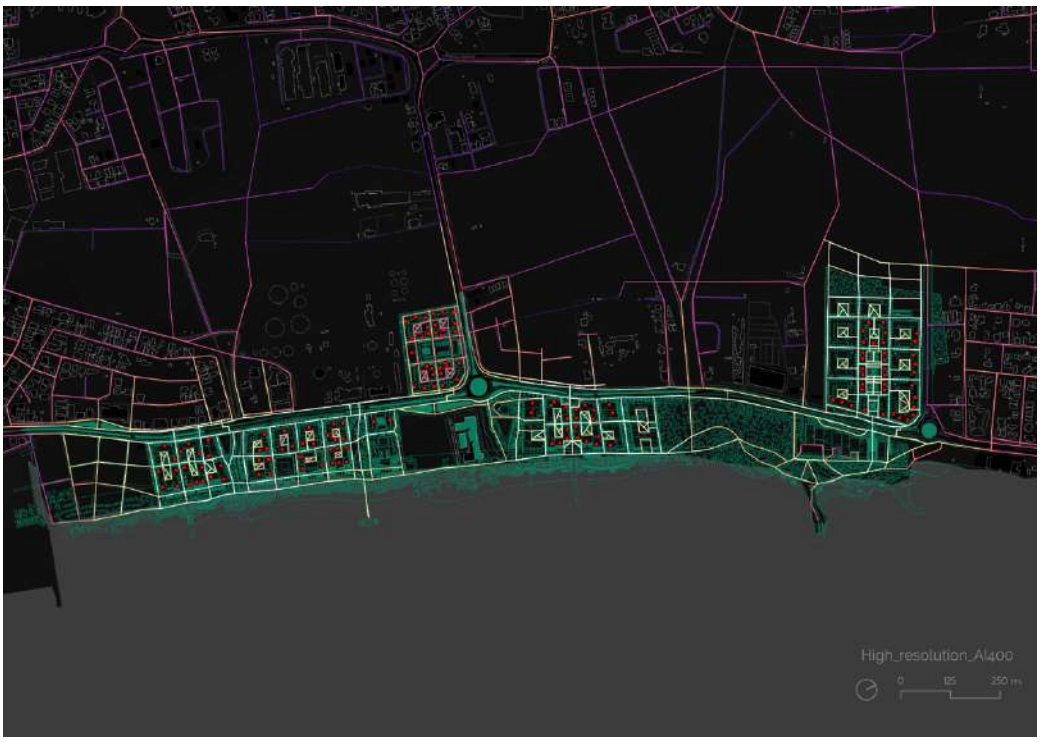

Figure 52. Overlapping POIs to the analysis of Integration for 400 meters

In summary, the evaluation of the waterfront masterplan through spatial network analysis provides a nuanced understanding of its accessibility and reach performance across different scales and planning conditions. The findings highlight a masterplan that is highly effective at the local scale, demonstrating considerable improvements in walkability, pedestrian connectivity, and internal circulation. However, these strengths are not consistently translated into regional or city-scale performance, where the development's spatial integration remains limited. At the core of the masterplan's success is its fine-grained pedestrian network, which establishes integrated corridors and local nodes of movement. The alignment of these corridors with proposed Points of Interest indicates a well-considered spatial logic, capable of supporting everyday mobility and fostering social activity.

2.5.4. Assessing applicability using the **EBDP applicability matrix**

2.5.4.1. EBDP applicability matrix

The EBDP Applicability Matrix (Deliverable 4.3, University of Cyprus 2025) was designed to assess whether the Evidence-Based Design and Planning approach can be feasibly applied in a specific urban design or planning project. **Feasibility** is understood broadly, encompassing both technical and institutional dimensions: the availability and quality of data, analytical tools, and expertise, as well as policy alignment, stakeholder support, and resource capacity.

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The EBDP Applicability Matrix can be employed both before and during project implementation to evaluate the feasibility of adopting an evidence-based approach. Prior to project initiation, it serves as a readiness assessment tool, enabling municipalities or clients to evaluate whether the conditions for EBDP are in place. For example, bidders for an urban design or planning study may be required to complete the matrix, allowing comparison of methodological rigour and preparedness across proposals. Within ongoing projects, the matrix functions as a diagnostic framework, helping teams to systematically identify constraints—such as data gaps, limited analytical capacity, or weak policy support—and to plan appropriate mitigation measures. In both applications, it facilitates a structured discussion of feasibility, promoting transparency and informed decision-making about when and how an EBDP approach can be effectively applied.

The prototype matrix distinguishes two main categories of conditions: a) Institutional support: stakeholder commitment, policy alignment, and resource availability and b) Technical capability: evidence validity, data availability and quality, degree of data processing automation, availability of analytical tools, and team competence, and answers two core questions: a) is there institutional and stakeholder support for adopting an EBDP approach? and b) can a Hybrid Spatial Model (see section 2.4.3) be technically developed based on available evidence, data, and analytical capacity?

Structurally, the matrix consists of rows representing EBDP research questions derived from the design brief or stakeholder dialogue, and columns representing the enabling conditions or constraints that determine whether these questions can be addressed through an evidence-based approach. The process begins with interpreting the design brief and formulating questions that allow both a baseline assessment and an evaluation of design scenarios—each requiring a Hybrid Spatial Model that captures relevant aspects of the built environment.

Rather than producing a single feasibility score, the matrix promotes a dual-layered assessment—horizontal (by question) and vertical (by constraint)—to reveal specific gaps and mitigation options. For instance, missing data might be addressed through open-source proxies or additional resources, but only if institutional support allows flexibility. Each parameter is rated on a 0–3 scale, where 0 indicates absence (e.g., no data or policy support) and 3 denotes optimal conditions (e.g., validated evidence, open high-quality data, automated workflows, and full institutional commitment). Separate averages for institutional and technical readiness allow comparison across cases and inform targeted improvements before or during implementation.

2.5.4.2. Evaluation of the 3 case studies through the EBDP Applicability matrix to diagnose readiness

Case Study 1. Assessing citizen services provision across urban and rural areas (Figure 53)

The spatial analysis evaluated the accessibility of existing and proposed Citizens' Service Centres (KEPs) and Citizens' Centres (KEPOs) across three scales, national, regional, and urban, using multimodal measures encompassing walking, cycling, driving, and public transport. The analysis examined the proportion of the population able to reach each service point within distances of 400 m, 1,200 m, 2 km, and 5 km, corresponding to typical ranges for walking, cycling, and driving. Public

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transport accessibility was assessed by identifying populations located within 200–400 m of bus stops directly connected to routes serving stops within 400 m of a service centre. These indicators enabled a systematic comparison of existing and proposed locations, highlighting spatial gaps in service coverage and informing equitable, evidence-based decisions about future provision. From an institutional standpoint, stakeholder engagement was strong, with both commissioning bodies contributing data, co-defining scenarios, and validating outcomes. Although policy support for evidence-based planning was implicit rather than formalized, the project benefited from clear institutional commitment and operational collaboration.

PROJECT NAME: Citizen services center provision																			
	Technical EBDP Constraints											EBDP Support							
	Evidence		Data Availability		Data processing		Tools		Competence		SCORE Constraints	Stakeholder support		Policy Support		Resources		SCORE Support	
Question 1 - population catchment of existing and new service points using diffient means of transportation	Available but not quantified	1	Available, open and high quality	3	Partially automated	2	Available and open	3	skills to conduct tasks and interpret results	3	2.4	Priority and EBDP required	3	Policy support but not quantified	2	Extra resources and time	3	2.7	
Dataset 1 - Population Density			*Available, open and high quality*	*3*	*Partially automated*	2													
Dataset 2 - service points			*Available, open and high quality*	*3*	*Majority manually*	1													
Dataset 3 - network			*Available, open and high quality*	*3*	*Partially automated*	2													
Question 2 - population catchment of existing and new service points using public transportation	Available but not quantified	1	Available, open and high quality	3	Partially automated	2	Available and open	3	skills to conduct tasks and interpret results	3	2.4	Priority and EBDP required	3	Policy support but not quantified	2	Extra resources and time	3	2.7	
Dataset 1 - population Density			*Available, open and high quality*	*3*	*Partially automated*	2													
Dataset 2 - service points			*Available, open and high quality*	*3*	*Majority manually*	1													
Dataset 3 - public transport			*Available, open and high quality*	*3*	*Majority automated*	3													
SCORE		1.0		3.0		2.0		3.0		3.0	2.4		3.0		2.0		3.0	2.7	

Figure 53. Applicability Matrix for: CASE STUDY 1

Technically, the main limitations concerned data availability and processing: official population and service-point datasets were incomplete and required reliance on open-source data and manual corrections. Nevertheless, open-access tools and the research team's expertise allowed for reliable modelling across scales.

The Applicability Matrix indicated moderate to high feasibility, with average scores of 2.4 for technical readiness and 2.7 for institutional support. While data automation and standardization remain areas for improvement, the study demonstrated that EBDP can be effectively implemented under constrained data conditions, providing actionable insights for equitable and transparent service provision.

Case Study 2. Assessing Accessibility and Connectivity to Green Spaces in Nicosia Linear Park (Figure 54)
The spatial analysis assessed the current and proposed accessibility of the 9.5 km Pedieos Linear Park, focusing on three questions: population reach within 1,200 m of existing entrances, projected accessibility after new entrances proposed in the masterplan, and the inclusivity of amenity distribution along the park.

Stakeholder engagement, coordinated through the Nicosia Intermunicipal Development Projects Company (DAEL), included municipal representatives, residents, and NGOs. Focus groups emphasized the need for safer, better-connected routes, barrier-free access, and expanded social and cultural

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facilities. While institutional support for EBDP was informal, collaboration and willingness to engage were strong, even in the absence of formal policy requirements or external funding.

On the technical side, feasibility was moderate, with scores between 2.0 and 2.6 across analytical questions. Core datasets—street network, population, and amenity data—were accessible but required extensive manual preparation and field verification, particularly for entrances and activities. Despite these constraints, open-source tools and strong analytical expertise enabled reliable results. Institutional feasibility scored lower, averaging 1.7, reflecting the absence of formal mandates or resource frameworks for evidence-based approaches. Overall, the Applicability Matrix reveals a technical–institutional gap: while analytical capacity and methods are well established, limited policy integration constrains their wider adoption. The case underscores the need for institutional mechanisms to translate evidence-based analysis into long-term planning practice.

PROJECT NAME: Linear Park																			
	Technical EBDP Constraints											EBDP Support							
	Evidence		Data Availability		Data processing		Tools		Competense		SCORE Constrains	Stakeholder support		Policy Support		Resources		SCORE Support
Question 1 - Assessing the existing population catchment to the linear park	Validated evidence	3	Available and open	2	Partially automated	2	Available and open	3	skills to conduct tasks and interpret results	3	2.6	Priority but EBDP not required	2	No policy support	0	Extra resources and time	3	1.7
Dataset 1- Population Density			*Available and open*	*2*	*Partially automated*	2												
Dataset 2- Entrances			*Available*	*1*	*Majority manually*	1												
Dataset 3- network			*Available and open*	*2*	*Partially automated*	2												
Question 2 - Assessing the proposed interventions aiming to increase the population catchment to the linear park	Validated evidence	3	Available and open	2	Majority manually	1	Available and open	3	skills to conduct tasks and interpret results	3	2.4	Priority but EBDP not required	2	No policy support	0	Extra resources and time	3	1.7
Dataset 1- Population Density			*Available and open*	*2*	*Partially automated*	2												
Dataset 2- New Entrances			*Available*	*1*	*Majority manually*	1												
Dataset 3- Modified network			*Available and open*	*2*	*Majority manually*	1												
Question 3 - Assessing the spatial distribution of proposed activities within the linear park to residence areas	Available but not quantified	1	Available	1	Partially automated	2	Available and open	3	skills to conduct tasks and interpret results	3	2.0	Priority but EBDP not required	2	No policy support	0	Extra resources and time	3	1.7
Dataset 1- Residence buildings			*Available*	*1*	*Majority automated*	3												
Dataset 2- Activities points			*Available*	*1*	*Majority manually*	1												
Dataset 3- network			*Available and open*	*2*	*Partially automated*	2												
SCORE		2.3		1.7		1.7		3.0		3.0	2.3		2.0		0.0		3.0	1.7

Figure54. Applicability Matrix for: CASE STUDY 2

Case Study 3. Assessing Urban Accessibility in the 'Land of Tomorrow' Master Plan (Figure 55)

The assessment of the Land of Tomorrow masterplan in Larnaca examined the spatial performance of proposed urban interventions through two core dimensions: accessibility, measuring pedestrian movement potential via street network centrality within 400–800 m walking distances, and reach, evaluating how commercial and civic land uses align with pedestrian flows and key Points of Interest (POIs).

Stakeholder engagement was led by the local design consultancy responsible for the masterplan. Iterative exchanges before and after the analysis ensured that the findings directly informed design revisions, particularly regarding the balance between pedestrian movement, land-use intensity, and

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environmental integration. Institutional support for EBDP was exemplary: the consultancy recognized evidence-based analysis as both a methodological benchmark and a contractual requirement, with clear alignment to sustainability and walkability objectives.
Technically, the project relied on consultant-provided datasets that required extensive manual preparation. While datasets were available, they were not open-access, limiting automation and reproducibility. Analytical tools and expertise were fully sufficient, but the manual modelling of network and land-use data constrained efficiency.

The Applicability Matrix results reflect this asymmetry. Institutional support achieved the maximum score (3.0) across all criteria, indicating strong stakeholder commitment, policy alignment, and resource provision. Technical readiness averaged 2.0, driven by solid evidence and skills but hindered by manual data handling. Overall, the case demonstrates that even under constrained data workflows, strong institutional mandates can operationalize EBDP effectively—though long-term success depends on parallel investments in data infrastructure and automation.

PROJECT NAME: Larnaca waterfront																			
	Technical EBDP Constraints											EBDP Support							
	Evidence		Data Availability		Data processing		Tools		Competence		SCORE Constraints	Stakeholder support		Policy Support		Resources		SCORE Support	
Question 1 - Assessing proposed street network for pedestrian-scale movement	Validated evidence	3	Available	1	Majority manually	1	Available and open	3	Skills to conduct tasks and interpret results	3	2.2	Priority and EBDP required	3	Policy support with benchmarks	3	Extra resources and time	3	3.0	
Dataset 1 - Proposed network			*Available*	*1*	*Majority manually*	1													
Dataset 2 - City's network			*Available and open*	*2*	*Majority automated*	3													
Question 2 - Assessing the spatial location of commercial land use in relation to the centerality measurements	Validated evidence	3	Available	1	Majority manually	1	Available and open	3	Skills to conduct tasks and interpret results	3	2.2	Priority and EBDP required	3	Policy support with benchmarks	3	Extra resources and time	3	3.0	
Dataset 1 - Proposed network			*Available*	*1*	*Majority manually*	1													
Dataset 2 - Activities points			*Available*	*1*	*Majority manually*	1													
Dataset 3 - City's network			*Available and open*	*2*	*Majority automated*	3													
SCORE		3.0		1.0		1.0		3.0		3.0	2.2		3.0		3.0		3.0	3.0	

Figure 55. Applicability Matrix for: CASE STUDY 3

Tables 6 and 7 summarize the Data used and the Stakeholder interaction for the 3 case studies. Most of the data sources were the same, confirming the minimum data requirements outlined in section 2.3. Data layers specific to the case study questions were added complementing the general data model. Regarding the street network model, both the hybrid (manually edited) and the fully automated model were used depending on the type and scale of the analysis needed. For large-scale centrality analysis (e.g. national, territorial scale) the automated model was utilized, while the hybrid model was more suitable for centrality analysis in smaller scales.

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Table 6. Comparing the data model needed across case studies with different scales

	Case 1			Case 2			Case 3		
Scale	**National and Urban**			**Urban**			**Project**		
Spatial Analysis	Accessibility analysis			Accessibility Analysis Centrality Analysis			Accessibility Analysis Centrality Analysis		
Data Needed	**Data**	**Availability**	**Modelling**	**Data**	**Availability**	**Modelling**	**Data**	**Availability**	**Modelling**
	Services points	Official	Manual	Projects' Amenities	Official	Manually	Projects' Amenities	Official	Manually
	Population	Opensource	Automated	Population	Opensource	Automated	Population	Opensource	Automated
	Street Network	Opensource	Hybrid & Automated	Street network	Opensource	Hybrid	Street network	Opensource	Hybrid & Automated
	Public Transport	Official	Automated	Public Transport	Official	Automated	Public Transport	Official	Automated
	Buildings	Official	Automated	Buildings	Official	Automated	Buildings	Official	Automated
				POIs	Opensource	Automated	POIs	Opensource	Automated

Table 7. Summary of Stakeholder interaction for the 3 case studies

Case Study	Stakeholder Groups	Engagement Methods	Purpose	Key Outcomes
Citizens' Service Centres (National & local)	Ministry of Transport, Communications and Works; Cyprus Post administration	Focus groups, scenario evaluation	Align policy and operations; assess alternative service-centre locations	Validated accessibility assumptions; informed policy on equitable service provision
Pedieos Linear Park (Nicosia)	Municipal planners, NGOs, small enterprises, residents	Workshops, (SDD), participatory voting	Define priorities for accessibility, safety, and inclusivity; evaluate masterplan scenarios	43 proposals generated; strong emphasis on barrier-free access, lighting, and community use
Land of Tomorrow (Larnaca)	Architects, urban planners, design consultants	Focus groups, scenario testing	Co-formulate research questions; interpret spatial outputs; evaluate design alternatives	Refined spatial indicators for walkability and connectivity; informed sustainable design decisions

2.5.5. Comparative assessment of applicability.

The comparative results in Table 8, demonstrate the matrix's ability to identify context-specific readiness patterns. Case 1 shows that EBDP can be effectively implemented even in data-scarce environments when institutional collaboration and open data substitutes exist. Case 2 underscores the risk of limited policy backing, where research-driven initiatives depend on temporary funding and individual commitment. Case 3 illustrates that strong institutional and policy alignment alone does not guarantee efficient implementation without investments in open, standardized data infrastructures.

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Together, these findings confirm that the **EBDP Applicability Matrix is both a diagnostic and comparative tool**, enabling planners, municipalities, and policymakers to evaluate readiness, allocate resources strategically, and adopt mitigation measures that strengthen evidence-based planning capacity.

Table 8. Comparative results of EBDP Applicability Matrix

Case Study	Scale	Stakeholder & Policy Support	Technical Readiness	Key Constraints	Average Scores*
Citizens' Service Centres	National / Regional	Strong stakeholder support, moderate policy backing, limited external funding	Solid evidence base; good data availability; partly manual processing	Lack of automation; limited official datasets	Institutional: 2.7 / Technical: 2.4
Pedieos Linear Park (Nicosia)	Local / Urban	Stakeholder interest but no formal policy mandate; internal research funding	Validated evidence, but manual data collection; limited data formats	No policy benchmark; uneven data quality	Institutional: 1.7 / Technical: 2.3
Land of Tomorrow Masterplan (Larnaca)	District / Waterfront	Full stakeholder and policy support; EBDP both priority and requirement	Strong evidence and competence; data mostly manual and not open	Manual data workflows; limited openness	Institutional: 3.0 / Technical: 2.0

2.5.5.1. Assessing the applicability of spatial data models.

Across the three case studies, the spatial analyses demonstrated the adaptability of evidence-based methods to diverse planning scales, metrics, and institutional settings. Each case employed distinct indicators and datasets tailored to its spatial and policy context: national-level accessibility measures for service provision, urban-scale connectivity metrics for green infrastructure, and project-level centrality and reach analysis for master planning. At the national and urban scales, the Citizens' Service Centres study quantified access across transport modes, revealing that while 77% of the population can reach an existing centre within 15 km, accessibility for non-drivers remains limited, highlighting the need to align service provision with future public transport strategies. At the urban scale, the Pedieos Linear Park analysis found that the park currently reaches only around 19% of Nicosia's population within a 15-minute walking radius; the proposed masterplan modestly increases reach but fails to fully redress inequalities in amenity distribution and connectivity. At the project scale, the Land of Tomorrow evaluation showed a well-integrated local street network that supports strong pedestrian flows and well-positioned commercial corridors, though regional connectivity remains incomplete.

The **evidence** needed to answer our core research questions, which covered multiple scales, stakeholders, and datasets was successfully gathered. Despite challenges with data availability, processing, and stakeholder engagement methods, our approach proved effective and reproducible. By relying on open-source data and automated workflows, we were able to overcome common obstacles like limited institutional capacity and scarce data. The resulting case studies provided clear guidance for stakeholders and actionable policy briefs for decision-makers, demonstrating that our framework is

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robust and adaptable across different contexts. The following section details the technical requirements for operating in such challenging environments.

Obtaining data. Most foundational data obtained from official sources (e.g., developers, municipal offices, or government agencies) was provided in document formats like PDFs. These documents often contained lists in tables or drawings, which required conversion into georeferenced formats (e.g., GIS-compatible files) to enable spatial analysis. Other critical data lacked documentation entirely, necessitating manual processing through field visits or online research. Validating this data was essential to ensure it was up-to-date and accurately reflected real-world conditions. Such efforts are inherently time-intensive and resource-dependent.

These challenges are amplified when working with large datasets, such as those covering national-scale infrastructure (e.g., buildings, population distribution, street networks) or regional details (e.g., points of interest, and land use). For such projects, open data sources emerged as a practical solution. These platforms provided accessible geospatial data, coding frameworks, software tools, and plugins, significantly reducing the time, labour, and specialized expertise required. By leveraging open-source resources, we streamlined workflows while maintaining accuracy and scalability, even for expansive projects.

Most of the data sources used across the case studies were the same, confirming the minimum data requirements outlined in section 2.3. Data layers specific to the case study questions were added complementing the general data model.

Modelling. Across the three projects, the evaluation of data and model preparation centred on assembling a coherent, multi-source spatial dataset capable of supporting analysis under varying institutional and technical constraints. The modelling framework relied on a combination of official, open-source, and manually collected datasets, including population grids, building footprints, street networks, public transport routes, service points, project amenities, and points of interest. Population and building data were primarily sourced from open-access and official datasets and processed through automated routines to ensure consistency and full spatial coverage. Street network data, available through open-source platforms, required hybrid preparation, merging automated extraction with manual corrections to ensure topological accuracy for reach and centrality calculations. Public transport data, provided through official digital sources, could be integrated through automated processing, enabling multimodal accessibility assessments. Project-specific amenities and service locations required manual preparation due to their heterogeneous formats and the absence of centralised repositories.

Regarding the street network model, both the hybrid (manually edited) and the fully automated model were used (see section 2.4.) depending on the type and scale of the analysis needed. For large-scale centrality analysis (e.g. national, territorial scale) the automated model was utilized, while the hybrid model was more suitable for centrality analysis in smaller scales.

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This combined modelling approach allowed the modelling process to function consistently across national, urban, and project scales while accommodating the limitations typical of fragmented data environments. The evaluation of model readiness demonstrated that lightweight, open-source routines were sufficient for producing validated base layers, provided that targeted manual interventions were used to correct spatial inconsistencies and supplement missing attributes (see Table 6). The blended strategy of automated, open-source, and manual data preparation, therefore, enabled the construction of reliable input models, ensuring that each case could move forward to the analytical stage with an internally consistent and reproducible dataset.

2.5.5.2. Evaluating the Role of Spatial Analysis in Co-Evaluating Scenarios and Trade-Offs

The spatial analysis phase played a central role in examining alternative development scenarios, identifying accessibility disparities, and revealing trade-offs across scales and transport modes. All three studies employed reach analysis to measure population catchments, amenity access, and service coverage under existing and proposed conditions. This allowed planners to quantify how different design or service configurations affected walkability, multimodal accessibility, and proximity to key urban functions. Centrality analysis, using integration and betweenness across 400 m, 1200 m, and 2000 m radii, was used to assess connectivity and spatial integration, revealing how proposed interventions would reshape movement patterns, internal circulation, and regional accessibility. By applying these metrics across multiple scales, the analyses demonstrated that spatial performance often varies significantly between local and city-region levels, highlighting a key trade-off between finely tuned neighbourhood interventions and broader metropolitan reach.

Table 9. Comparative results of the spatial analysis across cases.

	Case 1	Case 2	Case 3
Scale	National and Urban	Urban	Project
Spatial Analysis	Reach Analysis	Reach Analysis Centrality Analysis	Reach Analysis Centrality Analysis
Method	The analysis assessed how accessible the new service points are compared to other locations both within the city and across the nation. We focused on population and building density. At the city level, we tested several scenarios that combine different locations to find the most efficient layout for new services and to guide future development.	The spatial analysis involved assessing the park's current accessibility based on population reach and proximity to key amenities within and adjacent to the linear park. Data was collected on population reach within different accessibility radii. In addition, accessibility to amenities from and within the park. A comparison was conducted between the existing situation and the proposed master plan to evaluate improvements in accessibility.	To systematically assess accessibility, we employ two primary centrality measurements: integration and betweenness. The assessment is carried out at three spatial scales: the local, district, and city region. Additionally, the project assesses reachability to points of interest (POIs) to evaluate whether the proposed POIs enhance spatial equity. The analysis examines how well these POIs integrate with the existing urban structure.

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Together, the analytical techniques supported a co-evaluation process in which planners and stakeholders could compare the consequences of alternative layouts, weigh accessibility benefits against local constraints, and identify underserved populations or poorly integrated amenities. The ability to test multiple scenarios, service location options, master plan iterations, and new POI configurations enabled stakeholders to understand the relative performance of each option and to identify where design refinements or strategic infrastructure improvements were needed (see Table 9). Through this process, spatial analysis became not only a diagnostic tool but also a structured mechanism for evaluating trade-offs, guiding evidence-based decision-making, and aligning proposed developments with principles of spatial equity and multimodal accessibility.

2.6. Discussion

This study began by framing data scarcity not as a temporary deficiency but as a constitutive condition of planning under uncertainty (Davoudi, 2012). The Cypriot case studies confirm that this uncertainty is not primarily technical but institutional and epistemic. **The feasibility of applying Evidence-Based Design and Planning (EBDP) is shaped less by the availability of raw data than by the capacity of planning institutions to mobilise, interpret, and act on evidence within fragmented governance structures.** This finding challenges the implicit assumption, widespread in data-driven urbanism, that increasing data volume alone will improve decision-making. Instead, it highlights that what matters most is how data circulates between actors, how it is translated into planning discourse, and how institutional structures accommodate iterative learning.

The three case studies reveal that EBDP operates within a complex **interplay of technical possibility and institutional willingness**. Across scales, planners could perform robust spatial analyses using open data and hybrid models, yet their capacity to embed findings into planning decisions varied dramatically. Where EBDP was explicitly supported by policy mandates and stakeholder engagement, most notably in the Land of Tomorrow masterplan, evidence became a tool for negotiation and accountability. In contrast, where institutional alignment was partial or informal, as in the Pedieos Linear Park study, evidence remained peripheral to formal decision-making, dependent on the initiative of researchers rather than policy structures. These contrasts confirm that the success of EBDP depends on institutional readiness, a condition that combines technical competence with organisational commitment and a governance framework that legitimises evidence as a basis for action.

The **Applicability Matrix** proved instrumental in exposing the institutional and technical dynamics that condition the feasibility of Evidence-Based Design and Planning (EBDP). By translating readiness into measurable dimensions, ranging from data quality and analytical capacity to stakeholder and policy support, it offered a shared language through which barriers could be identified, compared, and addressed. Rather than quantifying success, the matrix makes visible the structural conditions that enable or prevent evidence-based practices from taking root. In doing so, it reframes EBDP as a capacity-building process rather than a fixed methodology; one that evolves incrementally through the alignment of data infrastructures, institutional procedures, and professional cultures. This context-adaptive, reflexive character echoes Davoudi's notion of *planning as learning*, where knowledge is

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produced through cycles of reflection, experimentation, and feedback rather than through definitive truths.

The Matrix can be **replicable** across diverse planning systems, institutional capacities, and project types, guided by three key principles:

a) **starting with relevance, not data**: analyses must emerge from stakeholder-defined questions to ensure local salience, especially in data-scarce contexts where available datasets must be repurposed to address socially meaningful concerns rather than dictating them;

b) **embedding assessment early**: applying the matrix at project inception enables teams to anticipate barriers, data gaps, competence shortages, or weak policy frameworks, and to plan mitigation strategies proactively;

c) **maintaining comparability through consistent indicators**: the 0–3 rating scale provides a basis for benchmarking readiness across municipalities or project types, while allowing for additional dimensions, such as climate resilience or social equity, to be integrated without compromising structure.

Operationally, the **replication workflow** can unfold through four iterative phases:

1. **Context framing**: interpret the design brief and define EBDP questions collaboratively
2. **Diagnostic assessment**: complete the matrix jointly with technical and institutional partners
3. **Method adaptation**: develop mitigation strategies for identified gaps, such as targeted data acquisition, training, or policy adjustment
4. **Implementation and reflection**: apply the EBDP analysis, reassess readiness, and document learning outcomes.

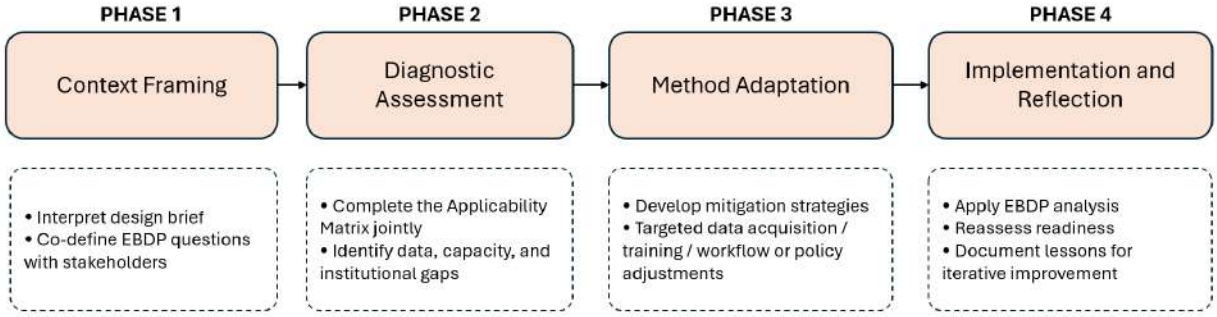

Figure. Four iterative phases of Replication workflow of EBDP

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Through this cyclical process, the matrix shifts to an instrument for institutional learning and iterative improvement. It promotes a **progressive strengthening of local readiness, transforming EBDP from a product of data availability into a practice of adaptive governance capable of functioning even under uncertainty.**

The findings also invite a reconsideration of **what constitutes evidence in design and planning**. In all three cases, the use of spatial models, whether for accessibility, reach, or centrality, was even more meaningful once discussed and interpreted with stakeholders. These dialogues transformed models from abstract representations into shared frameworks for negotiation. This process of co-evaluation, rather than co-production in the traditional participatory sense, situates EBDP within a more democratic epistemology: evidence gains legitimacy not only through analytical rigor but through its interpretability and relevance to those affected by planning outcomes. Such an approach aligns with the participatory strand of EBDP (Innes & Booher, 2015) and offers a corrective to the technocratic tendencies of data-driven planning by reintroducing deliberation into the evaluation of evidence. The spatial analysis also helped in the contextualization of the provided evidence, besides the evaluation of design alternatives using spatial analysis. This makes its role in the process come to the foreground.

Importantly, the **Cypriot context** demonstrates that **data scarcity can be a source of innovation rather than constraint**. Operating with limited official datasets compelled the development of hybrid workflows that combined open-source data, lightweight modelling, and manual validation. This adaptive approach produced reliable insights at relatively low cost, while promoting transparency through open platforms. It shows that **methodological adaptability**, rather than technological sophistication, is what enables evidence-based practices to thrive in constrained environments. However, this adaptability must be institutionalized to achieve continuity. Without policy mandates, consistent funding, and clear expectations in procurement processes, the integration of evidence remains episodic and dependent on individual initiative.

From a **theoretical standpoint**, these findings extend the discourse on evidence-based planning in three ways. **First**, they reconceptualise EBDP as a governance capability distributed across institutions rather than a purely analytical framework; a collective competence to generate, interpret, and act on spatial evidence. **Second**, they advance the concept of readiness as a measurable yet context-sensitive condition that bridges the gap between epistemic ambition and institutional reality. **Third,** they reposition the debate on data-driven urbanism away from the fetish of data accumulation toward the cultivation of trust, transparency, and translation between evidence and policy.

In summary, the discussion reveals that the real question for evidence-based planning in data-scarce contexts is not whether enough data exists, but also whether institutions are organised to make sense of it collectively. **The challenge is therefore as much cultural as technical: to transform planning organisations into learning systems capable of iteratively testing and refining their assumptions**. The EBDP Applicability Matrix, by rendering these institutional conditions explicit and comparable, provides a practical entry point for that transformation.

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2.7. Conclusion

This study has explored how Evidence-Based Design and Planning (EBDP) can be operationalised under conditions of data scarcity and institutional fragmentation. Using Cyprus as an illustrative case, it demonstrated that the primary barriers to evidence-informed urbanism lie not in the absence of data per se, but in the systems that govern its production, accessibility, and interpretation. **The proposed methodology, combining stakeholder-driven question formulation, hybrid spatial modelling, and the EBDP Applicability Matrix, offers a transferable framework for diagnosing and strengthening readiness for EBDP across varied planning contexts**.

The **implications extend beyond Cyprus**. Many small and mid-sized cities face similar structural barriers, fragmented data systems, limited capacity, and weak policy integration, that constrain the translation of evidence into planning decisions. The proposed framework offers a pathway to bridge these gaps: embedding readiness assessment within project lifecycles, institutionalising stakeholder dialogue, and aligning local priorities with spatial evidence. The findings show that institutional alignment, data integration, and participatory co-evaluation are decisive for embedding evidence in decision-making. In summary, the analysis reveals that the core challenge for evidence-based planning in data-scarce environments is not simply the availability of data, but whether institutions are organised to make sense of it collectively.

Equally, the study shows that the **value of spatial evidence does not lie in the evidence itself, but in the context-sensitive assessment of that evidence through appropriate spatial analysis**. The lightweight variant in modelling experiments demonstrates that even modest datasets, when interpreted through reach and centrality metrics and examined jointly with stakeholders, can yield meaningful insights into accessibility, equity, and scenario trade-offs. This underscores that the critical task is not generating ever more evidence, but cultivating the institutional capability to interpret, debate, and apply spatial analysis in a way that reflects local priorities and planning cultures.

By reframing EBDP as a governance capability rather than a purely analytical process, the study advances both a conceptual lens and a practical framework for transparent, adaptive, and accountable planning. This shift recognises that planning under uncertainty requires continuous cycles of learning, reflection, and adjustment, rather than the pursuit of definitive solutions.

Methodologically, **the framework demonstrates that robust spatial analysis can be achieved even in data-limited environments, highlighting that analytical rigour needs to be coupled with collaborative sense-making**. Institutionally, the Applicability matrix functions as a diagnostic and capacity-building tool, supporting early-stage feasibility assessment, iterative evaluation, and progressive institutional learning. Future research should expand its application to different governance systems, testing how iterative use of the matrix supports long-term institutional change and the co-evolution of data, policy, and practice.

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3. Developing less data-intensive spatial models for EBDP

Chapter 3 presents Research Package 2 and addresses a key barrier to the wider uptake of Evidence-Based Design and Planning: the high data and technical demands of conventional spatial models. The chapter introduces the SOAR framework (Scalable, Open, Automated, and Reproducible) as a methodological approach for developing lighter-weight spatial models that remain analytically robust while being applicable in data-constrained environments. The chapter argues that EBDP must move beyond dependence on detailed proprietary datasets if it is to be widely adopted. The SOAR framework responds by prioritising open-source data, automated workflows, and reproducibility, thereby reducing manual labour, subjectivity, and institutional barriers.

ACADEMIC DISSEMINATION OUTPUTS (full list in 5.5)	
Submitted Scientific Journal Articles	• Abdeldayem et al. (2025a), Environment and Planning B • Charalambous et al. (2025a), Cities
Conference Presentations	• Abdeldayem (2025a), CUPUM 2025 • Charalambous, N. (2024) EDMSET 2024 • Geddes (2024), KIOS GIS Day
SOAR **Scripts, Workflows**	Simons, G. (2025). ba-ebdp-toolkit, GitHub. https://github.com/UCL/ba-ebdp-toolkit
Open Datasets (Zenodo)	https://doi.org/10.5281/zenodo.16411132 https://doi.org/10.5281/zenodo.16411188 https://doi.org/10.5281/zenodo.16600733
Open Science & Preregistration	Simons, G., et al. (2024, May 27). https://doi.org/10.17605/OSF.IO/DX4WS
Blog	Simons, G. (2025, February 17). *Blog #4:* https://twin2expand.surf.com.cy/news-and-events/blog-4-introducing-soar-a-scalable-open-automated-and-reproducible-urban-data-model-for-the-eu/ Charalambous, N. et al (2025, 30 August) Medium

The framework is designed to function across different spatial scales and planning contexts, enabling comparative analysis and early-stage evidence generation. Methodologically, the chapter details the use of open datasets, primarily Overture Maps and open population and land-cover data, combined with Python-based automated workflows for data retrieval, cleaning, simplification, and analysis. The resulting spatial models generate core analytical outputs relevant to EBDP, including measures of connectivity, centrality, accessibility, and functional reach. These outputs form a flexible analytical baseline that can be incrementally refined as more detailed data become available. Chapter 3 concludes that less data-intensive, open, and automated models can meaningfully support evidence-based planning without undermining analytical credibility. The SOAR framework lowers the entry threshold for EBDP, making it accessible to smaller municipalities, data-scarce regions, and cross-

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national research contexts, while complementing more detailed modelling approaches where data permit.

Evidence-Based Design and Planning (EBDP) rely on spatial analytical workflows to derive insights from street network structure, land-use proximities, demographic patterns, and other urban datasets. However, creating such models is often time- and resource-intensive, particularly when manual preprocessing is required to fetch, clean, and prepare data. Manual workflows remain labour-intensive and prone to user subjectivity, which limits reproducibility and scalability, two qualities essential for robust and transferable urban modelling (Fleischmann et al., 2025).

Automated workflows leveraging open-source tools and data have emerged as a promising alternative. Automation can substantially reduce preprocessing time and effort, enabling researchers to focus on higher-level analysis and interpretation (Boeing, 2017; Porta et al., 2006). Recent advances demonstrate the potential of large-scale automated models, including nationwide street network analyses in the US (Boeing, 2018), multi-variable urban form models in the UK (Simons, 2021), and global city datasets (Yap & Biljecki, 2023). Automated workflows also improve reproducibility, as standardised procedures reduce subjective decision-making during data handling (Kitchin, 2014). Meanwhile, the reliability of open-source, community-generated datasets such as OpenStreetMap has been repeatedly demonstrated when coupled with robust automated cleaning routines (Haklay, 2010). These qualities make automation particularly valuable for comparative studies and for scaling analyses across multiple cities (Batty, 2017; Longley, 2015).

The aim of Research Package 2 is to investigate the use of open analytical models that are less data-demanding but still rigorous and reliable. The goal is to reach new adaptive, comparable, and generalisable EBDP models and method suitable for diverse planning environments and governance frameworks. These models aim to make EBDP more accessible to practitioners working in data-scarce environments and to enhance its flexibility across different types of projects. The question is 'what should a 'lightweight model' (i.e. less data intensive) include at the minimum to be effective and accurate in assessing the impacts of design and planning interventions from a socio-economic and a social-ecologic perspective'?

Besides the independent outcomes of this research package, the developed data models and workflows feed into Research Package 1 and Research Package 3. The fully automated workflow for the creation of the street network model for Cyprus that was already presented in Section 2.4.3. and was tested for reliability of results (section 2.4.4) and for applicability in real projects (section 2.4.5) is a direct outcome of Research package 2. The automatised analytical methodologies developed for Cyprus were further developed and scaled up to create the SOAR, an EU-wide Scalable, Open, Automated, Reproducible data model, that will be presented in the following section.

3.1. The SOAR (Scalable, Open, Automated, Reproducible) model

The SOAR (Scalable, Open, Automated, Reproducible) model explores this topic within the European Union. Globally scoped models (e.g., from OpenStreetMap or Overture Maps) can be more variable in

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data quality and lack detailed census data. Conversely, national-scale datasets may offer richer, more consistent data but are limited to a single country and can have restrictive licensing. The interest of the project extents greater than a single country, meaning that we are still interested in datasets with global coverage. The approach used for SOAR represents **a methodological trade-off by limiting the extent to the EU, which allows EU-specific open datasets to be leveraged in addition to global datasets.**

SOAR integrates open EU datasets, including Eurostat's 2021 High-Density Clusters & 1x1km census statistics (population density, employment, demographics, and population change), and Copernicus Urban Atlas providing data on urban blocks, building heights, and tree canopies. These are complemented by Overture Maps data, supplying detailed information on street networks, infrastructure, points of interest, and enhanced building footprints supplemented with data from Google and Microsoft.

Using 'lightweight' reproducible workflows, SOAR processes 11.37 million street segments across 699 EU towns and cities, as defined by Eurostat High Density Clusters. It computes per-segment street centralities, land-use proximities and counts (for a range of pedestrian distances) for 24 land use themes, access to green spaces, nine building and five block morphological metrics, and interpolates twelve census categories

3.1.1. Methodology, Data Sources, and Processing

To ensure transparency and reproducibility, the SOAR model is built using open-source tools and open data sources. The code is licenced under AGPLv3 (GNU Affero General Public License, version 3) and is published on GitHub: https://github.com/UCL/ba-ebdp-toolkit

3.1.1.1. Data sources

A key aspect of the SOAR methodology was the integration of specific, high-value datasets (where available for the EU) with global sources of data:

- Eurostat (2021): Provides High-Density Cluster data to rigorously define urban extents, and homogenised 1x1km census statistics (population, employment, etc.). Link: https://ec.europa.eu/eurostat/web/main/home
- Copernicus: The Urban Atlas (2018) is used to derive urban blocks, building heights, and tree canopy data. Link: https://land.copernicus.eu/en/products/urban-atlas
- Global Datasets (Overture Maps): The project opted for Overture Maps (instead of OpenStreetMap) for street networks, infrastructure, Points of Interest (POIs), and building footprints. This choice was based on Overture's more formalised data release cycle, improved data validation (for POIs), and expanded building footprint coverage (supplemented with Google and Microsoft data). Link: https://overturemaps.org

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Figure 56. Urban centres (High-density clusters): clusters of contiguous grid cells of 1 km² with a density of at least 1 500 inhabitants per km² and a minimum population of 50 000 after gap-filling.

3.1.1.2. Workflow

The workflow is based on Python and makes use of readily available open-source packages such as:

- cityseer (https://github.com/benchmark-urbanism/cityseer-api/) (Simons 2023)
- momepy (https://docs.momepy.org/)
- geopandas (https://geopandas.org/)

The workflow includes:

- **Data Ingestion:** Scripts automatically process EU data sources (boundaries, urban blocks, trees, building heights) and extract Overture data (streets, POIs, buildings) for each of the urban boundaries (Figure 59).

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- **Network Processing:** The cityseer package is used to apply automated street network cleaning workflows. This includes level-aware cleaning to correctly handle bridges and targeted merging based on highway classifications (Figure 58).
- **Metric Computation:** Packages such as cityseer and momepy run the core analysis, and outputs the final metrics.
- **Dissemination:** All data is stored and processed as GeoPackage (.gpkg) files to simplify workflows and dissemination (developmental iterations of SOAR used a Postgres database instead).

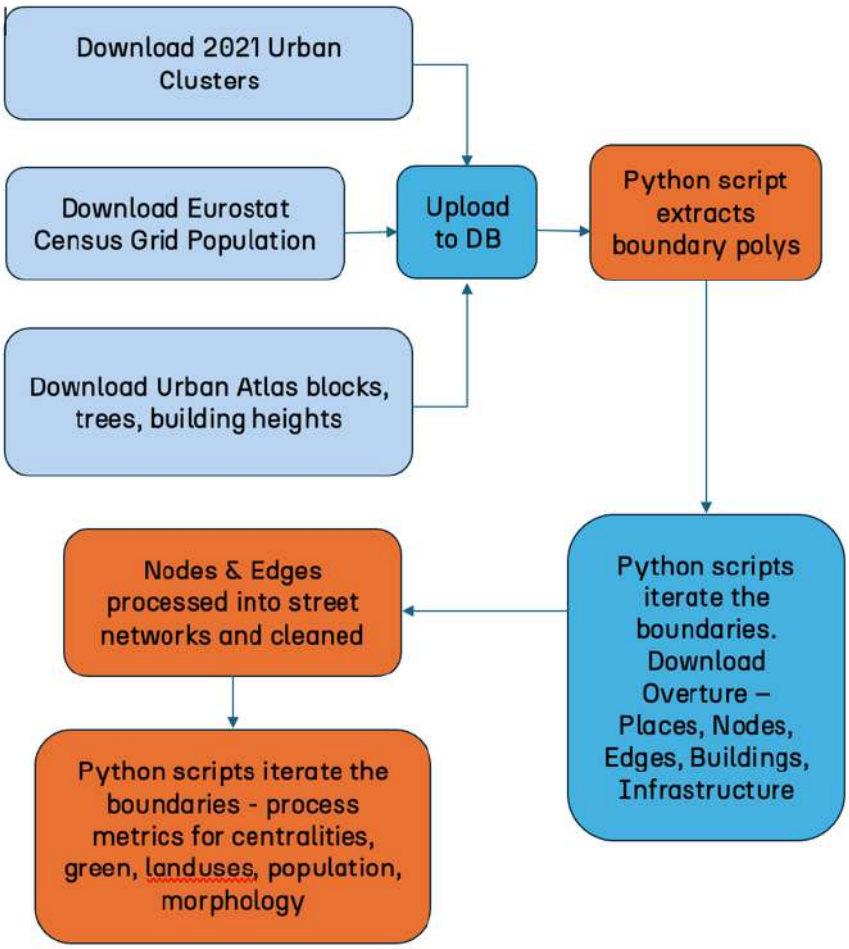

Figure 57. General workflow

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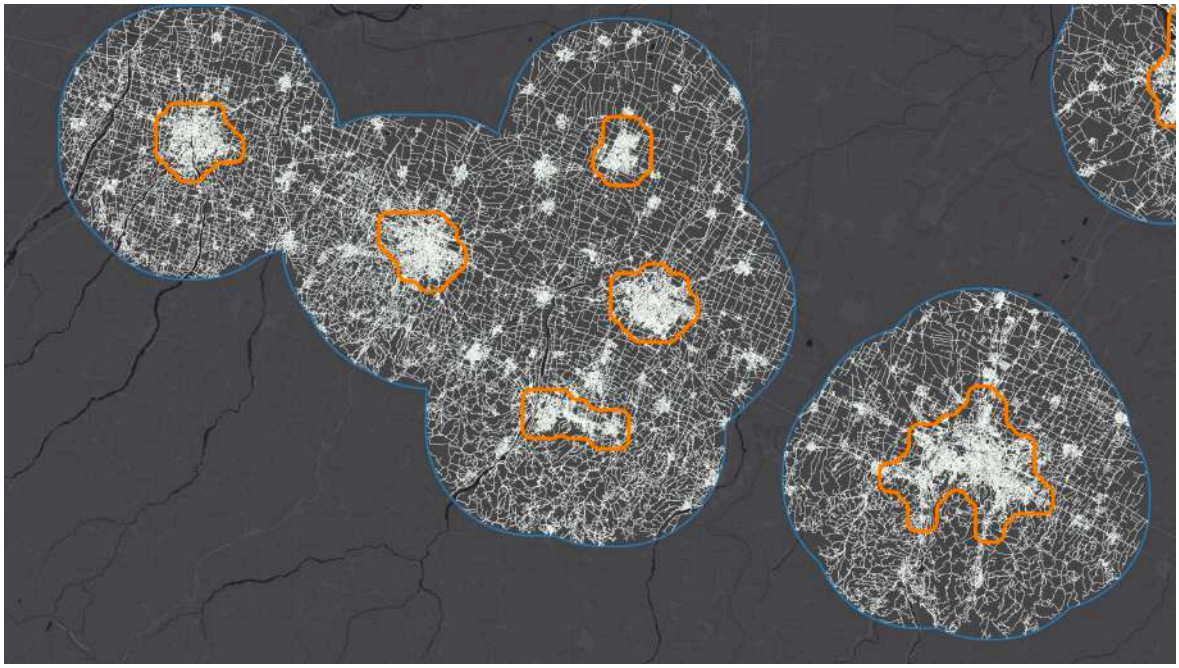

Figure 58. Overture streets data is loaded and cleaned for the 10km buffered geometries

Figure 59. Overture POI data is loaded and categorized for the 2km buffered geometries

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3.1.2. Key Analytical Outputs (The Data Model)

The primary output of the SOAR project is a data-model. It provides the foundational, pre-computed data for others to use. For each of the ~11 million street segments, the model provides:

- **Street Centralities:** Analysis of the street network's connectivity, closeness and betweenness centrality up to 10km distances (Figure 60).
- **Land-Use Access:** Proximity counts and accessibility metrics for 24 different land-use themes (calculated at various pedestrian distances from 400m to 1,600m). (Figure 61)
- **Green Space Access:** Metrics quantifying access to tree canopies and urban green spaces (same distances). (Figure 62)
- **Urban Morphology:** Eleven building (e.g. area, compactness, orientation, volume) and five block-level (e.g. area, perimeter, orientation) morphological metrics.
- **Census Data:** Twelve census categories interpolated onto the street network (e.g. male, female, employed, age).

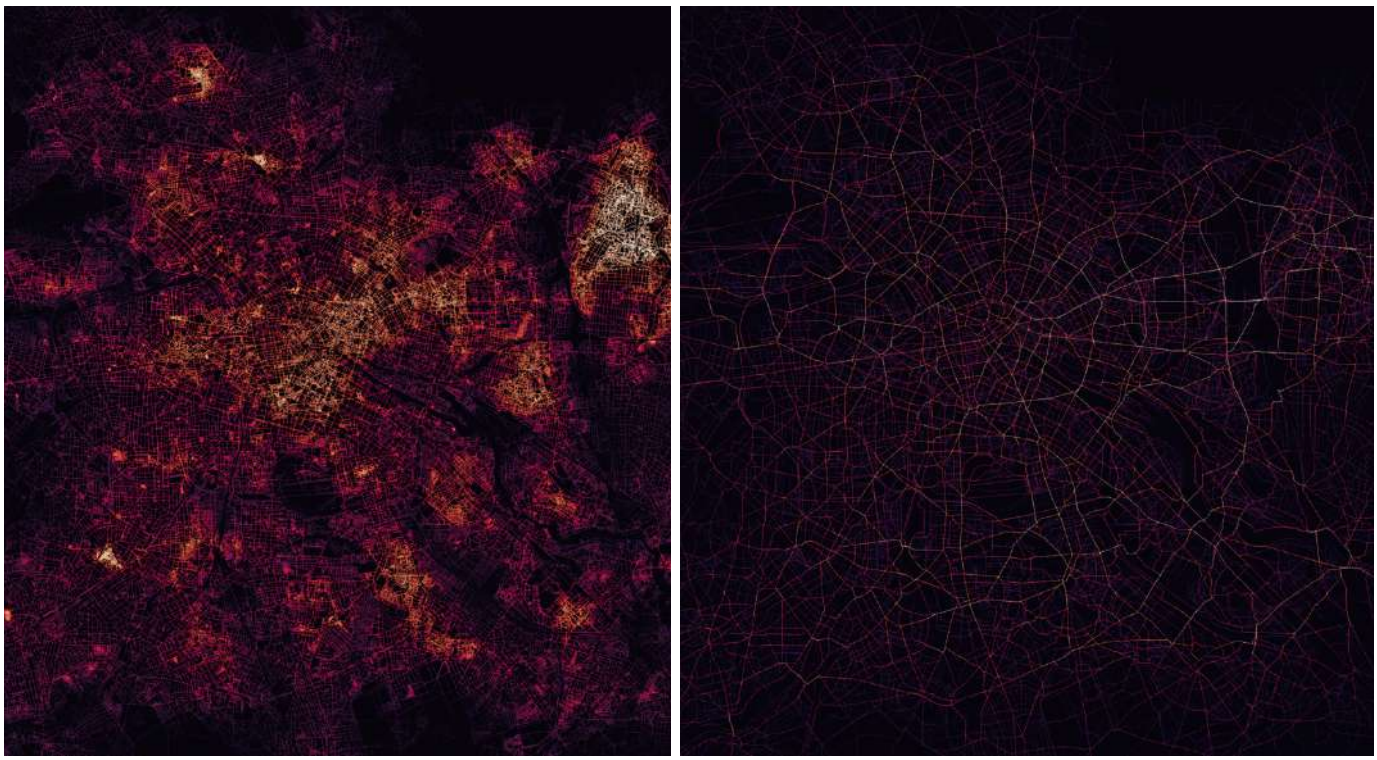

Figure 60. Closeness (left) and Betweenness (right) centrality calculated for Paris

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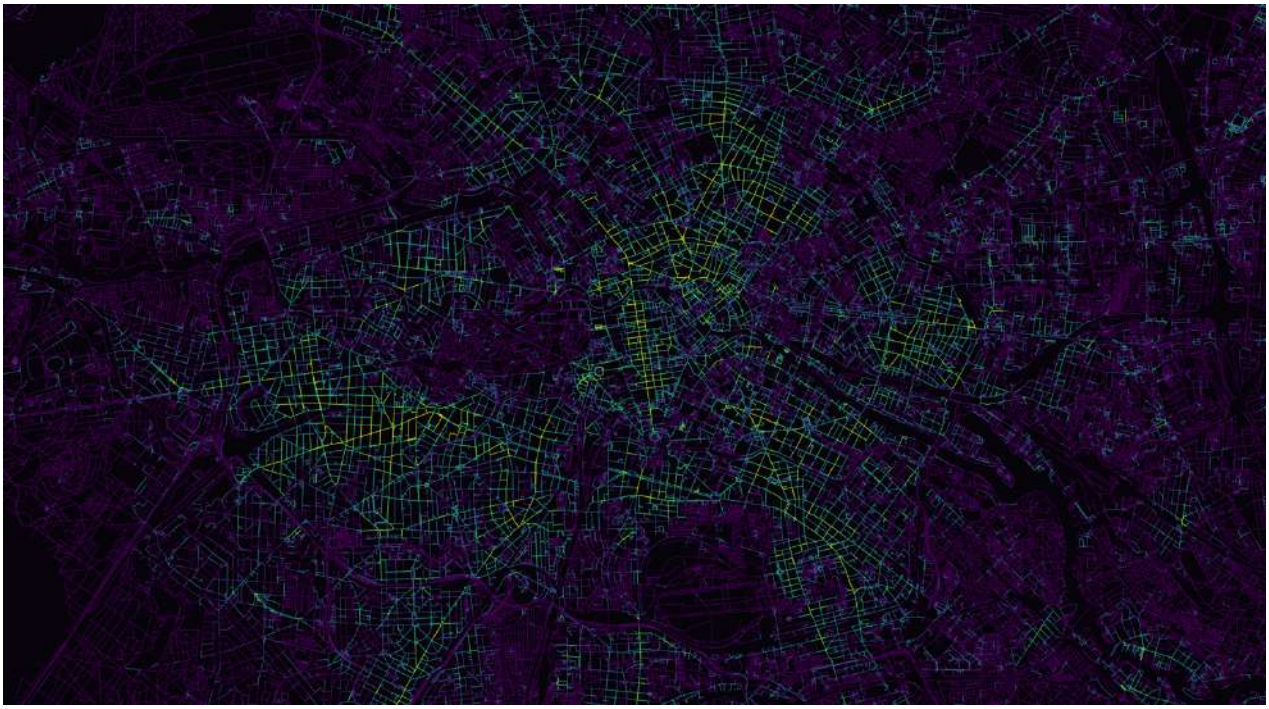

Figure 61. Access to 23 land uses e.g. retail. Paris

Figure 62. Distance to nearest trees (left) and green space (right), Paris

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3.2. Contribution and Future Application

By creating the presented automated workflow, the project delivers the SOAR, a scalable, open, automated and reproducible data model. This resource is intended to empower the EBDP community by providing the data for two primary types of future research. First, the model can be used for **location-specific analysis**. Researchers can select any of the included cities and use the detailed, pre-computed metrics as the starting point for local studies. Second, the model can be utilised for **broad EU-wide comparative analysis**. The SOAR data model is ideal for "horizontal" studies, allowing researchers to compare the properties, spatial patterns, and morphological characteristics of towns and cities across the entire European Union.

A primary objective of the research was to demonstrate the feasibility of the automated modelling approach for the EU context. The project confirmed the utility of the stated open EU data sources for large-scale spatial analysis. The workflow successfully incorporated the computation of standard urban metrics, such as network centralities and land-use accessibilities, key indicators to support EBDP. The potentials and limitations of the automated procedures were explored through a location-specific analysis in Nicosia, Cyprus, where the automated network processing techniques were compared to a manually curated model, providing insights into the method's real-world application. The developed automated model for Cyprus was presented in section 2.4.3, and its comparison with a manually developed model was presented in section 2.4.4. of this report. Its applicability for EBDP was also assessed in a real case study in Cyprus, presented in section 2.5.1. The automated model proved reliable and especially valuable for large-scale centrality analysis in projects of territorial and national scale, as well as for accessibility analysis, where fine-grained connectivity plays a critical role.

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4. Integrating socio-ecological performance in EBDP

Chapter 4 presents Research Package 3. It extends the EBDP framework beyond the state-of-the-art, to integrate social-ecological performance, hence addressing a major limitation of many existing evidence-based approaches that focus primarily on socio-economic outcomes. The chapter is grounded in the emerging field of Social-Ecological Urbanism, which conceptualises cities as coupled human-environment systems. The chapter introduces a conceptual modelling framework linking urban form to ecological outcomes, with a particular focus on human-wildlife interactions (Section 4.2).

SCIENTIFIC DISSEMINATION OUTPUTS (full list in 5.5)	
Scientific Article (Deliverable 4.2)	**Eldesoky et al. (2025a), Nature, Scientific Data https://doi.org/10.1038/s41597-025-05481-z**
Submitted Scientific Articles	Eldesoky et al. (2025c), Nature, *npj Urban Sustainability*
Conference Poster	Eldesoky et al. (2025d), ICUC 12
Conference Presentations	Eldesoky et al. (2024a), ISUF 2024
Open Datasets (Zenodo)	https://doi.org/10.5281/zenodo.15490818
Scripts, workflows	Eldesoky(2025). *BirdMonitoringGothenburg*h ttps://github.com/SMoG-Chalmers/BirdMonitoringGothenburg
Open Science & Preregistration	Eldesoky et al. (2024b), OSF, https://doi.org/10.17605/OSF.IO/SPHTY
Blog	Berghauser Pont, M. (2025, May 6). *Blog #5 https://twin2expand.surf.com.cy/news-and-events/blog-5-expanding-evidence-based-design-and-planning-to-embrace-social-ecological-urbanism/*
Podcasts	• Sveriges Radio. (2024, March • Verapodden. (2024, May 10).

The chapter reports on an empirical study examining the relationship between urban density and biodiversity in compact urban environments, using Gothenburg, Sweden, as a case study (Section 4.3). Birds are used as an indicator group due to their broad diversity and distribution, their sensitivity to urban morphology and their relevance to ecosystem services and human well-being. Using Passive Acoustic Monitoring (PAM), bird species richness and composition were recorded across different building typologies and reference sites. Spatial analysis, habitat network modelling, and statistical analysis reveal that dense urban forms do not inherently reduce biodiversity; instead, ecological performance depends on local habitat quality, green connectivity, and spatial configuration. Besides the scientific value of the empirical findings, which challenge deterministic assumptions about density and biodiversity, this work demonstrates how social-ecological indicators can be quantitatively assessed and embedded within EBDP workflows alongside socio-economic measures. Rather than treating ecological impacts as post-design assessments, the chapter embeds them within the evidence-generation process of planning and design and showcases *how EBDP can evolve into a holistic framework capable of addressing climate, biodiversity, and urban sustainability challenges simultaneously.*

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4.1. Aim and Objectives

As cities across Europe respond to the pressures of rapid urbanization and the climate crisis, the urban planning toolbox is evolving. One critical advancement advocated by the Twin2Expand project is the transformation of the Evidence-Based Design and Planning (EBDP) framework, not only to evaluate social and economic impacts but to fully integrate social-ecological dimensions. This is central to achieving Sustainable Development Goal 11: making cities inclusive, safe, resilient, and sustainable.

As described in the Introduction, traditionally, EBDP has focused on measurable outcomes that tied densification and accessibility; increased walkability, reduced car dependency, improved air quality, and support for active lifestyles. However, the challenge is more complex: **How do we build denser cities that are also greener, healthier, and more resilient?** Addressing this question is at the heart of the third research objective of this research project, which is to **integrate socio-ecological performance in EBDP**.

The scientific insights compiled in 'Den byggda formens betydelse' ("The Significance of Built Form") present a compelling case for this evolution (Berghauser Pont et al 2024). The report argues for a **broader planning lens**, one that not only mitigates carbon emissions through compact urban design but also **enhances cities' adaptive capacity to climate change; one that can help stop the rapid decline of biodiversity and improve human health and wellbeing.** This requires rethinking how we design and assess our urban environments; not just in terms of form and function but also in terms of biodiversity and human-nature interactions.

Cities must be seen as complex social-ecological systems, where built and green infrastructures co-exist and interact. For example, densification may offer transport and health benefits, but it can also reduce green space and limit biodiversity, which affects both microclimates and mental well-being (Berghauser Pont et al. 2021). The **shift to a socially and ecologically informed EBDP** is not just about adding more indicators. It's about changing the narrative of what makes a city successful. It's no longer enough to measure walkability or density. We must also consider biotope connectivity, microclimate regulation, mental health outcomes, and species diversity.

Effectively integrating ecological perspectives into urban planning requires more than new metrics- it requires new tools. A recent breakthrough was the development of the Habitat Network Analysis Tool (HNAT, https://github.com/SMoG-Chalmers/hnat). This open-source QGIS plugin enables planners to analyse habitat functionality and connectivity with a level of nuance that accounts for both ecological quality and dispersal barriers like buildings and traffic infrastructure. HNAT was designed to support multi-species habitat network analyses. It calculates habitat functionality, a composite measure of both habitat quality and connectivity, by using advanced cost-distance algorithms that are sensitive to real urban obstacles. In a recent case study in Gothenburg, the tool accurately predicted amphibian habitats by factoring in green space quality, building heights, and traffic volumes (Kindvall et al 2024).

HNAT exemplifies the **synergistic potential of combining urban morphology with ecological modelling**.

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The integration of these urban variables, missing in other tools, is important for urban planning and design as it allows to evaluate the trade-offs between urbanization and green space fragmentation.

In an era of climate emergency, to address sustainability holistically, EBDP must evolve towards an **integrated socio-ecological framework** capable of assessing trade-offs and synergies between environmental, social, and economic outcomes. To that end, there is a need to strengthen the conceptual and analytical foundations, the spatial models, as well as the empirical evidence base that can support such integrated frameworks.

The **objective of research package 3** is to expand the EBDP framework to include social-ecological dimensions by developing a new conceptual model, measures, spatial models and tools capable of assessing urban interventions in terms of their combined social and ecological impacts. The objective is to **exemplify a comprehensive analytical framework from conceptual modelling to real-world data collection** that can support model validation and integrated socio-ecological assessment. In doing so the project identifies the methodological challenges regarding the integration of social-ecological assessment in EBDP.

4.1.1. A brief introduction to the emerging area of social-ecological urbanism (SEU)

Social-ecological system (SES) theory builds on the concept that humans are a part of - not separate from - nature, supporting views established by e.g. Berkes et al. (2003). **Social-ecological urbanism (SEU) is a concept in line with SES theory but with emphasis on its role in urban planning and design** (Colding et al. 2022; Berghauser Pont et al. 2022).

In sustainable urban development (SUD), the balancing between social, economic and environmental priorities is central and both SUD and SEU have embraced the concept of resilience. However, in SUD, it means foremost that consequences are described from these three perspectives, while SEU goes much further in the integration of the different systems and approach resilience in different ways. If we compare the more engineering perspective still dominant in SUD with SEU, we can characterize the city as a machine in the former and as an organism in the latter (i.e. SEU); robustness as the goal in the former and adaptability in the latter; maintain status quo in the former, while facilitating evolution in the latter. The SET theory has successfully contributed to overcoming the limitation of a socio-technological approach by adding the ecological perspective but overlooks the critical role of technology (i.e. infrastructure, buildings), while SEU identifies this as a fundamental component and driver of urban system dynamics. In response to this, Chester et al. (2023) propose to add the technological dimensions of urban systems in the social-ecological-technological systems (SETS) conceptual framework (Figure 63).

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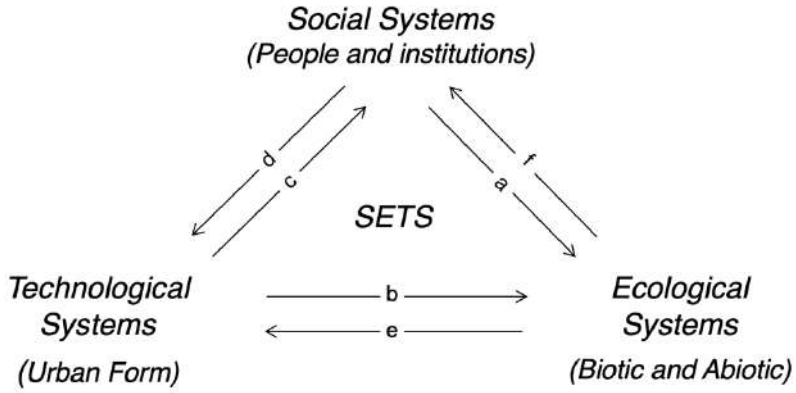

Figure 63. Urban form (or the built environment) in the broader framework of social-ecological-technological (SETS) systems

Despite the important addition of technology in the SETS framework, it still divides social components (e.g. individuals, households, but also the cultural norms and governance structures) from ecological components (e.g. individual organisms and their populations, but also the physical environment) and technological components (e.g. built structures like roads, buildings as well as the knowledge and information systems that govern their operation). This distinction, we argue, reproduces the divide between humans and nature that SES and SETS aimed to overcome. Therefore, instead of simply entangling the social, ecological, and technological systems as is proposed in Chester et al. (2023), we propose to redefine the technological component as a social-ecological technology (Figure 64). This means that the physical environment must be described based on a combination of the concepts central to landscape ecology (e.g. patches, corridors and matrixes) and urban morphology (e.g. streets, plots and buildings) as explored in two recent articles by Marcus et al. (2019, 2020).

4.2. A conceptual modelling framework to understand the role of urban form in shaping human-wildlife interactions in cities

Urbanization is among the major trends posing risks to achieving some of the sustainable development goals, especially with rates of urbanization unprecedentedly increasing globally. In this regard, urban form plays a crucial role since it has proven to influence different social and ecological phenomena in cities. However, most of the research in urban morphology has studied the relationship between urban form and these phenomena in isolation, limiting our understanding of the bidirectional relationships among urban form, humans and nature that are essential for fostering resilient and sustainable cities.

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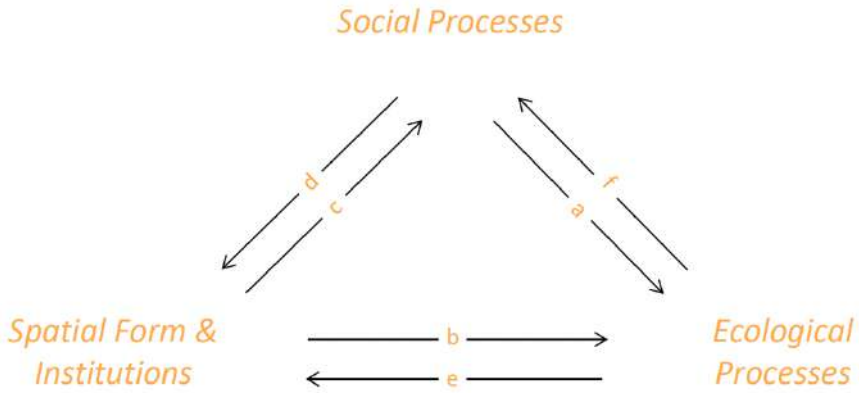

Figure 64. Spatial form as a social-ecological technology.

To support the evidence-based SEU practice, a **modelling framework** is proposed that considers the nature of social-ecological phenomena (Figure 65). This framework is thus not very specific to one social-ecological phenomenon but includes what should be conceded in any model aiming to describe, explain and predict (or enable experimentation of) social-ecological phenomena.

This framework follows the scientific process of model building (Lowry, 1965; Batty, 2009; van der Leeuw, 2004) and has **two domains**: **a problem domain** where one must describe what is being modelled (the social-ecological phenomenon) and for which purpose (the SEU evidence-based practice). Further, based on theory and evidence (from literature, observations) or hypotheses, key components of the model will be identified that make up the social-ecological technology and, importantly, are relevant for the SEU evidence-based practice. Besides the problem domain, there is also **the model design domain** including the spatial representation of the key elements, the relevant scales (levels of aggregation), the treatment of time, and the definition of measurable variables of the social-ecological technology (or proxies) used in the model and their method of calculation. Finally, the design domain of the framework also includes defining the way in which the model will be implemented and tested based on its predetermined function (e.g. descriptive, explanatory, predictive).

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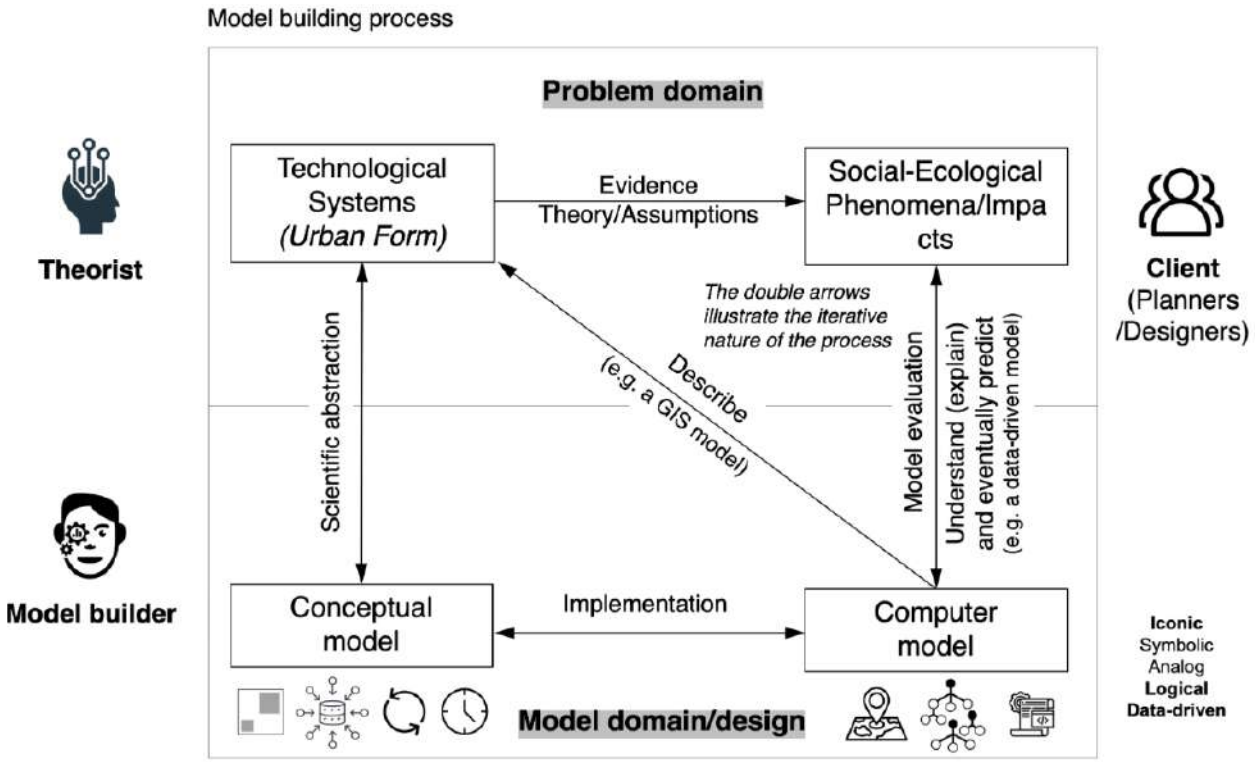

Figure 65. Modelling framework

4.2.1. Modelling human-wildlife interactions

We exemplify the general conceptual framework to study an important **social-ecological phenomenon in cities** that is influenced by urban form: **human-wildlife interactions**. This is a critical phenomenon because it provides benefits (e.g. ecosystem services) but also disbenefits (e.g. injuries, diseases) for people. Also, **humans can be a threat to other species and biodiversity**, which is important for human health and well-being; however, it has been less studied compared to other ecosystem services.

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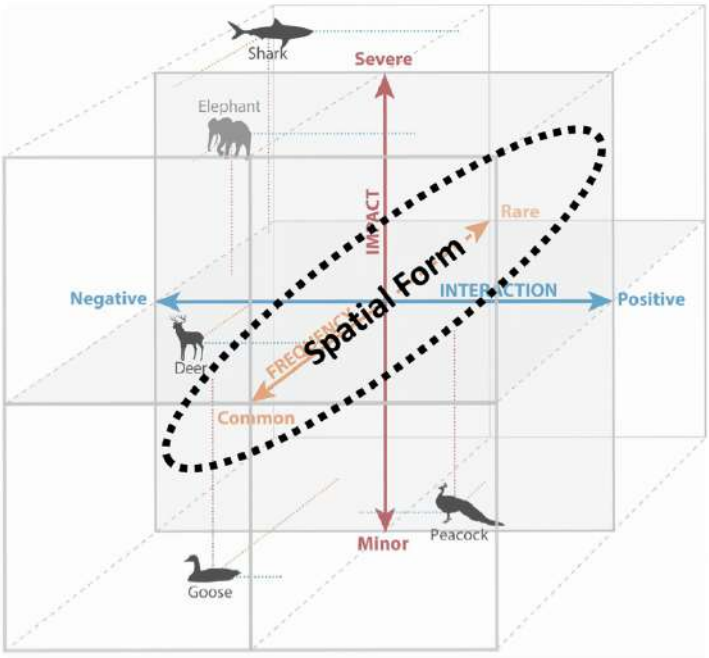

Figure 66. Interactions between humans and fauna (adopted by Nyhus, 2016)

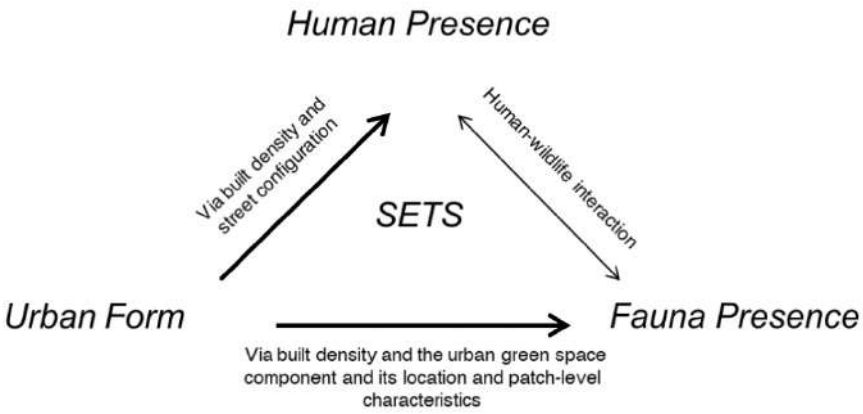

Figure 67. Urban form's influence on human-wildlife interactions

Urban form plays a role in the frequency of interactions between humans and wildlife by influencing the presence of both people (e.g. through the configurational characteristics of streets and built density) and wildlife (e.g. through green space patch-level characteristics and their connectivity, which also influence species diversity) (Figures 66, 67).

Here, we propose a **modelling framework to understand the connections and dynamic interactions between urban form, people and animals** (Figure 68). The proposed framework, is a stock-flow model

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that identifies the interconnected elements (with a focus on the urban form ones) that, together, influence the presence of both people and animals and, in turn, their frequency of interaction. It also identifies some positive and negative outcomes of these interactions.

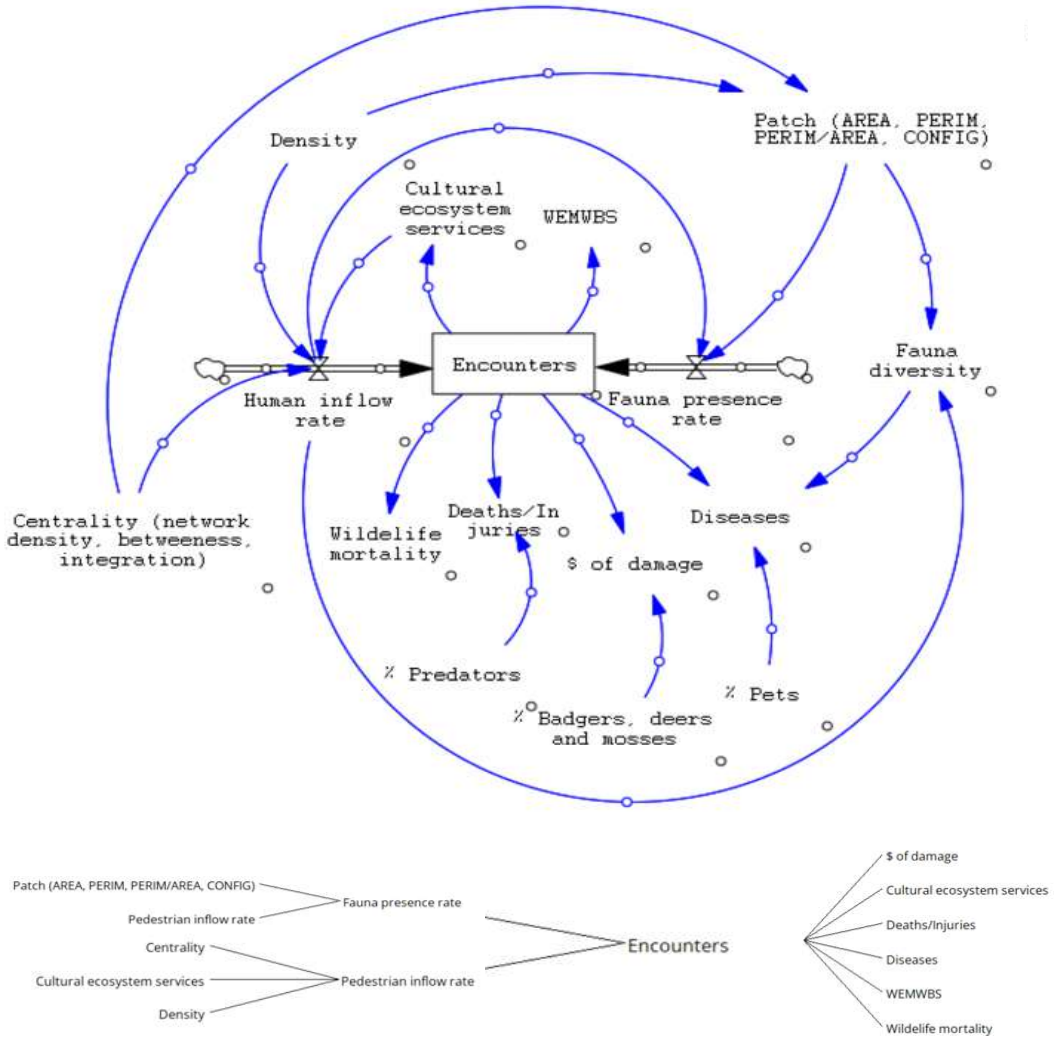

Figure 68. Conceptual (stock-flow) modelling of human-wildlife interactions

4.3. Assessing social-ecological performance of urban form. Creating new evidence for the relation of urban density and biodiversity

One aim of research package 3 is to develop an analytical framework that supports a socially and ecologically informed EBDP. We designed a study with the objective **to exemplify this integrated analytical framework from conceptual modelling to real-world data collection**. In doing so, **we produce new empirical evidence** on one of the most pressing questions of current urban design and planning

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practice: **How do we build denser cities that are also greener, healthier, and more resilient?** In particular, we ask: **Can we build denser cities without jeopardising biodiversity?**

The main question is divided in two sub questions:

- What impact does density (which we already know its impact on human presence and movement) have on the presence and diversity of wildlife?
- What impact do the characteristics (location, geometric and configurational) of urban green spaces (which we also know, to some extent, impact human presence and movement) have on the presence and diversity of wildlife?

4.3.1. State-of-the-art and knowledge gaps.

To achieve global sustainability goals, urban planners and decision-makers worldwide have adopted strategies that promote denser and more compact urban areas. While higher densities can have positive effects at larger scales of entire cities or regions (e.g., for technical public infrastructure, transport, and economics), existing evidence suggests that they often have negative effects locally (e.g., environmental, social, and health impacts) (Berghauser Pont et al., 2021). Among these negative effects is the loss of biodiversity, which is crucial for human health and well-being (Marselle et al., 2021), and has now become a legally binding and urgent priority, especially with the enforcement of new policies and legal frameworks, such as the EU Nature Restoration Law. The latter mandates EU cities to restore biodiversity and degraded ecosystems and sets specific targets for urban ecosystems, including no net loss of green urban space and tree cover by 2030, and a steady increase in their total area thereafter. Therefore, a central challenge for sustainable urban development is to identify ways to build dense urban areas without compromising biodiversity.

In urban design and planning, understanding how urban density influences biodiversity and how its negative effects can be mitigated remains limited due to two main reasons. Firstly, the large majority of studies on urban biodiversity often focus on studying variations along the urban-rural gradient, with a lack of studies focusing on intra-urban variations in biotic conditions, especially in dense urban areas (Beninde et al., 2015).

Secondly, most studies rely on crude measures of population density (e.g., people/km2), which offer limited insights for urban design and planning practice (Berghauser Pont et al., 2021). This is because population density is not a good indicator of the spatial characteristics (or the urban form) of an urban area (Berghauser Pont and Haupt, 2023, 2010). For instance, neighbourhoods with high-rise developments can have similar population density as neighbourhoods with mid-rise perimeter building blocks. Similarly, for each building type, there is a broad range of population densities that is possible (McDonald et al., 2023).

A few studies (e.g., Amaya-Espinel et al., 2019; Steenberg, 2018) have investigated the impact of urban density, as a numerical variable that describes the relationship between built and non-built space, on biodiversity, such as the percentage of ground coverage on a certain area (GSI). However, at the same

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building parameters, such as GSI, building height, or total floor space area density (FSI or FAR), one can also design urban environments with different spatial characteristics, creating different social, economic, and environmental conditions (March and Martin, 1975; Ratti et al., 2003).

Also, although measuring urban (built) density as a numerical variable can reveal general trends (e.g., how species richness changes with increasing density), it remains one-dimensional, that is, it provides limited insight into whether and how biodiversity may differ between areas with the same density. This is particularly important if densification is considered a pathway toward sustainable development, since we need to understand not only overall trends but also how cities can be densified without jeopardizing biodiversity.

To measure urban density in ways that better describe urban form and performance, Berghauser Pont and Haupt (2023, 2010) have proposed the combination of two density measures (i.e.., GSI and FSI) in a two-dimensional categorical classification. This approach has been shown to be effective in measuring density while numerically distinguishing between building types with distinct morphological characteristics, even when they have the same density (e.g., FSI) (Steadman, 2014).

4.3.2. Research hypotheses and design.

In this empirical study, we take a first step towards a better understanding of how urban density affects an important component of biodiversity by examining the impact of different dense and compact building types (representing different combinations of GSI and FSI) on avian diversity and composition in Gothenburg, Sweden, and comparing these with sparsely built and semi-natural urban sites. The specific focus on avian communities is because birds are widely distributed, highly diverse, and relatively easy to detect and identify. Furthermore, birds provide key ecosystem services (e.g., pollination, seed dispersal, pest control, and cultural ecosystem services) and are sensitive to changes in the ecosystem, making them excellent study subjects in many areas of ecology.

We formulated three hypotheses linking density to biodiversity that we aimed to test with this study:

The **first hypothesis (H1)** was that, consistent with prior studies, dense and compact urban areas (characterized by higher GSI and FSI values) would exhibit lower species richness and different species composition compared to sparsely built or semi-natural urban areas.

The **second hypothesis (H2)** was that, within the same dense or compact building type, there can be variation in species richness and composition among sites (within-group variation). However, different dense or compact building types would have significantly different effects on bird species richness and composition (between-group variation).

Our **third hypothesis (H3)** was that variations in species richness and composition within the dense or compact building types are associated with site-specific and/or larger-scale characteristics that urban designers/planners can act upon when planning and designing more biodiversity-friendly cities.

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Examples of key site-specific and larger-scale variables that are well-recognized to influence bird species richness and composition include local habitat area and diversity, as well as landscape connectivity to surrounding suitable habitat types (Beninde et al., 2015; Mazerolle and Villard, 1999).

To test the three hypotheses, we analysed a rigorously validated dataset of bird species occurrences collected during spring 2024 across 30 urban sites (Figure 69) representing different urban form types (See section 4.3.3), published in Eldesoky et al., 2025a). Specifically, these included three urban form types characterized by high GSI (Ground Space Index) and FSI (Floor Space Index): 1) compact low-rise, 2) compact mid-rise, and 3) dense mid-rise buildings, as well as reference sites in semi-natural or sparsely built urban areas. The high-density types were based on a density typology introduced by Berghauser Pont et al. (2019a, 2019b).

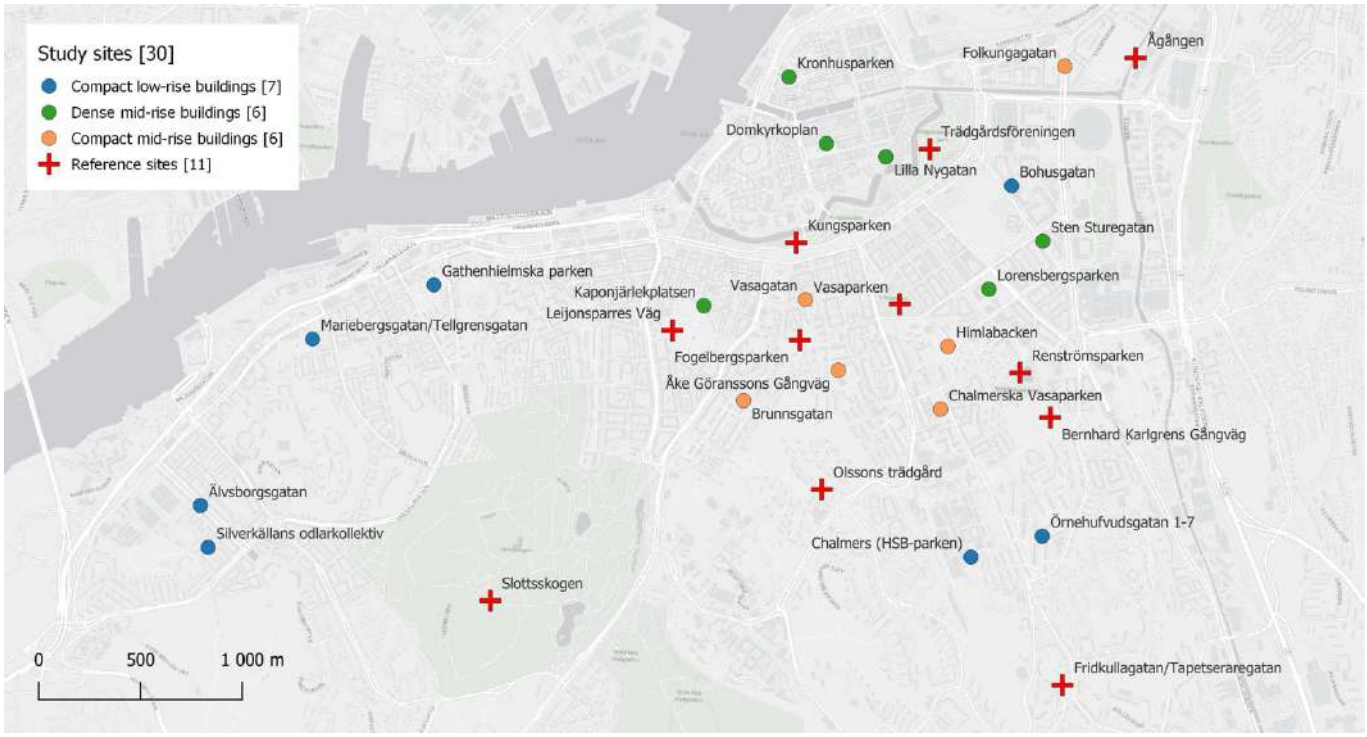

Figure 69. The 30 study sites across central Gothenburg, Sweden

Early in the process the need was identified to collect original data on bird occurrence. Understanding the relationship between higher density and different biotic conditions at the local scale requires collecting species data from within dense urban areas at high spatial and temporal resolution. Of particular importance is species occurrence data, which provide information on the presence or absence of a species (or other taxon) at specific locations and times. The availability of occurrence datasets has greatly increased in recent years, mainly due to the rise of citizen-science platforms that facilitate sharing observation data (Galvan et al 2022, Prenda et al. 2024). Among the most widely studied and recorded species in these occurrence datasets are birds (Amano et al. 2016). Nevertheless, existing

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citizen-science bird (or other species) occurrence datasets have several limitations. Most notably, the datasets are often unstructured, i.e., the data have not been systematically collected or the data collection method is unknown or not well-documented, making them subject to geographical, temporal, and taxonomic biases (Galvan et al. 2022, Prenda et al. 2024). The latter results in more easily identifiable species being more frequently recorded, exacerbated by a lack of rigorous review and validation (Ward 2014). Hence, these datasets are not very effective in capturing intra-urban variations in biotic conditions at fine spatial scales (Planilo et al. 2021).

To address the limitations in existing datasets, especially the geographical and temporal biases, we produced **a machine learning (ML) generated bird species occurrence dataset** based on 10,691 hours of passively recorded audio data in Gothenburg, Sweden. This dataset is unique in three ways. Firstly, the data were systematically collected across study sites, meaning that the data collection process followed a structured and consistent methodology, ensuring comparability across space and time. Secondly, we focused on collecting data from within dense urban areas to capture intra-urban variations in biotic conditions, rather than the conventionally studied urban-rural gradient (Beninde et al. 2015). Thirdly, the dataset underwent rigorous validation and post-processing, where an expert ornithologist manually reviewed a sample of the automated species detections to ensure the overall reliability and accuracy of the dataset.

4.3.3. Method

4.3.3.1. Spatial and temporal sampling

We collected bird species occurrence data during the 2024 breeding season, when bird vocal activity is at its peak (Furnas and McGrann 2018). **Bird richness at each site was estimated as the accumulated number of distinct species observed during the whole study period.** Specifically, the data were collected from the 21st of April to the 16th of June 2024 across 30 sites in Gothenburg, Sweden (Figure 69). Of these, 19 sites represented three distinct types of dense urban forms: compact low-rise buildings, compact mid-rise buildings, and dense mid-rise buildings (see Berghauser Pont et al. 2019a, 2019b for a detailed description).

Acoustic recorders were placed at 6–7 representative sites of each of the three dense urban form types, attached to trees in publicly accessible urban green spaces between buildings or to trees along streets. The other 11 sites were designated as reference sites, i.e., where bird vocalization activity is expected to be higher, such as big urban parks, woodlands, and more spacious urban form types with abundance of vegetation.

Considering that acoustic recording may raise privacy concerns, before the insitu deployment, we acquired ethical approval from Chalmers University of Technology's Institutional Review Board on Research Ethics (Dr.nr: M2 2023-0194:6D) and conducted a Data Protection Impact Assessment (DPIA). The DPIA outlines the actions taken to minimize data protection risks. This included, for instance: automatically identifying and excluding audio files with human vocalizations; setting a

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recording schedule with intermittent short clips to minimize the capture of complete conversations (if any occur near the recorders); and making good-faith efforts to inform the public that recording is occurring. Furthermore, we obtained placement permits from the municipality of Gothenburg to legally deploy acoustic recorders on public land.

4.3.3.2. Bird observations. Passive Acoustic Monitoring (PAM)

The method selected for monitoring bird occurrence combined **Passive Acoustic Monitoring (PAM)** and **Machine Learning (ML).** PAM relies on passive acoustic recorders (e.g., microphones, hydrophones) to monitor wildlife based on their sound characteristics (e.g., frequency and amplitude) (Browning et al. 2017). This approach has been used in several previous studies (e.g. Biffi et al. 2024, Bota et al. 2024) and is promising for monitoring species occurrence for several reasons. Most importantly, it allows for: systematic and standardized collection of data over extended periods (weeks to months); broader geographic coverage; reduced subjectivity and observer bias; less disturbance to species; and monitoring nocturnal or hard-to-detect animals, such as bats (Ambrahams 2018, Palmeirim et al. 2024).

PAM has become more popular due to the advances in acoustic recorders that have become **affordable, off-the-shelf, autonomous, programmable, and full-spectrum** (Shonfield and Bayne 2017). On the other hand, advances in **ML** have made detecting animal vocalizations in passively recorded audio data more **automated and cost-effective**, particularly through the use of image segmentation techniques on labelled spectrograms (Kahl et al. 2021). However, there are several limitations to this approach. PAM is suitable only for vocalizing animals and primarily provides information on species presence or absence, activity patterns, and diversity. However, some studies have also used PAM to infer population density and abundance based on, for example, vocal activity rates (Perez-Granados et al. 2019, Perez-Granados and Traba 2021). Also, some animal vocalizations can be challenging to distinguish, especially for species with similar calls or those that mimic other species. Furthermore, when used in urban areas, anthropogenic background noise (e.g., from traffic) can interfere with recordings and mask biophony (Cretois et al. 2024), making it difficult to detect or accurately classify vocalizations (Browning et al. 2017). PAM also requires special data storage infrastructure and continuous improvements in the ML classification models in terms of prediction accuracy.

In the following section, we provide further methodological details on how the data were collected, processed, validated, and produced in the final format (Figure 70). The method and resulted dataset of the study was published in Eldesoky et al. (2025a, b).

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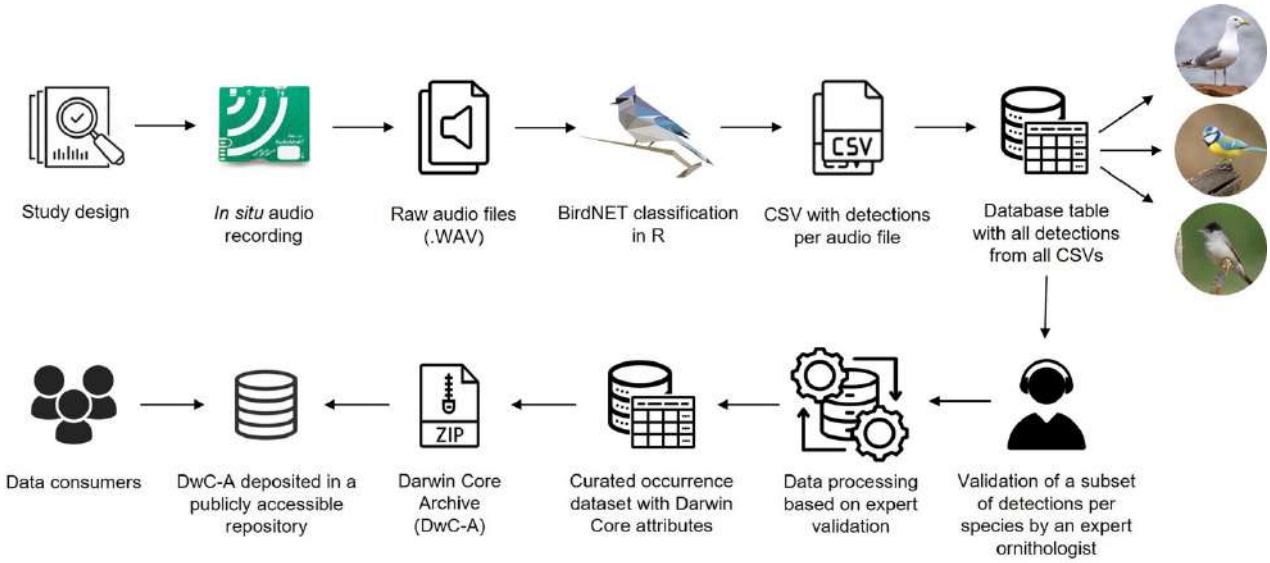

Figure 70. The methodology for producing the bird species occurrence dataset.

Hardware (acoustic recorder equipment)

The hardware used for the PAM across the 30 sites was the AudioMoth (v1.2.0)26, a low-cost (< €100), full-spectrum (up to 192 kHz) acoustic recorder with a small size (5.8 x 4.8 x 1.5 cm). It records uncompressed WAV files to a microSD card to preserve audio quality and is powered by three AA batteries. The AudioMoths were housed in waterproof injection-molded cases (IPX7) that were tested to ensure sound quality. A detailed guide on getting the necessary supplies (microSD cards, batteries, cases, etc.) and assembling and configuring an AudioMoth can be found, for example, in Rhinehart and Guzman27.

Recording configuration

Each AudioMoth was configured to record at a sampling rate of 96 kHz with a medium gain setting (i.e., a boost in amplitude applied to the audio signal). A sampling rate of at least twice the highest call frequency of interest, known as the Nyquist frequency, is required to resolve all frequency information (Browning et al. 2017). Determining the optimal gain typically requires experimenting with different gain settings, depending on the field conditions (Lapp et al. 20123). However, in most cases, a medium gain setting is appropriate to capture quieter sounds at good quality while minimizing the risk of clipping or excessive background noise, especially in urban areas (Metcalf et al. 2022a). For privacy protection, battery life, data storage, and computational considerations, we employed a targeted “on-off” time sampling approach focused on the times of peak bird vocal activity (around the main dawn, morning, and evening chorus times). Specifically, the AudioMoths were configured to record for 1 minute every 2 minutes over a total of 12 hours per day (3 hours before sunrise to 4 hours after, and 2 hours before sunset to 3 hours after). This approach was found to capture data highly comparable to continuous recordings while avoiding an overwhelming data mountain (Metcalf et al. 2022b, Shaw et al. 2022).

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Pilot sampling
Prior to the large-scale deployment, we conducted small-scale pilots at a subset of the planned sites to test and confirm the recording configurations, deployment conditions, and analysis methods.

In situ deployment, maintenance, and data retrieval
For each of the 30 sites, recorders were positioned horizontally at around 3 meters above the ground on tree trunks to improve sound quality and protect them from theft or vandalism (Figure 71). Furthermore, recorders were placed away from branches and leaves as much as possible and oriented to face away from streets to reduce background noise (Browning et al. 2017, Abrahams 2018, Rhinehart and Guzman 2024). In addition to the recorders, signs were placed at each site, in compliance with the DPIA, to inform the public that recording was taking place with more details about the recording times, the purpose of the study, and contact information for inquiries.

Throughout the deployment period, batteries were replaced regularly, and the audio files were retrieved from the microSD cards before they became full. Furthermore, site metadata (e.g., name, latitude, longitude, recorder unique ID, microSD card number, deployment and pickup dates and times, and notes) were recorded during the initial deployment and updated with each subsequent site visit.

Figure 71. AudioMoth recorders housed in IPX7 waterproof cases and strapped to tree trunks in different study sites in Gothenburg, Sweden.

4.3.3.3. Data management, analysis, and wrangling

In total, we collected 641,502 audio files, amounting to approximately 10,691 hours of recordings and around 7 TB of data. Each audio file was named with date and time information and stored in a directory structure organized by the round of data collection (a total of five rounds), site, and date.

The raw audio files were used as input for a convolutional neural network (CNN) model to identify vocalizing bird species based on 3-second clips/spectrograms, namely BirdNET (Kahl et al. 2021).

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BirdNET is a state-of-the-art CNN model that is pre-trained on 6,522 species (v1.3.1, version used) and has shown good accuracy in several studies (Perz-Granados 2023). The BirdNET model was run in R (v4.4.1) using the NSNSDAAcoustics package (https://github.com/nationalparkservice/NSNSDAcoustics) to process the audio files, applying the default inference settings (detection sensitivity of 1.0, no segment overlap, and a minimum confidence threshold of 0.1), and using a custom species list.

Sensitivity controls how responsive BirdNET is to faint or background vocalizations, with higher values leading to more detections. Overlap determines whether each 3-second prediction segment should begin immediately after the previous segment or start earlier, allowing for a temporal overlap between segments. Recently, some studies have shown that increasing sensitivity and/or overlap values from default settings can improve BirdNET's performance (e.g., by reducing false negatives and thereby increasing recall), particularly for short recording schemes and lower temporal aggregations (e.g., minute-, day-, or week-level) (Thomson et al. 2025, Fairbairn et al. 2024, Funosas et al. 2024, Perez-Granados 2023). However, with longer and more frequent data collection, as in our case (i.e., recording for 1 minute every 2 minutes over 12 hours per day for two months), this may not be necessary, as bird calls potentially missed due to being cut off at segment edges are likely to recur (Fairbairn et al. 2024). Also, higher sensitivity and/or overlap settings can increase the false positive rate, which requires more extensive manual validation (Perez-Granados 2023). This also significantly increases processing time, which can become a major challenge when processing large amounts of audio data without much improvement in recall (Kahl et al. 2021, Funosas et al. 2024).

The confidence score is "a unitless, numeric expression of BirdNET's confidence in its prediction [ranging from 0 to 1]" (Wood and Kahl 2024, p.778). A higher confidence score indicates a higher likelihood of correct classification (Funosas et al. 2024). The choice of a minimum confidence score threshold to filter the detections directly impacts the number of species detected, with lower confidence scores resulting in a larger number of species detected (Perez-Granados 2023). Therefore, selecting an appropriate minimum confidence threshold and manual validation of resulting species detections by an expert ornithologist is essential to ensure the accuracy of the results (Cole et al. 2022). To identify the best minimum confidence threshold, we ran the BirdNET analysis using the default low confidence level (0.1) to obtain a complete list of detections, which could then be filtered by testing different confidence thresholds as explained in the next section.

The custom species list used was generated using all publicly available data from the Swedish Species Observation System (Artportalen; https://artportalen.se/) on bird species observed in Gothenburg, Sweden, and included 351 species. Artportalen is the main repository for Swedish species observations and is well acknowledged for its successful gathering of data from ornithologists active in Sweden (Knape et al. 2022, Snäll et al. 2011). Using a custom species list—either by supplying BirdNET with location and week-of-year information or by manually compiling a list—is recommended to improve performance, as it helps exclude unlikely species beforehand, reducing false positives (Fairbairn et al. 2024). The custom list was first compared to the list of species on which the BirdNET model was trained (6,522 bird and non-bird species) to identify any inconsistencies or missing species. Six bird species

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had scientific name synonyms, and eight local species were completely missing from BirdNET's training data: *Gulosus aristotelis, Alle alle, Glareola nordmanni, Polysticta stelleri, Anas crecca carolinensis, Falco eleonorae, Pagophila eburnea, and Branta ruficollis.* However, these eight species were deemed unlikely to occur in the study sites when evaluated by an expert ecologist (O.K). Therefore, the final species list used for analysis included 343 species. In addition to the bird species, we included in the custom species list three labels for human-produced sounds that BirdNET can detect, namely "Human vocal", "Human non-vocal", and "Human whistle". These labels were included to facilitate the identification and exclusion of audio files containing human vocalizations, in compliance with the DPIA mentioned earlier.

The output of the BirdNET model is a CSV file per WAV file, containing a list of detections (rows) and corresponding attributes (columns), such as the path to the processed audio file (named with the date and time information), species' scientific name, start and end seconds of the detection, and confidence score. In the next step, the CSV files were merged into a database table with 4,664,290 rows (observations) and a total of 338 unique bird species detected out of the 343 in the custom species list. The dataset was then processed to extract the site, date, and time information from the file path into separate columns and to create a unique recording identifier column for easier data manipulation.

Technical validation, post-processing, and production of the final dataset

To identify an appropriate minimum confidence threshold for expert validation, we first set a high threshold of 0.85, which resulted in 206 unique bird species (out of the 338 detected at the minimum threshold of 0.1). We then lowered the threshold to 0.80, where 15 additional species were included. These 15 species had only one or two detections, all of which were found to be false positives after an expert ornithologist (L.J) listened to the recordings, suggesting that a threshold of 0.85 is suitable for this study. However, this does not necessarily mean that the detections of the remaining 132 species with confidence scores below 0.85 are entirely false positives. Therefore, these 132 species were further scrutinized by the expert ecologist on a case-by-case basis to determine which species were likely to occur at the specific study sites. Nine species were identified as such: *Emberiza schoeniclus, Carpodacus erythrinus, Podiceps cristatus, Oenanthe oenanthe, Jynx torquilla, Linaria cannabina, Luscinia luscinia, Acrocephalus schoenobaenus, and Alauda arvensis*. For each of these nine species, the expert ornithologist listened to a random sample of audio files in which the species was detected (up to 50 per species where available, totaling 442 one-minute recordings). All examined detections were confirmed to be false positives. The dataset used for expert validation, therefore, includes 206 unique species with 250,472 occurrence records (at a minimum confidence of 0.85).

Following Sethi et al. (2024), Bick et al. (2024), and Fairbairn et al. (2024), for each of the 206 species we randomly retrieved 50 unique audio files in which that species was detected with a minimum confidence of 0.85, ensuring that no two detections of the same species selected for validation came from the same audio file. If a species was detected less than 50 times, all available audio files were retrieved. This resulted in a validation dataset of 5,007 one-minute audio files. The expert ornithologist then listened to each audio file and classified each associated detection as correct, incorrect, or unsure. For records classified as incorrect or unsure, the ornithologist, when confident, provided suggestions

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for the likely species or sound. The ornithologist-validated dataset was used to reclassify and/or remove records and to train a predictive classification model to produce the final curated dataset, as explained in more detail below. The validation results (Figure 72) show that 43 species achieved a classification accuracy of over 60% (with 26 species having a 100% accuracy), 17 species had an accuracy between 60% and 2%, while all the remaining 146 species were false positives.

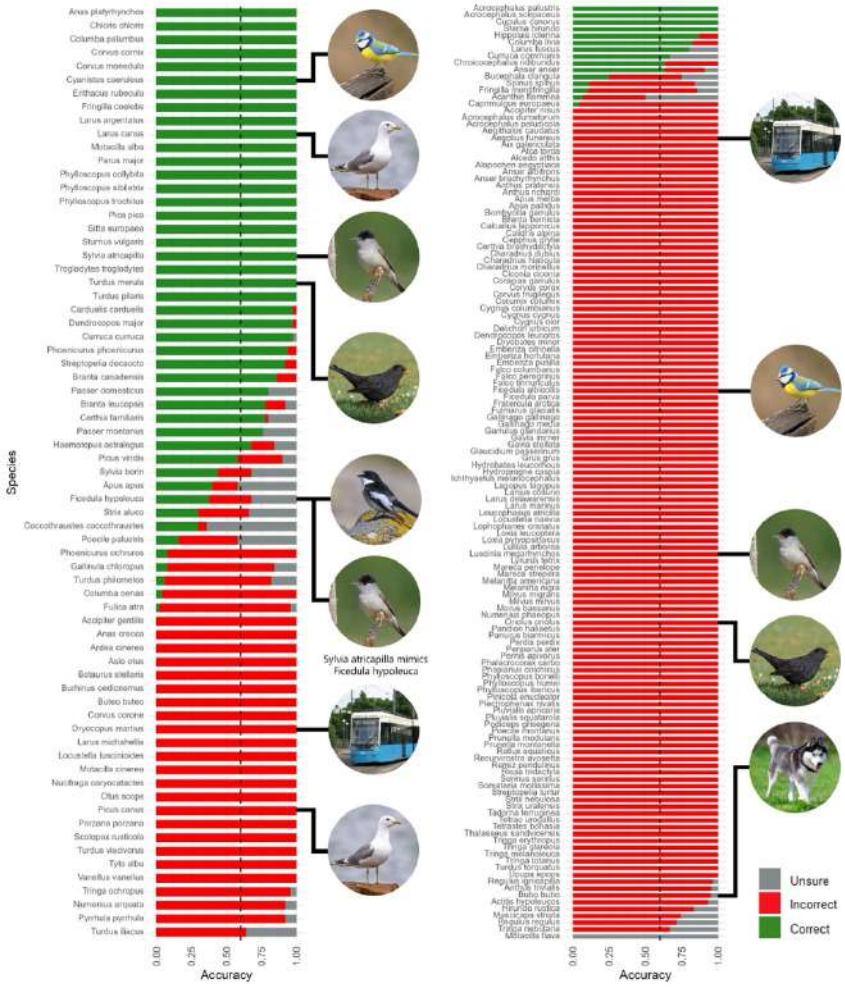

Figure72. Ornithologists' validation of BirdNET's classification results. The figure shows the percentage of correctly classified detections per species (with 50 validated detections, left, and < 50 validated detections, right). The vertical dashed lines mark a 60% accuracy threshold. The figure style is adapted from Sethi et al. 2024.

Based on the validation results, we further processed the dataset (with 250,472 records) as follows. For the 5,007 "validated" records by the ornithologist, we retained those that were correctly classified, reclassified records that were incorrectly classified and the ornithologist suggested other species, and removed records that were incorrectly classified and the ornithologist could not recognize the species/sound or was unsure (Figure 73).

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For the "non-validated" records, we trained a binary Random Forest (RF) probabilistic classifier based on the ornithologist-validated dataset to estimate the probability that each record was correctly classified by BirdNET. The model training and evaluation process is described in more detail below. In the final dataset, we retained only non-validated records with an estimated probability above 50% (Figure 73). This process resulted in a curated dataset with 239,597 occurrence records of 61 species. This includes 60 species that achieved an accuracy above zero (Figure 72), plus one species (i.e., *Regulus regulus*), which the ornithologist identified during validation to be the correct classification for a false positive detection of another species (i.e., *Regulus ignicapilla*).

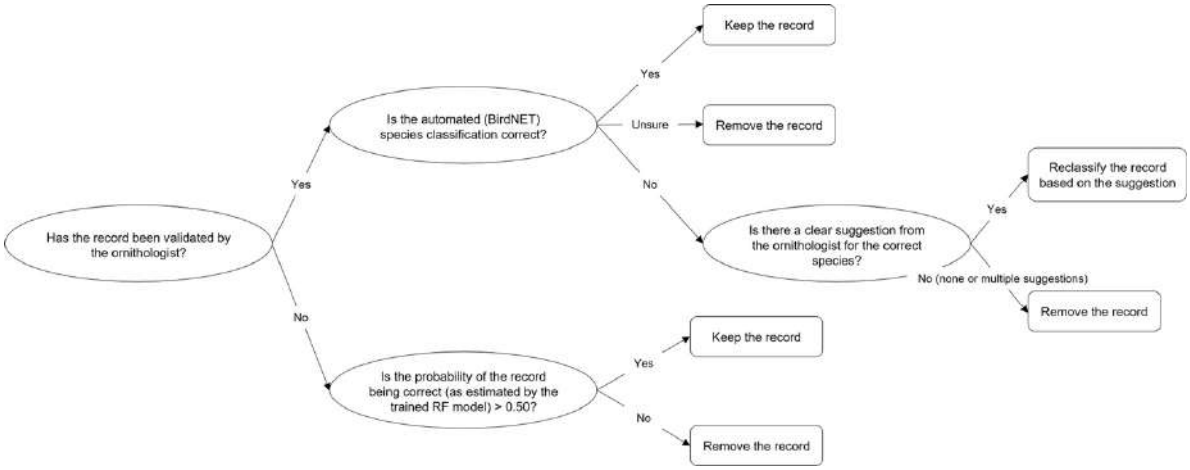

Figure 73. Decision tree for the data records exclusion or reclassification based on the validation results.

The RF classifier model was implemented in R using the 'ranger' package (Wright et al. 2017, v0.17.0). It was configured with 500 decision trees and trained on 2,496 ornithologist-validated records from the 60 species that achieved an accuracy above zero (Figure 72). Three predictors were used: 1. species name (BirdNET classification); 2. BirdNET confidence score; and 3. whether the detection was isolated. The latter indicates whether a bird detection is not preceded or followed by another detection of the same species within a 9-second window. Isolated detections have been found to increase false positives (Biffi et al. 2024, Wood et al. 2021).

To evaluate the model performance and select the best-performing RF model hyperparameters, specifically the number of variables considered at each split (*mtry*) and the node splitting rule (*splitrule*), we used repeated cross-validation (5 folds, repeated 5 times). Model performance was measured using the area under the ROC (receiver operating characteristic) curve (AUC), a threshold-invariant metric widely used for evaluating binary classifiers (Fawcett 2006). The hyperparameter configuration with the highest average AUC across all cross-validation sets was selected. The ROC curve shows the model's performance in terms of sensitivity (true positive rate) and specificity (1 – false positive rate) across all possible probability thresholds, with AUC values closer to 1 indicating better model performance in terms of distinguishing between classes. Figure 74 shows the ROC curves from all the cross-validation sets. The best-performing RF model hyperparameter configuration (*mtry*

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= 2, *splitrule* = gini) resulted in an average AUC of 0.95 across all cross-validation sets. This indicates a high model's ability to distinguish between the positive and negative classes. The best-performing hyperparameter configuration was used to train the final model on the entire training dataset (2,496 records), and the trained model was then used to estimate probabilities for the non-validated records of 60 species.

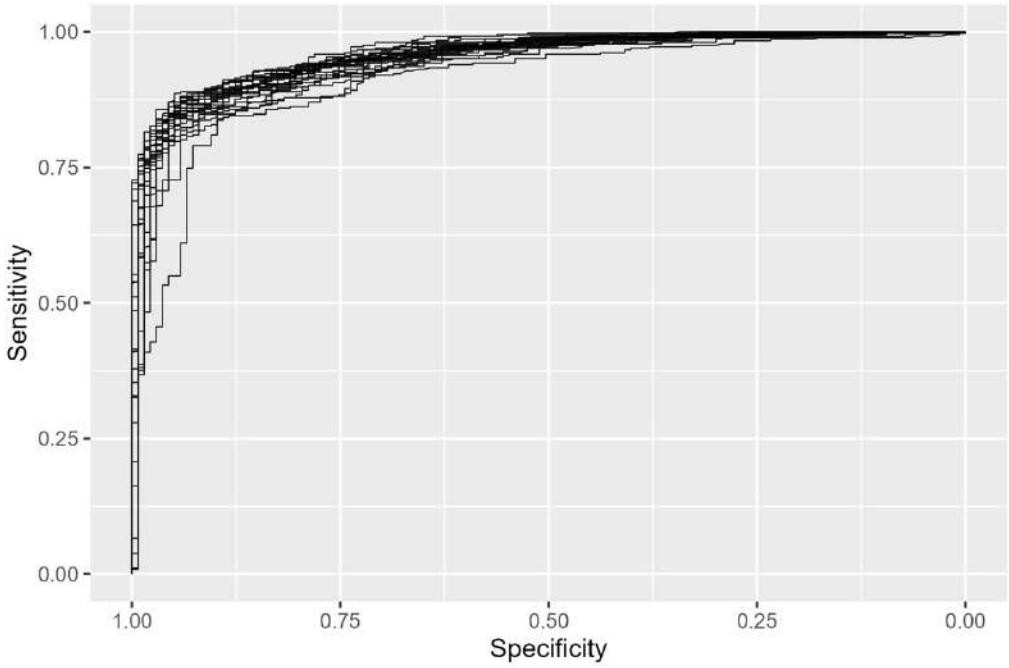

Figure 74. ROC curves from all 25 cross-validation sets (5 folds, repeated 5 times). The average AUC across all curves is 0.95.

In the final step, the curated dataset was further processed by renaming existing attributes and creating new ones in accordance with the Darwin Core standard (Wieczorek et al. 2012) (see next section).

Data Records

The resulted data package associated was published on Zenodo (version 2.0.0) (Eldesoky et al. 2025b, https://doi.org/10.5281/zenodo.15490818). The main data product in the package is the bird species occurrence file in a comma-delimited format (csv). The file has 239,597 rows and 30 columns, where each row represents a detection and each column represents an attribute (or "term" as described by the Darwin Core standard). A list and description of the Darwin Core and custom attributes included in the occurrence dataset are provided in Table S2 (Appendix D) are also available online with more information at (https://smog-chalmers.github.io/BirdMonitoringGothenburg/).

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4.3.3.4. Habitat network analysis

Since we hypothesize that bird species richness in urban areas depends on the accessibility of bird habitats of different types, if more types of essential habitats are available within reach for the birds on a daily basis, more species can be expected to be present at a certain site within the city. To enable analyses of the connectivity and availability of habitat types used by different bird species, we compiled information about which habitats different bird species use for foraging and nesting sites (Table S1, Appendix C). This data was collected from both the Swedish Species Information Centre (https://artfakta.se) and the AVONET dataset on bird traits (Tobias et al. 2022). For some species, we added information based on our own experience. This was mainly done for those species of birds that have adapted to the urban landscape by, for example, foraging at outdoor restaurants or nesting on the roofs of buildings. This information is to a large extent lacking in the eBird database (https://ebird.org/), and the degree to which a species has adapted to the urban environment may differ between cities. For example, the Hooded Crow (*Corvus corone Linnaeus*, 1758) often feeds at outdoor restaurants in Gothenburg, but much less or never in many other Swedish cities. Another example of this local adaptation is the Lesser Black-backed Gull (*Larus fuscus Linnaeus*, 1758), which in most parts of its north European range nests mainly on treeless skerries or small rocks along the coast, typically far from urban influences. However, in recent years, this species has been found nesting on rooftops in cities, including Gothenburg.

Biotope map

To enable analyses of bird species richness in relation to existing habitats at or near all the sampling sites, we created a biotope map covering the whole study area showing all bird habitats listed in Table S1 (Appendix C). For this, we used the Swedish National Land Cover Map (version NMD2023; metadata[6]), which can be downloaded free of charge from the Swedish Environmental Protection Agency[7]. The basic raster layer of NMD2023 has a spatial resolution of 10x10 meters per pixel. Its pixel values represent 25 different habitat classes, where 16 constitute different types of wet and dry forests. As most bird species do not show any apparent preference for specific tree species, we replaced the forest classes with three new classes, which are much more relevant for birds found in Gothenburg, i.e., Trees (201) and Valuable trees (202). The valuable trees were added from a point layer downloaded from open open-access database provided by the Swedish Species Information Centre. We also added a new class for bushes (200). This was done by combining the habitat class for open land with vegetation in NMD2023, i.e., 42, with information from a data layer included in NMD2023, which indicates the vegetation height within the range of 0-5 meters.

As many bird species put their nests in different types of habitats very close to water, we defined a set of beach habitats based on the distance to all identified water pixels in the basic NMD2023 raster. These include Cliff beach (241), Grassland beach (242), and Shaded beach (243). Specifically, all pixels

[6] https://data.europa.eu/api/hub/repo/distributions/63f74a71-8946-4a5a-b9ba-84250adf43c5.rdf

[7] https://geodata.naturvardsverket.se/nedladdning/marktacke/NMD2023/Basskikt_v0_x/NMD2023_basskikt_v0_2.zip

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originally classified as Non-vegetated open land (41) and adjacent to water habitats (61, 62) were reclassified as Cliff beach (241). Similarly, pixels from the Vegetated open land class (42) that were adjacent to water (61, 62) were reclassified as Grassland beach (242). Pixels adjacent to water that were initially classified as Bushes (200) or Trees (201) were reclassified as Shaded beaches (243). Reeds (444) is another specific nesting habitat for some bird species identified in Gothenburg. This habitat was identified as pixels from the basic raster layer of NMD2023 classified as Open wetland (2) that were located near Inland water (61).

Many urban bird species have adopted a regular behaviour of feeding at outdoor restaurants and cafés. We therefore added a specific new habitat class for Cafés and restaurants (500) based on a point layer of all such objects within the city of Gothenburg, which can be downloaded from (source). The resulting biotope map is shown in Figure 75.

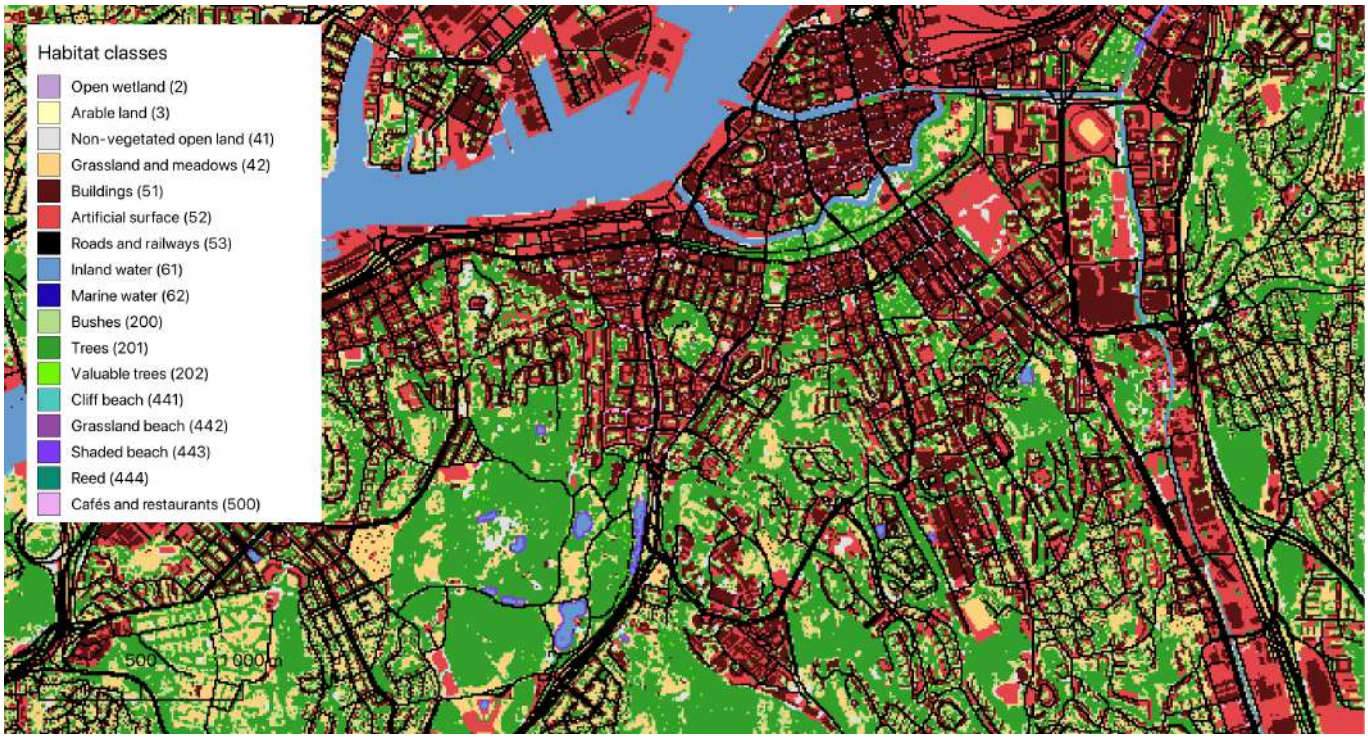

Figure75. Biotope map

Habitat connectivity and availability.
We calculated three measures that describe habitat connectivity and availability in the sample sites, using the biotope map:

- **Area of natural habitats within a 70 m buffer around each sampling location,** including only natural habitats because they are the non-urban component, otherwise the area is the same. We treat all of the natural habitat the same.

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- **Diversity of natural habitats within a 70m buffer around the sampling location**: Local habitat diversity within each buffer was measured using the Shannon diversity index:

$$H' = -\sum_{i=1}^{m} p_i \ln(p_i),$$

where p_i is the proportion of habitat type i.

- **Landscape (structural) connectivity to surrounding suitable habitats**: landscape connectivity was measured as the inverse of the average Euclidean distance to all suitable natural habitats, calculated within multiple buffer distances (200–4000 m) around each site.

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

where n is the number of suitable habitat pixels and d_j is Euclidian distance to habitat pixel j.

4.3.3.5. Statistical analysis

To test the first and second hypotheses linking bird species richness with building density types and building typologies, we tested the statistical significance of differences in species richness among the 3 building types and reference sites using non-parametric ANOVA (Kruskal-Wallis test) and post-hoc tests. To test the third hypothesis linking bird species richness we used Generalized Linear Models (GLMs), to statistically model the relationship between bird species richness and the three explanatory variables of habitat connectivity and availability, across the 3 building types.
The specific statistical tests will be further detailed in the presentation of Results in the next section.

4.3.4. Results

Across the 30 urban sites monitored during spring 2024 (from April 21 to June 16), a total of 61 bird species, representing 25 families, were observed. Table S1 lists all observed bird species (see Appendix C). In the following subsections, we present the results of the different analyses conducted to test each of our three hypotheses.

4.3.4.1. Differences in bird species richness and composition between dense/compact building types and reference sites

To test whether species richness and composition differed between dense and compact sites and reference semi-natural or sparsely-built urban sites (H1), we compared the two groups using the Mann–

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Whitney U test (Figure 76) and Permutational Multivariate Analysis of Variance (PERMANOVA), respectively. Species richness was significantly lower in the dense and compact sites than in the reference urban sites (median = 24 vs. 33 species; Wilcoxon rank-sum test: $W = 27$, $p = 0.0009$).

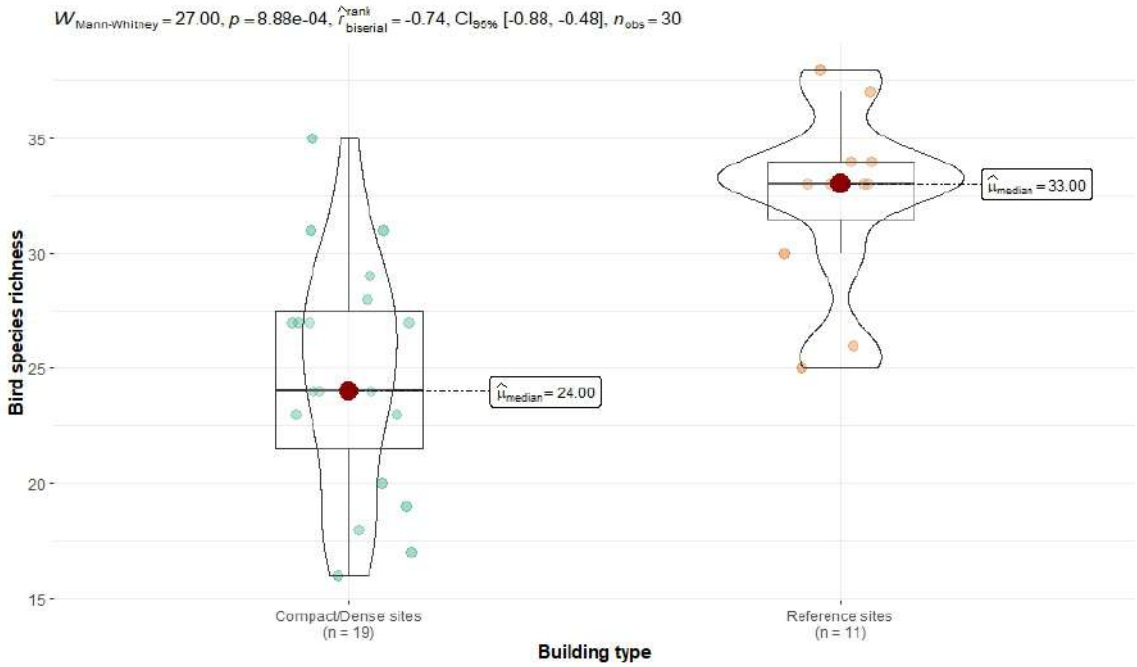

Figure 76. Box and violin plots showing differences in bird species richness between compact/dense sites and reference sites. Points represent observed values; red points denote group medians, and boxes show the interquartile range (IQR).

Similarly, PERMANOVA analysis showed that there **were statistically significant differences in bird communities between the compact/dense sites and reference sites** ($F = 5.3626$, $R^2 = 0.16$, $p < 0.01$). However, *Permutational Multivariate Analysis of Dispersion (*PERMDISP) showed that the two groups also differed significantly in their within-group multivariate dispersion ($p = 0.016$). Given the unbalanced design (11 vs. 19 sites), this means that the significant PERMANOVA result may reflect differences in centroid location, differences in dispersion, or a combination of both (Anderson et al., 2008; Bakker, 2024; Warton et al., 2012). The NMDS ordination plot (Figure 77) supports both effects: the two groups show a shift in centroid position (a location effect), while the compact/dense sites show a more dispersed cloud of points (a dispersion effect). PERMANOVA results from 1000 bootstrap resamples—used to obtain test statistics based on balanced designs, for which PERMANOVA is largely unaffected by heterogeneity—remained consistently significant (median $p = 0.0015$, IQR = 0.0032, range = 0.0001–0.0407). This further suggests that compact/dense and reference sites differ in bird community composition. Table 10 shows the bird species unique to each group.

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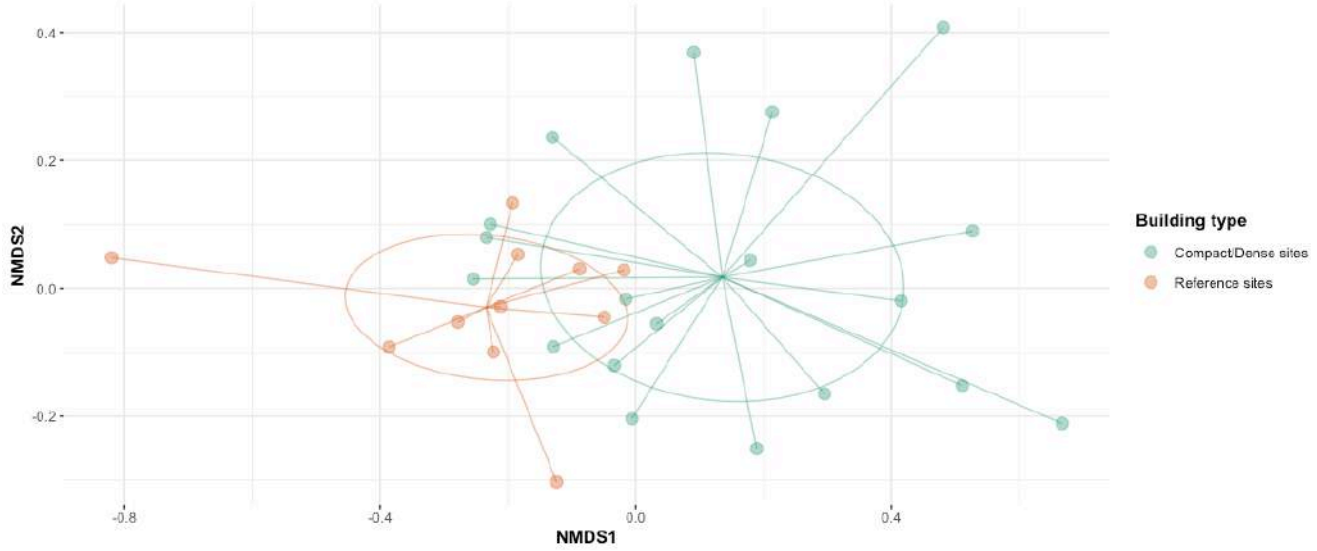

Figure 77. 2D NMDS ordination based on Jaccard dissimilarity. Points represent individual sites; ellipses show the standard-deviation dispersion of each group, and spider lines connect sites to their group centroid.

Table 10. Bird species observed only in either the compact/dense building types or the reference sites.

Group	Species only found in this group
Compact/Dense sites	*Columba oenas* (skogsduva), *Curruca communis* (törnsångare), *Larus fuscus* (silltrut), *Sterna Hirundo* (fisktärna)
Reference sites	*Acrocephalus palustris* (kärrsångare), *Acrocephalus scirpaceus* (rörsångare), *Bucephala clangula* (knipa), *Caprimulgus europaeus* (nattskärra), *Cuculus canorus* (gök), *Fringilla montifringilla* (bergfink), *Regulus regulus* (kungsfågel)

Overall, **these results, together with the significant differences found in species richness, support H1 and align with previous studies showing that higher building density and reduced natural habitat cover negatively affect bird richness and composition in urban areas.**

4.3.4.2. Variation in species richness and composition within and among the dense and compact building types

We next **examined variation in species richness and composition within and among the three dense and compact building types (H2).** As shown in Figure 78, species richness varied within each building type, as indicated by differences in the interquartile range (IQR) and overall range. More specifically, among the three types, the compact mid-rise exhibited the widest within-group variation (IQR = 6; range = 13), followed by the compact low-rise (IQR = 4.5; range = 19) and dense mid-rise (IQR = 4; range = 14).

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A Kruskal–Wallis test **revealed no significant differences in species richness among the three building types** ($\chi^2 = 1.12$, df = 2, p = 0.57).

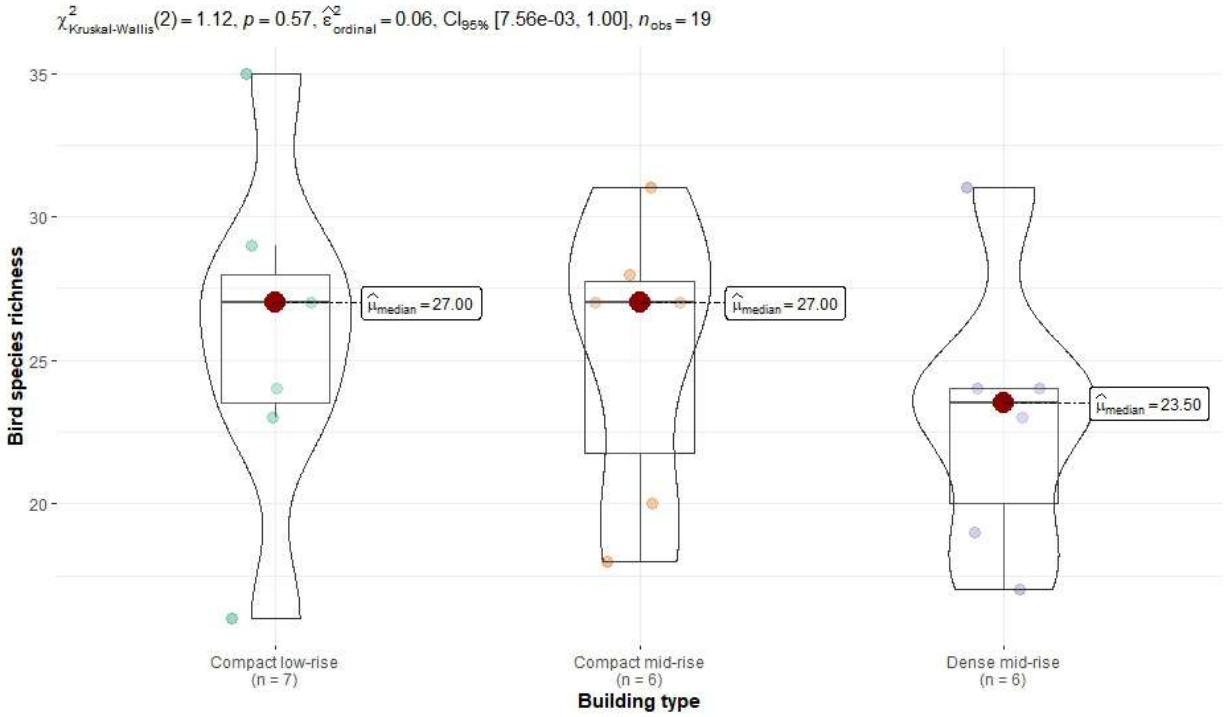

Figure 78. Box and violin plots showing bird species richness across the three dense and compact building types. Points represent observed values; red points denote group medians, and boxes show the IQR.

As for species composition, the NMDS ordination plot (Figure 79) shows that all building types exhibited within-group dissimilarity in species composition, indicating that sites within each building type differed in their bird communities. However, the three types exhibited strong overlap in ordination space, with no clear compositional separation among them.

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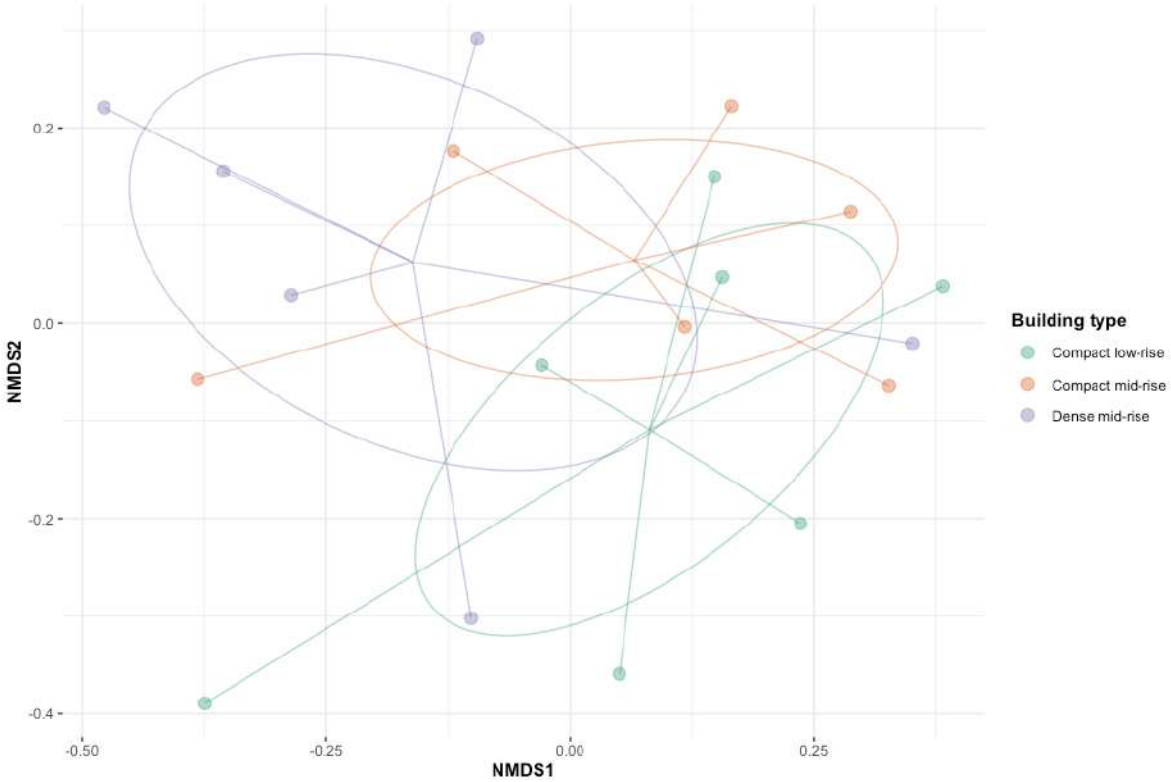

Figure 79. 2D-NMDS (non-metric multidimensional scaling) plots showing the distribution and distance between sites and the dense/compact and reference building types.

The PERMANOVA analysis showed that **the difference in species composition among the three building types was borderline significant** ($F = 1.77$, $p = 0.049$, $R^2 = 0.18$), and no pairwise comparison remained significant after correction for multiple testing (BH-adjusted p-values: 0.078–0.504). This suggests that no individual pair of building types differed significantly in community composition. The species unique to each building type (Table 11) further suggest that the borderline significant differences detected in the PERMANOVA reflect the surrounding landscape context or local habitat characteristics of individual sites, rather than the building types themselves. For example, *Sterna hirundo*, a water-dependent species, was observed only at dense mid-rise sites, most likely because this type is predominantly located by the Göta älv river (Figure 68). Similarly, *Columba oenas*, which is rarely recorded in urban environments, was observed only at a compact mid-rise site (Chalmerska Vasaparken), suggesting favourable local habitat conditions rather than an effect of building type. Overall, these findings suggest that, similar to **species richness, species composition varied within building types but did not differ significantly between them**. Thus, **H2 was only partially supported**.

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Table 11. Bird species observed only in one of the three dense and compact building types.

Building type	Species only observed in this type
Compact low-rise	*Phoenicurus ochruros* (svart rödstjärt), *Poecile palustris* (entita), *Spinus spinus* (grönsiska)
Compact mid-rise	*Columba oenas* (skogsduva), *Hippolais icterina* (härmsångare), *Turdus philomelos* (taltrast)
Dense mid-rise	*Acanthis flammea* (gråsiska), *Curruca communis* (törnsångare), *Sterna Hirundo* (fisktärna)

4.3.4.3. Relationship between site-specific and larger-scale variables and bird species richness and composition across the dense and compact building types

To assess **whether variation in bird species richness and composition within dense and compact building types was associated with site-specific and larger-scale variables (H3), we fitted two sets of models.** Specifically, we ran 75 Conway-Maxwell Poisson generalized linear models (GLMs) for species richness and 75 PERMANOVA models for species composition, using all possible combinations of the three variables introduced in Section 4.3.3.4. Briefly, local-scale variables included the area (m2) and diversity (Shannon–Wiener index) of suitable habitat types within a 70 m buffer around each site, whereas the larger-scale variable included structural connectivity, measured as the average Euclidean distance to surrounding suitable habitats within multiple buffer distances (200–4000 m) to assess sensitivity to spatial scales.

Among the fitted models, the model combining local habitat area and structural connectivity measured within 1800 m yielded the lowest AICc (Akaike information criterion corrected for small sample size), indicating the most parsimonious model. The model combining local habitat area and connectivity at 1600 m also had strong support (ΔAICc = 1.26). These two models exhibited better relative fit compared to all other candidate models (pseudo-R^2 = 0.81–0.82), and diagnostic checks (Figure 80) confirmed that the model assumptions were met and supported the adequacy of the most parsimonious model. More specifically, residuals showed no systematic patterns and closely followed the expected theoretical distribution, and there was no evidence of residual spatial autocorrelation (Moran's I = 0.0409; p = 0.15).

In both models, **local habitat area and structural connectivity revealed statistically significant positive associations with species richness (p < 0.01), with habitat area showing a stronger association** (Table 12; Figure 81). Specifically, a one–standard-deviation increase in local habitat area was associated with 16% (12–21%) increase in expected species richness (IRR = 1.16, 95% CI [1.12, 1.21]) after accounting for structural connectivity, whereas a one–standard-deviation increase in structural connectivity was associated with 10% (5–15%) increase (IRR = 1.10, 95% CI [1.05, 1.15]).

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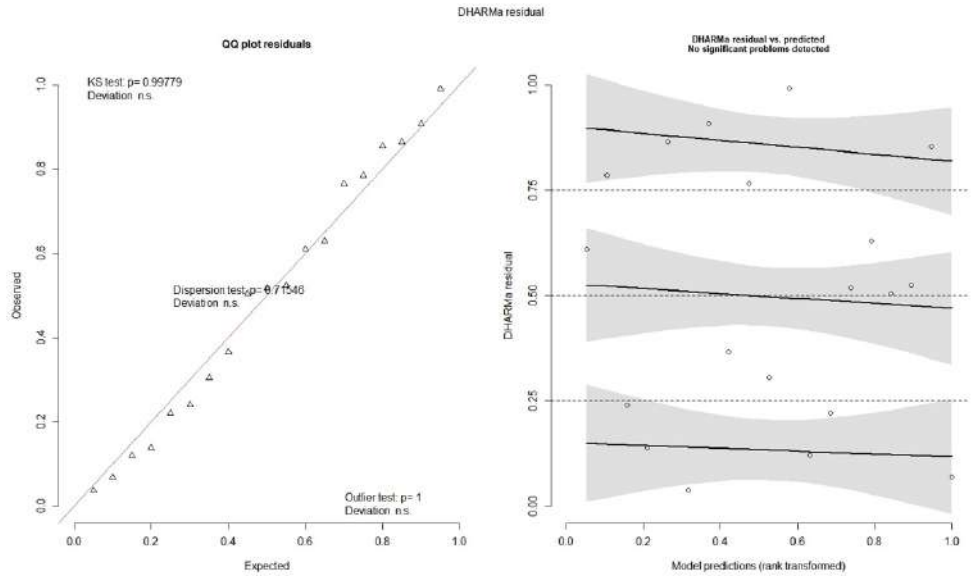

Figure 80. QQ-plot to detect overall deviations from the expected distribution, left, and DHARMa residuals plotted against the model predictions (rank-transformed), right.

Table 12. Best-performing candidate models (ΔAICc < 2). IRR = Incidence Rate Ratio (exponentiated estimate); CI = Confidence Interval (To be noted that more combinations of models were tested. We report on the two best performing)

Model ID	Variables	IRR	95% CI for IRR	p-value	pseudo-R^2	AICc
27	Intercept	24.3	[23.3, 25.4]	< 2e-16***	0.81	**95.13**
	Habitat area	1.16	[1.11, 1.21]	3.28e-12***		
	Connectivity (1600 m)	1.09	[1.05, 1.14]	6.60e-05***		
28	Intercept	24.3	[23.4, 25.3]	< 2e-16***	0.82	**93.87**
	Habitat area	1.16	[1.12, 1.21]	5.36e-13***		
	Connectivity (1800 m)	1.10	[1.05. 1.15]	2.05e-05***		

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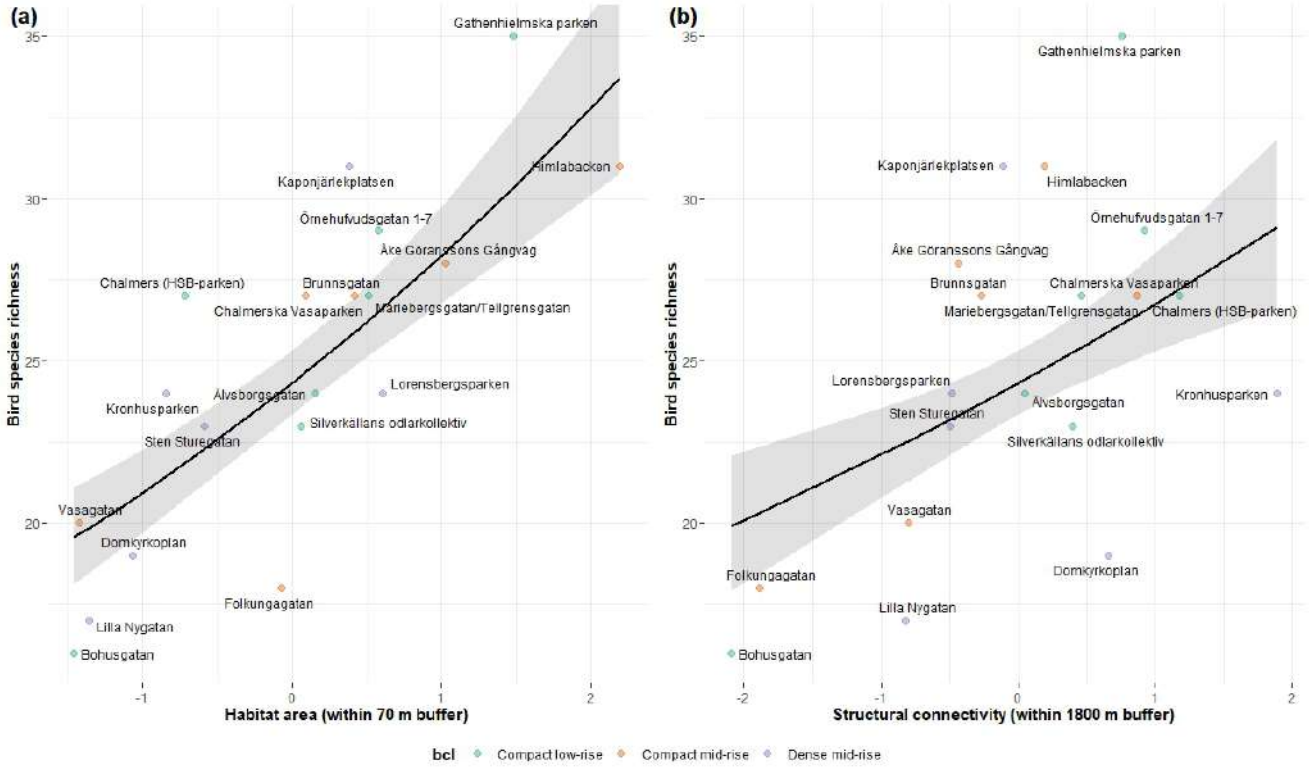

Figure 81. Marginal relationships between bird species richness and (a) local habitat area (within 70 m buffer) and (b) structural connectivity (within 1800 m buffer). Points represent observed values; the solid line shows the model-predicted mean from the fitted model, and the shaded ribbon indicates the 95% confidence interval. Habitat area and structural connectivity were standardized using z scores before modelling.

Across all fitted models, only structural connectivity measured within 1400–2400 m showed statistically significant relationships with species richness when combined with habitat area, with connectivity at 1600 m and 1800 m yielding the strongest associations and lowest AICc values. The Shannon–Wiener index did not show a statistically significant relationship with species richness in any models that included local habitat area. Although it was significant in models incorporating connectivity measured at 1600, 1800, or 2000 m, those models had ΔAICc > 10, indicating essentially no support. **This is likely because the Shannon–Wiener index exhibited little variation across the three building-density types (Figure 82), which provided minimal improvement in model fit**.

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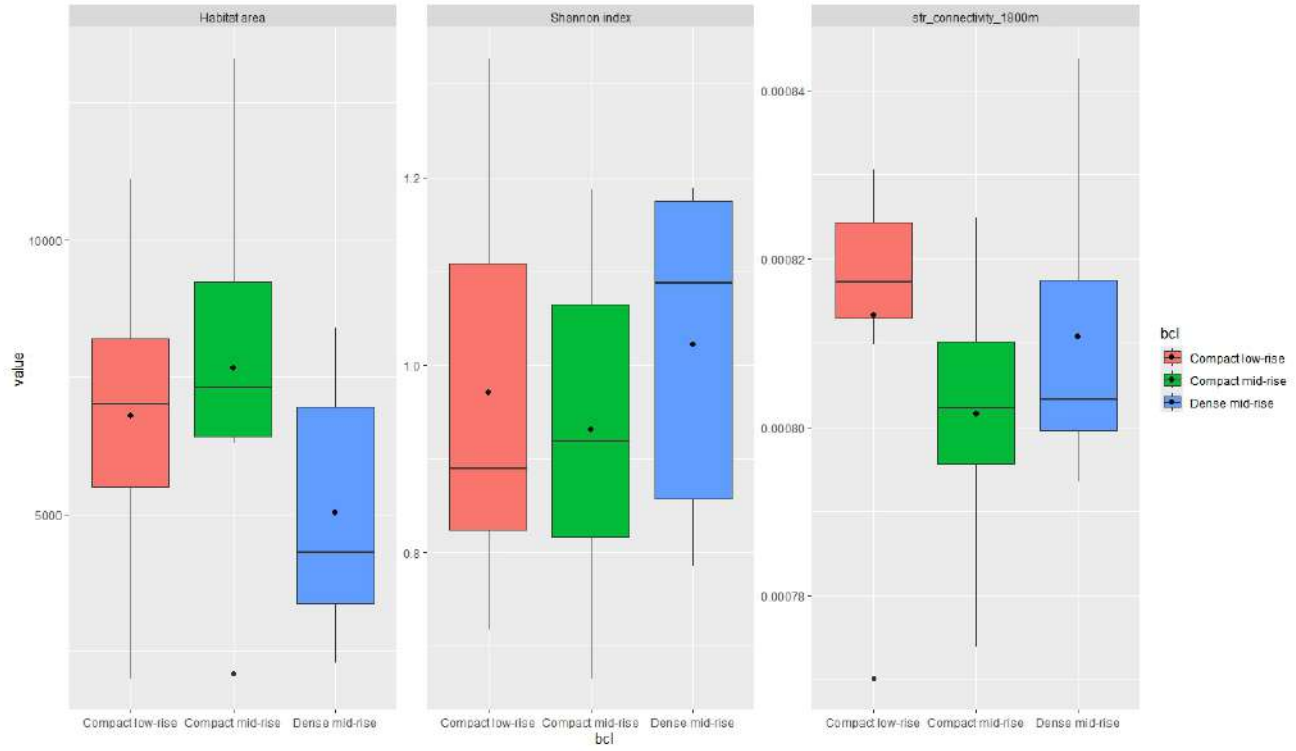

Figure 82. Variation of Habitat area, Shannon-Wiener index and Structural connectivity (1800m) across building density types.

As for species composition, PERMANOVA results assessing **marginal effects** of each of the three variables on community dissimilarity, showed that local **habitat area was the only variable significantly associated with community dissimilarity in all models** (marginal $R^2 \approx 0.14–0.22$, $p < 0.01$). In contrast, **connectivity was not significant in any of the models that included habitat area**, indicating that variation in species composition is mainly associated with habitat area rather than with landscape connectivity. Similar to the results for species richness, the Shannon index showed no significant marginal effect on bird community composition.

Overall, **these results support H3 that variation in bird species richness and composition within dense and compact urban areas is associated with local habitat conditions and/or larger-scale landscape connectivity.**

4.3.5. Conclusions and Discussion

A central challenge in sustainable urban development is balancing the benefits and costs of high urban densities. In this study, **we questioned whether there is a potential to reduce the biodiversity loss associated with urban densification strategies**. We argued that understanding how high urban density influences biodiversity has been limited in the scientific agenda for several reasons, most importantly

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because research has largely focused on urban–rural gradients and because urban density is often measured in crude ways that do not reflect aspects of urban form and performance.

To take a first step towards a more nuanced of the relationship between urban density and biodiversity, **we tested a set of hypotheses** using data on bird species distributions across three distinct urban form types. These included areas characterized by high ground space index (GSI) and floor space index (FSI), as well as reference semi-natural or sparsely built urban sites in Gothenburg, Sweden.

Our findings show:

- Although **species richness and community composition differed significantly between dense/compact urban sites and semi-natural/sparsely-built reference sites,** consistent with previous studies, **there was no significant difference among the different dense and compact building types.**

- Most importantly, **sites of the same dense/compact type differed largely in both richness and composition.**

- Specifically, dense and compact urban sites with **higher local natural habitat area and/or better connectivity to surrounding natural habitats (within 1.6–1.8 km) supported higher bird species richness,** whereas **community composition was driven primarily by local habitat area.**

These are important findings for urban planning and design because even if expanding natural habitats within dense and compact urban areas is constrained by limited space and competing land-use demands, there **remains an opportunity to reduce biodiversity loss through broader-scale planning for habitat connectivity**. In urban design and planning practice, the latter is often overlooked in favour of site-specific characteristics that are known to promote local biodiversity, or more specifically, composition (e.g., native tree cover, ponds, and freshwater sources).

A parallel spin-off study (Eldesoky et al., 2025d) complements the findings presented in this chapter by showing that relationships between urban microclimate and bird biodiversity are non-linear and species-specific. Using the same bird dataset combined with modelled microclimate indicators, the study demonstrates that community-level bird diversity peaks at intermediate levels of microclimatic variability, while individual species respond differently to temperature conditions. These results indicate that **urban form and function influence ecological outcomes not only directly, but also indirectly through microclimate**. They reinforce the argument that cities are coupled social–ecological systems, where biodiversity outcomes cannot be explained by density or spatial form alone. Instead, ecological responses emerge from interactions between urban morphology, green connectivity, habitat characteristics, and environmental conditions. The results underline **the importance of evidence-based, context-sensitive planning, as uniform design or climate mitigation strategies may lead to uneven ecological effects**. Integrating biodiversity indicators, microclimate modelling, and spatial analysis within EBDP therefore enables a more nuanced and actionable understanding of ecological processes,

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strengthening the case for embedding socio-ecological and climatic evidence early in planning and design workflows.

These findings also relate to the broader **"land sharing vs. land sparing" debate** in urban ecology (Soga et al., 2014). Several previous studies have suggested that land sparing, characterized by compact/dense development spared from larger areas of conserved habitat, reduces biodiversity within the dense/compact urban area but helps maintain higher overall biodiversity at the city scale (Caryl et al., 2016; Geschke et al., 2018; Sushinsky et al., 2013). **Our results support this general pattern but add nuance by suggesting that biodiversity loss within compact/dense urban areas can be reduced through careful planning for landscape connectivity.** Also, several species rarely recorded in urban environments (e.g., *Columba oenas*) were observed at certain compact/dense sites, suggesting that **even dense/compact urban forms can support species of conservation interest when favourable local habitat features or surrounding landscape contexts are present.**

5. Summary of findings, scientific contributions and policy implications

5.1. Synthesis of findings

This research set out to examine how Evidence-Based Design and Planning (EBDP) can be strengthened as a practical, transferable, and forward-looking approach to urban planning and design. By addressing applicability across diverse contexts, reducing data and technical barriers, and integrating social-ecological performance, the research responds to key limitations in existing evidence-based approaches and contributes to their evolution in line with contemporary urban challenges.

A central insight emerging across all three chapters is that **analytical robustness and practical applicability are not synonymous with high data intensity**. The findings from Chapter 2 demonstrate that EBDP can be meaningfully applied in data-fragmented and institutionally constrained contexts when minimum data requirements are clearly defined, and methodological trade-offs are explicitly acknowledged. The comparison of manually curated and fully automated modelling workflows highlights that while expert-curated models remain valuable, scalable and reproducible automated approaches can generate comparable spatial patterns for key indicators such as accessibility and centrality. This challenges prevailing assumptions in spatial analysis and underscores the importance of transparency, scalability, and reproducibility over model complexity alone.

Building on this, Chapter 3 reframes methodological rigor in EBDP through the development of less data-intensive analytical frameworks. The SOAR framework demonstrates that **open data and automated workflows can provide a reliable analytical baseline** capable of supporting early-stage planning, scenario testing, and cross-context comparison in the European context. Rather than

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positioning lightweight models as inferior substitutes, the research shows how they can function as foundational analytical layers that are incrementally enhanced as additional data become available. This perspective has important implications for the democratization of evidence-based planning, particularly in regions and municipalities with limited analytical capacity.

Chapter 4 extends this methodological evolution beyond the state-of-the-art by integrating social-ecological performance into the EBDP framework. The findings demonstrate that **ecological considerations can be operationalised within spatial analysis rather than treated as external or post hoc assessments**. The empirical evidence on biodiversity in dense and compact urban environments challenges deterministic narratives that frame urban density as inherently incompatible with ecological quality. Instead, the research highlights the role of spatial configuration, habitat quality, and green connectivity in shaping ecological outcomes. This integration marks a significant conceptual shift toward viewing cities as coupled social-ecological systems and positions EBDP as a tool capable of addressing climate and biodiversity challenges in a more holistic manner.

Across the three chapters, the research also highlights the **institutional dimension of evidence-based planning**. The introduction of the **EBDP Applicability Matrix demonstrates that technical feasibility alone is insufficient to ensure meaningful implementation**. Institutional readiness, governance structures, and stakeholder engagement play a decisive role in determining whether analytical insights translate into planning and design decisions. This reinforces the need to align analytical ambition with institutional capacity and to embed evidence-based approaches within existing governance frameworks.

Taken together, the research advances EBDP as a **scalable, context-sensitive, and interdisciplinary framework**. It shows that EBDP can be adapted to diverse planning environments, expanded to include social-ecological performance, and aligned with digitalisation and open science principles. At the same time, the research acknowledges important limitations, including the reliance on open datasets of variable quality, the need for further validation across different geographical and institutional contexts, and the challenges of translating analytical outputs into binding policy and regulatory instruments. In conclusion, this research demonstrates that the future relevance of Evidence-Based Design and Planning lies not in increasingly complex models, but in **methodological clarity, openness, and integration**. By bridging spatial, socio-economic and social-ecological perspectives and by grounding analytical innovation in real planning contexts, the research provides a robust foundation for more resilient, inclusive, and environmentally responsible urban planning and design.

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5.2. Contribution to the advancement of EBDP

The research successfully **met the three research objectives** defined in Work Package 4 through a **combination of methodological development, empirical testing, and applied case studies**. Each objective was addressed through a dedicated research package, with clear outputs and demonstrable results (Table 13).

Table 13. Summary of achievements and deliverables in relation to research objectives

Research Objective	Achievements (How it was met)
Objective 1: Assess the applicability of EBDP across different planning contexts and scales	Conducted a comprehensive **data audit** for Cyprus (EU, national, crowdsourced sources), identified key gaps and constraints, and defined a **minimum analytical data model** for EBDP. Developed two street network workflows (hybrid/manually curated and fully automated) and carried out a **systematic comparison** of analytical results. Introduced an EBDP framework that integrates data collection, stakeholder engagement, and spatial modelling. Demonstrated applicability through **three real-life case studies** at different scales and introduced the **EBDP Applicability Matrix** (Deliverable 4.3) to assess technical **and institutional readiness** across projects. Two **Policy Briefs** (Deliverable 4.4) are published, and two scientific papers are submitted for publication to a high-ranked journal.
Objective 2: Develop less data-intensive EBDP spatial models	Developed the **SOAR framework (Scalable, Open, Automated, Reproducible)** and implemented **open, automated workflows** based on European open data and open-source tools. Produced a lightweight model capable of generating core EBDP indicators (e.g., connectivity, centrality, accessibility, functional reach) with reduced manual effort and improved reproducibility. Demonstrated practical value by linking lightweight modelling to applied analyses and cross-context comparability.
Objective 3: Integrate social-ecological performance into EBDP	Developed a **social-ecological conceptual and analytical framework** grounded in Social-Ecological Urbanism. Collected **original empirical data** on bird occurrence using Passive Acoustic Monitoring and combined it with spatial analysis to assess biodiversity outcomes across compact and dense urban typologies. Provided **empirical evidence** that biodiversity can co-exist with high urban density, when habitat quality and connectivity are carefully designed, demonstrating that **ecological indicators can be quantified and integrated** into EBDP workflows alongside socio-economic measures. One **Scientific Paper** (Deliverable 4.2.) is published and a second is submitted for publication to a high-ranked journal.

This research advances Evidence-Based Design and Planning (EBDP) by strengthening its applicability, methodological robustness, and scope, positioning it as a more transferable and future-oriented framework for contemporary urban planning and design.

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- **First,** the research advances EBDP by demonstrating that evidence-based planning is not inherently dependent on high data intensity or proprietary tools. Through the definition of minimum data requirements and the validation of less data-intensive, open, and automated analytical workflows, the research reframes EBDP as an approach that can operate effectively in data-fragmented and institutionally constrained contexts. This significantly expands the potential reach of EBDP beyond data-rich metropolitan environments.

- **Second**, the research contributes to the methodological maturation of EBDP by prioritising transparency, reproducibility, and scalability. The comparative evaluation of manual and automated spatial modelling workflows provides empirical evidence on methodological trade-offs and establishes automated approaches as credible analytical foundations. The development of the SOAR framework further embeds EBDP within open science principles, supporting consistency, comparability, and cumulative knowledge building.

- **Third**, the research advances EBDP conceptually by extending it from a predominantly socio-spatial framework to a social-ecological planning paradigm. By integrating ecological performance, exemplified by bird diversity, within the evidence-generation phase of planning and design, the research demonstrates how EBDP can address ecological challenges, as climate and biodiversity, in a holistic and proactive manner, rather than as post hoc assessment.

- **Fourth**, the research strengthens the practical relevance of EBDP by explicitly addressing the institutional conditions under which, evidence is used. The EBDP Applicability Matrix represents a novel contribution that bridges analytical capability and governance readiness, recognising that evidence-based planning is as much an institutional challenge as a technical one.
- **Finally**, by grounding methodological innovation in real planning and design contexts, the research reinforces EBDP as a decision-support framework rather than an abstract analytical exercise. By integrating data collection, stakeholder engagement, and spatial modelling, it demonstrates how evidence can meaningfully inform decision makers about accessibility, equity, and environmental performance, supporting more transparent, accountable planning processes and enabling verifiable goal achievement.

Taken together, **this research advances EBDP toward a framework that is scalable, open, institutionally aware, and interdisciplinary, enhancing its relevance for policymakers, planners, and designers** working to address the complex sustainability challenges facing cities today.

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5.3. Knowledge contributions

Beyond advancing Evidence-Based Design and Planning conceptually and methodologically, this research generates a set of **transferable knowledge assets** that can be directly used by researchers, practitioners, and policymakers in other contexts. The **transferable outputs** are summarised in Table 14.

Table 14. Transferable key outputs

Key Output	Description and Reuse Potential
Minimum Data Model for EBDP	Defines a core set of essential spatial data layers enabling analyses of accessibility, connectivity, spatial equity, and urban form in data-constrained contexts. Reusable as a baseline for applying EBDP where comprehensive datasets are unavailable.
Validated Automated Spatial Workflows	Open, reproducible analytical workflows demonstrating how less data-intensive models can generate policy-relevant evidence. Includes guidance on trade-offs between manual and automated modelling, supporting scalable and cost-effective planning analysis.
SOAR Framework (Scalable, Open, Automated, Reproducible)	A transferable methodological framework for implementing EBDP using EU open data and open-source tools. Applicable across EU planning contexts and spatial scales, and extensible as additional data become available.
EBDP Applicability Matrix	A diagnostic tool assessing both technical feasibility and institutional readiness for evidence-based planning. Reusable for project scoping, capacity assessment, and aligning analytical ambition with governance conditions.
Integrated Social-Ecological Analytical Framework	An analytical framework linking urban form and spatial configuration with ecological performance, enabling biodiversity indicators to be assessed alongside socio-economic metrics within EBDP workflows.
Open Dataset on Urban Bird Occurrence	An openly accessible dataset of originally collected and processed bird occurrence data in Gothenburg, Sweden, generated through Passive Acoustic Monitoring in compact urban environments. Reusable for ecological research, comparative studies, and integration of biodiversity indicators into planning evidence.

In addition, **four scientific papers** have been published or submitted in high-ranked scientific journals (see Section 5.5.), going beyond the formal deliverables. The produced **workflows, codes and datasets** have been published in **open-access repositories**. These outputs together with **conference presentations, policy briefs, fact sheets, popular science publications, blogs** and **podcasts** disseminate the project's findings to the scientific community, practitioners and civic society. For the complete list, see Section 5.5.

This research advances the field of EBDP through concrete **methodological innovation**, **comparative analytical validation**, and **original empirical evidence**. Its contributions address key limitations of existing

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EBDP approaches, particularly their high data requirements, limited contextual transferability, and insufficient integration of ecological performance alongside socio-economic indicators.

5.3.1. Scientific contributions

5.3.1.1. Methodological Developments

A central methodological contribution of this research is the development of an **adaptable methodology** and an **integrated analytical framework for Evidence-Based Design and Planning** that operates across social, spatial, and ecological dimensions. The framework integrates data collection, stakeholder engagement, and spatial modelling. It explicitly links urban form, spatial configuration, accessibility, and environmental characteristics to both socio-economic and ecological outcomes, enabling EBDP to function as a social–ecological planning tool.

The research established a **minimum analytical data model** for EBDP, identifying the essential data layers required to support analyses of connectivity, centrality, accessibility, walkability, functional mix, and built density. This contribution challenges prevailing assumptions that evidence-based planning requires comprehensive and data-intensive cadastral datasets and provides a transferable baseline for applying EBDP in data-fragmented and institutionally constrained contexts.

A further methodological advancement is the **systematic comparison of hybrid (manually curated) and fully automated street network modelling workflows**. By rigorously testing centrality and accessibility measures across modelling approaches, the research demonstrates that automated, open-source workflows can reproduce key spatial patterns generated by expert-curated models, particularly at aggregated analytical scales. This contributes empirical clarity to ongoing methodological debates regarding precision, scalability, and reproducibility in spatial network analysis.

The research also introduced the **SOAR framework (Scalable, Open, Automated, Reproducible)** as a methodological foundation for lightweight spatial modelling. SOAR formalises the use of open data and automated workflows to generate core EBDP indicators while ensuring transparency, comparability, and cross-context transferability. This framework aligns EBDP practice with open science principles and computational urban analytics.

Critically, the research extends EBDP **beyond the state-of-the-art** through the development of an **analytical framework for integrating social-ecological performance**. Grounded in Social-Ecological Urbanism, this framework connects spatial configuration and urban morphology with ecological indicators, enabling environmental performance to be assessed alongside accessibility and spatial efficiency. Using bird diversity, a strong indicator of biodiversity, as an example, the framework demonstrates how ecological data and ecological performance can be operationalised within EBDP workflows, opening the way for further developments on that front.

In addition, the research produced **an original open-access dataset of bird occurrence** in Gothenburg, Sweden, with data collected through Passive Acoustic Monitoring. The dataset serves as an empirical foundation and can be used for further research and comparative studies. Besides the final dataset, the

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open-access state-of-the-art data processing workflow serves as a baseline and a transferable methodology to facilitate future data collection.

Finally, the **EBDP Applicability Matrix** represents a methodological innovation, a novel tool that integrates technical feasibility and institutional readiness within a single diagnostic tool.

5.3.1.2. Empirical Findings

Empirically, the research provides robust evidence on how spatial configuration, accessibility, and urban form influence both socio-economic and ecological outcomes across multiple planning scales.

Applied case studies demonstrate how EBDP methods can identify spatial inequalities in access to services in rural and peri-urban contexts, inform the evaluation and prioritisation of green infrastructure and public space networks in urban regeneration projects, and assess the accessibility and connectivity impacts of large-scale masterplans. **These findings confirm the practical value of EBDP for evidence-informed planning and design decisions.**

In the social-ecological domain, the research produces **original empirical evidence** on the relation of urban density and biodiversity, focusing on **bird richness, a strong indicator of urban biodiversity**. Birds were used as an indicator group because, due to their broad diversity and distribution, their sensitivity to urban morphology and their relevance to ecosystem services and human well-being, they are particularly well suited to bridging ecological performance with spatial and morphological indicators commonly used in EBDP. **The results demonstrate that urban density alone does not determine biodiversity outcomes; rather, habitat quality, vegetation structure, and green connectivity play a decisive role.** Complementary empirical findings further demonstrated that biodiversity responses to urban density are also mediated by intra-urban microclimatic conditions. **This evidence supports more nuanced planning approaches that reconcile compact urban form with biodiversity conservation**.

5.4. Policy implications

The outcomes of this research have **direct relevance for several flagship EU policy initiatives** that seek to advance sustainable, inclusive, and climate-resilient urban development. By strengthening the operational foundations of Evidence-Based Design and Planning (EBDP), the research contributes to translating high-level EU policy objectives into implementable planning and design practices.

5.4.1. Relevance for Sustainable Development Goals (SDGs)

This research contributes to the achievement of several United Nations Sustainable Development Goals by providing operational, evidence-based tools that support sustainable, inclusive, and resilient urban development across diverse planning contexts. The strongest alignment is with **SDG 11 (Sustainable Cities and Communities).**

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The research strengthens the capacity of urban planning and design processes to deliver **inclusive, safe, resilient, and sustainable cities through Evidence-Based Design and** Planning (EBDP). By operationalising EBDP across multiple spatial scales, the project provides practical tools to assess accessibility to services, connectivity of urban networks, and the spatial distribution of amenities and green infrastructure, **supporting access to basic services and inclusive public spaces (Targets 11.1, 11.7).** A key contribution lies in the ability to identify and quantify spatial inequalities in access to public services, transport, and green spaces, particularly in rural, peri-urban, and data-constrained contexts, **enabling more inclusive and sustainable urbanisation and integrated planning approaches (Target 11.3)**.

The research further advances SDG 11 by demonstrating how **compact and efficient urban form can be evaluated alongside social and environmental performance** rather than treated as an abstract planning objective. By integrating spatial form, socio-economic and social-ecological performance, the project enables planners to assess trade-offs between densification, quality of life, and environmental outcomes, supporting integrated and resilient urban development policies (Target 11.b). **A central challenge in sustainable urban development is balancing the benefits and costs of high urban densities, particularly concerning the environmental costs, such as biodiversity loss**. This is reflected in the **"land sharing vs. land sparing" debate** (Soga et al., 2014). Several previous studies have suggested that land sparing, characterized by compact/dense development spared from larger areas of conserved habitat, reduces biodiversity within the dense/compact urban area but helps maintain higher overall biodiversity at the city scale (Caryl et al., 2016; Geschke et al., 2018; Sushinsky et al., 2013). In this research, we investigated whether there is a **potential to reduce the biodiversity loss associated with urban densification strategies.** Our empirical findings show that biodiversity can co-exist with high urban density, when habitat quality and connectivity are carefully designed, and that even dense/compact urban forms can support species of conservation interest when favourable local habitat features or surrounding landscape contexts are present. These are important findings for urban planning and design because **even if expanding natural habitats within dense and compact urban areas is constrained by limited space and competing land-use demands, there remains an opportunity to reduce biodiversity loss through broader-scale planning for habitat connectivity**. In current urban design and planning practice, the latter is often overlooked in favour of site-specific characteristics that are known to promote local biodiversity, or more specifically, composition (e.g., native tree cover, ponds, and freshwater sources).

In addition, the **development of open, scalable, and reproducible analytical workflows**, such as the **SOAR** presented in this research, **lowers barriers to the adoption of evidence-based planning practices**, reinforcing **SDG 11's emphasis on strengthening planning capacity and governance**.

Beyond SDG 11, the integration of biodiversity and socio-ecological performance within EBDP contributes directly to **SDG 15 (Life on Land)** by demonstrating how urban planning and design decisions can mitigate biodiversity loss and enhance ecological quality in dense urban environments (Targets 15.1, 15.5). These findings also support **SDG 13 (Climate Action)** by enabling planners to assess climate adaptation and mitigation strategies alongside social and ecological outcomes (Target 13.1).

Through its focus on spatial inequalities in access to services and amenities, the research contributes to **SDG 10 (Reduced Inequalities)** by supporting more equitable infrastructure investment and service

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distribution (Target 10.2). The use of open, automated, and reproducible workflows aligns with **SDG 9 (Industry, Innovation and Infrastructure)** by promoting digital innovation, open science, and resilient planning systems (Target 9.1). Finally, by strengthening transparency, institutional readiness, and evidence-informed decision-making, the research supports **SDG 16 (Peace, Justice and Strong Institutions)** by reinforcing accountable and effective governance in spatial planning processes (Target 16.6).

5.4.2. Alignment with EU initiatives

The results of this research directly support several key European Union policy initiatives aimed at advancing sustainable, climate-resilient, inclusive, and biodiversity-positive urban development. By strengthening the methodological foundations and practical applicability of EBDP, the project contributes to bridging the gap between strategic EU policy objectives and local planning and design practice.

First, the research aligns strongly with the **European Green Deal** and the **EU Strategy on Adaptation to Climate Change**. These initiatives call for systemic transformations in how cities are planned, designed, and governed to achieve climate neutrality, resilience, and improved environmental performance**.** By providing analytical tools to assess accessibility, density, and spatial configuration alongside ecological indicators, the project enables planners to evaluate the climate and environmental implications of urban form at early decision-making stages. Importantly, the findings demonstrate that compact urban development, often promoted for climate mitigation, does not inherently undermine ecological performance, provided that green connectivity and habitat quality are appropriately integrated. This evidence supports more nuanced and effective implementation of Green Deal objectives at the urban scale.

The project also contributes directly to the **EU Biodiversity Strategy for 2030**, which emphasises the role of cities in halting biodiversity loss and restoring ecosystems. Traditional planning tools often address biodiversity through procedural Environmental Impact Assessments conducted late in the development process. In contrast, this research embeds biodiversity and socio-ecological performance within the evidence-generation phase of planning and design. Through empirical data collection and spatial modelling, the project provides quantitative evidence on how urban morphology, density, and green infrastructure influence species richness. This supports the EU Biodiversity Strategy's ambition to mainstream biodiversity considerations into spatial planning and urban governance.

The outcomes are also closely aligned with the principles of the **New European Bauhaus (NEB)** initiative, which promotes the integration of sustainability, inclusivity, and aesthetics in the built environment. By operationalising EBDP through open, transparent, and reproducible analytical workflows, the project strengthens the scientific and evidence-based dimension of design-led urban transformation. The integration of social accessibility and ecological performance into spatial analysis supports design approaches that are not only environmentally responsible but also socially inclusive and context-sensitive, reflecting the core values of the NEB.

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In relation to the **Urban Agenda for the EU** and **EU Cohesion Policy**, the research addresses the persistent challenge of uneven planning capacity across European regions. By defining minimum data requirements and developing less data-intensive, automated analytical models, the project enables smaller municipalities and data-constrained regions to adopt evidence-based planning practices. The EBDP Applicability Matrix further supports local and regional authorities in assessing institutional and technical readiness, improving governance capacity and supporting place-based policy implementation, which is central to Cohesion objectives.

The project is also fully aligned with the **EU Digital Strategy** and **Open Science policy**, which promote transparency, interoperability, and the reuse of data and tools in the public sector. The SOAR framework relies exclusively on open data, open-source software, and automated, reproducible workflows. This approach supports digital transformation in planning practice, enhances cross-border comparability, and enables knowledge transfer between EU cities and regions, in line with EU ambitions for a data-driven and digitally enabled public administration. Besides the SOAR all workflows, codes and datasets produced in the project adhere to the FAIR principles.

Finally, the research contributes to the objectives of the **EU Mission on Climate-Neutral and Smart Cities** by providing scalable analytical tools that support early-stage scenario testing, monitoring, and evaluation of urban interventions. The integration of accessibility, socio-economic performance, and ecological indicators supports holistic strategies for climate neutrality while safeguarding quality of life and environmental integrity. The project's transferable methods enable cities to benchmark progress and share evidence-based practices across the Mission network.

Overall, this research strengthens the EU policy framework by translating high-level sustainability, biodiversity, and digitalisation goals into **operational, evidence-based tools** for urban planning and design. It supports a transition toward more resilient, inclusive, and environmentally responsible cities, enabling ongoing and verifiable goal achievement, while lowering implementation barriers and enhancing policy coherence across European regions.

5.4.3. Implications for Local Policymakers

This research provides clear guidance for local policymakers on how EBDP can be realistically implemented and institutionalised within everyday planning practice, even in contexts characterised by data limitations, fragmented governance, and constrained resources.

First, the research demonstrates that evidence-based design and planning is feasible in data-constrained contexts when minimum data requirements and appropriate analytical workflows are clearly defined. Rather than requiring comprehensive or proprietary datasets, the research identifies a core set of spatial data layers sufficient to support key planning analyses related to accessibility, connectivity, and spatial equity. For local authorities, this shifts the focus from overcoming data scarcity to strategically using what is already available. It enables municipalities to begin applying EBDP incrementally, without waiting for fully developed data infrastructures, and supports more informed decision-making in rural, peri-urban, and small-scale urban contexts.

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Second, the validation of open, automated spatial models has important implications for the digitalisation of local planning practice. Automated workflows based on open data and open-source tools allow planning authorities to generate consistent and transparent evidence with reduced time and cost. This reduces reliance on proprietary software and external consultants, improves comparability across projects, and strengthens institutional knowledge retention. For local policymakers, this means that evidence generation can become a routine component of planning processes rather than an exceptional or outsourced activity.

Third, the research highlights that institutional readiness is as critical as technical capacity for the successful use of evidence in planning. Even when analytical tools are available, their impact depends on governance structures, stakeholder engagement, and decision-making cultures. The EBDP Applicability Matrix developed in the research provides local policymakers with a practical diagnostic tool to assess readiness, align analytical ambition with available resources, and identify capacity-building needs. This supports more realistic project scoping and reduces the risk of under-used or misaligned analytical investments.

Fourth, the integration of biodiversity and ecological performance into EBDP workflows has direct relevance for local policy agendas related to climate adaptation, environmental quality, and quality of life. The research shows that ecological considerations can be addressed at early planning and design stages, alongside accessibility and spatial efficiency, rather than being confined to late-stage environmental assessments. For local policymakers, this enables more balanced decisions that reconcile densification, regeneration, and environmental protection, and supports the delivery of climate-resilient and nature-positive urban environments.

Finally, the research underscores the importance of embedding EBDP within local policy frameworks, rather than treating it as a technical add-on. When evidence-based approaches are integrated into planning guidelines, development control processes, and strategic planning documents, they support more proactive, transparent, and accountable governance. This institutionalisation of EBDP strengthens the capacity of local authorities to justify decisions, communicate trade-offs to stakeholders, and align local development outcomes with national and EU sustainability objectives. Taken together, these findings suggest that the value of EBDP for local policymakers lies not only in improved analytical tools, but in a broader shift toward evidence-informed, integrated, and resilient planning practice. Table 15 summarises the key policy takeaways for decision makers.

Table 15. Key policy takeaways for decision makers

Policy Takeaways
• Evidence-based planning is feasible in data-constrained contexts when minimum data requirements and appropriate analytical workflows are defined.
• Open, automated spatial models can support transparent, scalable, and cost-effective planning, reducing reliance on proprietary tools.

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• Institutional readiness matters as much as technical capacity; diagnostic tools can help align ambition, resources, and governance structures.
• Biodiversity and ecological performance can be integrated into planning decisions early, supporting climate and nature objectives simultaneously.
• Embedding EBDP in policy frameworks enables more proactive, accountable, and resilient urban development across European regions.

5.4.4. Implications for Cyprus

The findings of this research have direct implications for spatial planning and urban governance in Cyprus, a context characterised by fragmented spatial data infrastructures, uneven institutional capacity, and complex geopolitical conditions. The research demonstrates that Evidence-Based Design and Planning is feasible in Cyprus despite persistent data constraints, provided that **methods are adapted to local realities** and **minimum data requirements are clearly defined**. Rather than relying on comprehensive and often inaccessible national datasets, the findings show that **less data-intensive, open and automated spatial models** can generate robust and policy-relevant evidence. In this context, open-source data emerge as a critical analytical backbone, enabling consistent coverage and reproducible modelling where official datasets are fragmented or restricted. This is particularly relevant for smaller municipalities and rural areas, where technical capacity and resources are limited.

The data audit further demonstrates that **barriers to evidence-based planning in Cyprus are not purely technical but are fundamentally institutional and governance-related.** Data scarcity is shaped by institutional silos, limited interoperability, and restricted access to existing datasets. Addressing these structural constraints through improved data governance, greater openness, and coordinated standards across public authorities would significantly enhance the feasibility, efficiency, and credibility of EBDP implementation and strengthen alignment with European open data initiatives.

The applied case studies illustrate how spatial analysis can reveal **inequalities in access to public services, transport, green infrastructure, and amenities**, particularly between urban and rural areas. These insights provide a strong evidence base for more targeted and equitable infrastructure investment, public transport planning, and service provision. At the urban and project scale, the research shows how accessibility and connectivity analysis can inform regeneration strategies and master-planning processes, allowing the impacts of proposed developments to be evaluated systematically before implementation rather than retrospectively.

The integration of **social-ecological performance** is particularly significant for Cyprus, given its high biodiversity value and exposure to climate risks. The findings demonstrate that compact urban development does not inherently compromise biodiversity, provided that green connectivity and habitat quality are prioritised. The complementary finding by Elsedoky et al. (2025d) that urban form influences biodiversity not only directly, but also indirectly through urban microclimate, are particularly relevant for Cyprus, where rising temperatures and limited vegetation cover intensify intra-urban microclimatic variation. Context-sensitive, evidence-based approaches to densification

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and green infrastructure planning that reconcile spatial efficiency with environmental protection are needed, as uniform design or climate mitigation strategies may lead to uneven ecological effects.

Finally, the introduction of the **EBDP Applicability Matrix** provides Cypriot planning authorities with a practical tool to assess both technical feasibility and institutional readiness. By aligning analytical ambition with governance capacity, the matrix supports more realistic project scoping, reduces reliance on ad hoc or precedent-driven decisions, and contributes to the gradual institutionalisation of **transparent, evidence-based, and resilient planning practices** in Cyprus.

Based on the findings of the applied Case studies, **three Policy reports**, **two Policy Briefs** tailored for Cyprus have been published disseminating the main findings (see Section 5.5).

5.5. Scientific publications and policy-relevant documents in WP4

5.5.1. Scientific articles

Published

Eldesoky, A.H., Gil, J., Kindvall, O., Stavroulaki, I., Jonasson, L., Bennet, D., Yang, W., Martínez, A., Lichter, R., Petrou, F., Berghauser Pont, M. (2025a) A bird species occurrence dataset from passive audio recordings across dense urban areas in Gothenburg, Sweden, *Scientific Data* **12**, 1180 https://doi.org/10.1038/s41597-025-05481-z

Karimi, K., Zhand, S., Simons, G., Abdeldayem, W. S., Charalambous, N., & Giraud, I. (2025). Framing Evidence-Based Design and Planning: An Analytical, Multi-Scalar and Iterative Framework for Urban Design and Planning. *Urban Science*, *9*(11), 457. https://doi.org/10.3390/urbansci9110457

Preprints, manuscripts submitted for publication

Charalambous, N., Karimi K., Berghauser Pont, M. (eds) (forthcoming book 2027) *Evidence-Based Urban Design and Planning -Principles, Practices, and Prospects*, Springer.

Abdeldayem, W., Geddes, I., Eldesoky, A., Stavroulaki, I., Simons, G., Berghauser Pont, M., Charalambous, N. (2025a) Automated versus Hybrid Street Network Modelling for Centrality and Accessibility Analysis. Manuscript submitted for publication in *Environment and Planning B: Urban Analytics and City Science* (Manuscript ID EPB-2025-0601), Preprint. Zenodo: https://doi.org/10.5281/zenodo.16609014

Charalambous, N., Abdeldayem, W., Geddes, I., Berghauser Pont, M., Karimi, K. (2025a) Assessing the applicability of Evidence-based design and planning: A Multi-scale Approach for data-challenging environments. Manuscript submitted for publication to *Cities: The International Journal of Urban Policy and Planning.*

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Eldesoky, A.H., Kindvall, O., Berghauser Pont, M., Stavroulaki, I., Gil, J., Charalambous, N. (2025c) How to build dense cities without jeopardizing biodiversity? Insights from bird observations in Gothenburg, Sweden. Manuscript submitted for publication *to npj Urban Sustainability,* ID ccfd8783-b223-47e3-80e4-d74f24d27a3a

5.5.2. Conference papers and presentations

Peer-reviewed Conference paper in proceedings

Ricchiardi, A., Giraud, I., Charalambous, N., & Geddes, I. (2024a). Challenges and barriers of integrating spatial models and tools for socio-economic performance assessment in data-scarce contexts. In *Proceedings of the 14th International Space Syntax Symposium*, Nicosia, Cyprus

Poster (awarded for early career researchers)

Eldesoky A.H, Ellenbroek, I., Kindvall, O., Lindberg, F., Berghauser Pont, M. (2025d) Investigating the effects of micro- and local climate variation on the diversity and breeding phenology of urban bird species in Gothenburg, Sweden. *12th International Conference on Urban Climate (ICUC12)*, Rotterdam, the Netherlands, July 7-11, 2025

Conference presentations

Abdeldayem, W., Geddes, I., Charalambous, N., Simons, G., Zhand, S. (2025b). Assessing urban connectivity and accessibility using open-source workflows in data-challenging environments. *XXXII International Seminar of Urban Form (ISUF2025),* Torino, Italy, June 17-20, 2025.

Abdeldayem, W. (2025a) Evaluating open-source automated workflow for street network analysis in Data-challenging context: insights from a case study of Nicosia. *19th International Conference on Computational Urban Planning and Urban Management (CUPUM),* University College London, June23–27, 2025.

Charalambous, N. (2025) Panel. Evidence-Based Participatory Design and Planning: Research to inform just design decisions and planning policies. 3rd Conference on Participatory Design: *Spatial Justice in the Era of Climate Crisis: Geographies & Communities of Greece, the Balkans and the Mediterranean*, Agricultural University of Athens, Athens, Greece, December 5–7, 2025.

Charalambous, N. (2025) Keynote. Planning for Integration: A Strategic Assessment of an Urban Green Space Network, *Green Urbanism international conference,* Rome Italy, 25-27 November, 2025.

Charalambous, N. (2024) Keynote. Expanding the application of Evidence-Based Design and Planning (EBDP) using comparative data models across different contexts, *EDMSET International Conference,* Dubai, UAE, 22-24 April, 2024.

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Charalambous, N., Psaras, M., Panayi, C., (2024) Co-Creating Urban Knowledge in Diverse Public Spaces: Combining Evidence-Based Design with Bottom-up Citizens Initiatives, *AESOP International Conference Game Changer? Planning for Just and Sustainable Urban Regions,* Paris France, 8-12 July, 2024.

Eldesoky, A.H., Berghauser Pont, M., Stavroulaki, I., Gil, J., Kindvall, O. (2024). Understanding the role of urban form in shaping human-wildlife interactions in cities. *XXXI International Seminar of Urban Form (ISUF2024),* Sao Paolo, Brazil, September 16-20, 2025

Geddes, I., Charalambous, N, Abdeldayem, W., Giraud, I., Ricchiardi, A. (2025a) The application of Evidence-Based Design and Planning in Data Challenging Contexts. *10th International Urban Planning and Architectural design for Sustainable development (UPADSD 2025-65)*, Florence, Italy October 21-23, 2025.

Geddes, I., (2024) The application of lightweight street network models for urban planning in data-challenging contexts. *6th KIOS GIS Da*y, Nicosia, Cyprus, November 20, 2024.

Geddes, I., Abdeldayem, W., Charalambous, N, Giraud, I., Ricchiardi, A. (2025b). Assessing citizen services provision across urban and rural areas based on accessible density measures. *XXXII International Seminar of Urban Form (ISUF2025),* Torino, Italy, June 17-20, 2025

Pasia, M., Charalambous, N., Abdeldayem, W., & Panayi, C. (2025) Assessing urban green space accessibility in Cyprus: The Pedieos Linear Park [Poster presentation]. 3rd Conference on Participatory Design: *Spatial Justice in the Era of Climate Crisis: Geographies & Communities of Greece, the Balkans and the Mediterranean*, Agricultural University of Athens, Athens, Greece, December 5–7, 2025.

5.5.3. Datasets, scripts, workflows

Datasets

Abdeldayem, W. (2025b). Nicosia's non-motorised segmented street network - automated. (Version 1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.16411132

Abdeldayem, W. (2025c). Nicosia's motorised segmented street network - automated. (Version 1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.16411188

Abdeldayem, W. (2025d). Cyprus Citizen Service Centers, Citizen Centers and Post offices [Data set]. Zenodo. https://doi.org/10.5281/zenodo.16409080

Abdeldayem, W., & Giraud, I. (2025). Nicosia Schools (Version 1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.16410567

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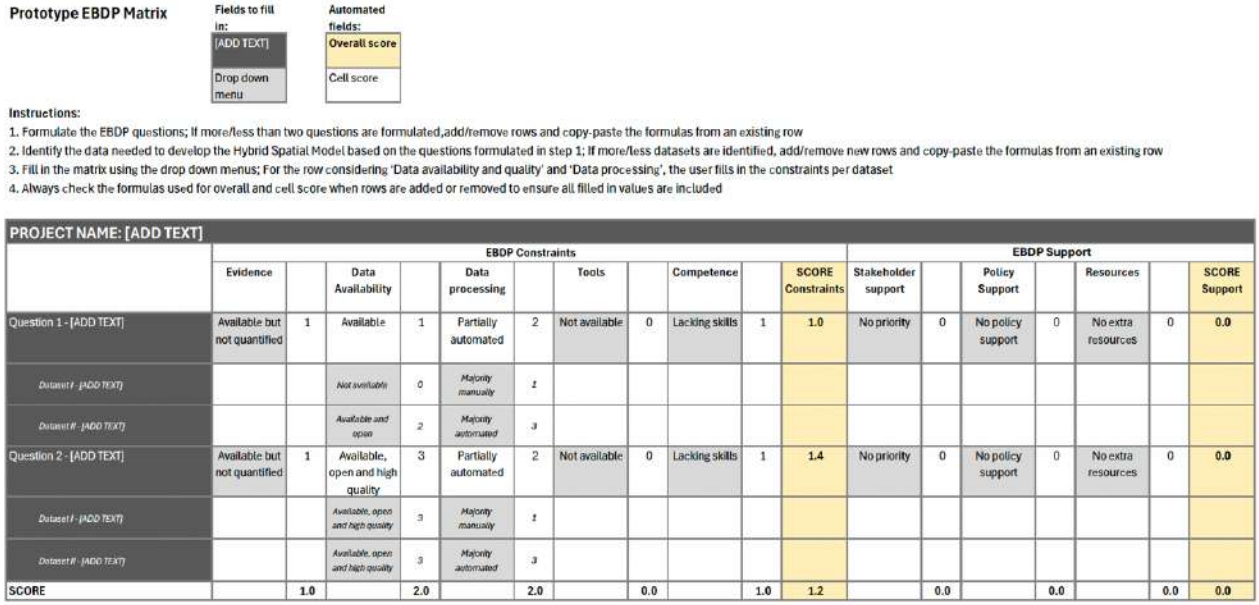
7. Appendices

7.1. Appendix A. EBDP Applicability Matrix

For the full report of the EBDP Applicability Matrix, please see Deliverable 4.3.



Prototype EBDP Matrix

Fields to fill in: [ADD TEXT] / Drop down menu

Automated fields: Overall score / Cell score

Instructions:

1. Formulate the EBDP questions; If more/less than two questions are formulated,add/remove rows and copy-paste the formulas from an existing row
2. Identify the data needed to develop the Hybrid Spatial Model based on the questions formulated in step 1; If more/less datasets are identified, add/remove new rows and copy-paste the formulas from an existing row
3. Fill in the matrix using the drop down menus; For the row considering 'Data availability and quality' and 'Data processing', the user fills in the constraints per dataset
4. Always check the formulas used for overall and cell score when rows are added or removed to ensure all filled in values are included

PROJECT NAME: [ADD TEXT]	EBDP Constraints											EBDP Support						
	Evidence		Data Availability		Data processing		Tools		Competence		SCORE Constraints	Stakeholder support		Policy Support		Resources		SCORE Support
Question 1 - [ADD TEXT]	Available but not quantified	1	Available	1	Partially automated	2	Not available	0	Lacking skills	1	1.0	No priority	0	No policy support	0	No extra resources	0	0.0
Dataset I - [ADD TEXT]			Not available	0	Majority manually	1												
Dataset II - [ADD TEXT]			Available and open	2	Majority automated	3												
Question 2 - [ADD TEXT]	Available but not quantified	1	Available, open and high quality	3	Partially automated	2	Not available	0	Lacking skills	1	1.4	No priority	0	No policy support	0	No extra resources	0	0.0
Dataset I - [ADD TEXT]			Available, open and high quality	3	Majority manually	1												
Dataset II - [ADD TEXT]			Available, open and high quality	3	Majority automated	3												
SCORE		1.0		2.0		2.0		0.0		1.0	1.2		0.0		0.0		0.0	0.0

Figure 83. Example of the Excell sheet of the EBDP Applicability Matrix, exemplified for Case study 1

Table 16. Assessment based on the EBDP Applicability Matrix.

CONSTRAINTS	**Assessment score**
Evidence	No evidence (0); Available but not quantified (1); Quantifiable evidence (2); Validated evidence (3)[8]
Data Availability and quality	Not available (0); Available (1); Available and open (2); Available, open and high quality (3)
Data processing	Majority manual (1); Partially automated (50:50) (2); Majority automated (3)
Tools	Not available (0); Available, not open and high cost (1); Available, not open and low cost (2); Available and open (3)
Competence	Lacking skills (1); skills to conduct tasks but not to interpret results (2); skills to conduct tasks and interpret results (3)
SUPPORT	**Assessment score**
Stakeholder support	No priority (0); low priority (1); Priority but not required (2); Priority and required (3)
Policy support	No support (0); Low support (1); Policy support but not quantified (2); Policy support with benchmarks (3)
Resources	No extra resources (0); No time constraints (1); Extra financial resources but lack of time (2); Extra financial resources and time (3)

[8] Levels of evidence for design decision making (published in Pilosof and Grobman, 2021) from review of precedents (low level) to case studies and large-scale validated studies (high level).

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7.2. Appendix B

EQUATIONS AND EXPLANATIONS[9]

Hillier Normalization (Unweighted)

$$AI_H(x) = \frac{N^2}{1 + \sum_{i \neq x} D(x,i)}$$

Where:
- AI_H(x): Hillier Angular Integration value for segment x
- N: Total number of nodes (segments), including x
- D(x, i): Angular depth from segment x to segment i, measured in degrees and divided by 90

Hillier Normalization (Weighted by Length)

$$AI_H(x) = \frac{(\sum_{i \neq x} l(i))^2}{1 + \sum_{i \neq x} D(x,i) \cdot l(i)}$$

Where:
- l(i): Length of segment i
- D(x, i): Angular depth from x to i (degrees/90)

Angular Betweenness

$$B(x) = \sum_{s \neq x \neq t} \frac{\sigma_{st}(x)}{\sigma_{st}}$$

Where:
- B(x): Betweenness centrality of node x
- σ_st: Number of shortest paths between node s and node t
- σ_st(x): Number of those paths that pass through x

Attraction Distance

$$AD(o) = \min_{a \in A} D\,(o,a)$$

Where:
- AD(o): Attraction distance from origin o
- A: Set of reachable attraction points within the given radius

[9] PST Documentation v3.3.1 241101 DOI 10.13140/RG.2.2.18816.03847/1

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- D(o, a): Shortest distance from origin o to attraction a

Attraction Reach

$$AR(o) = \sum_{a \in A} f(a) \cdot w\big(D(o,a)\big)$$

Where:
- AR(o): Attraction reach from origin o
- A: Set of reachable attraction points within the given radius
- f(a): Weight or value of attraction a (e.g., 1 if unweighted)
- D(o, a): Shortest distance from o to a
- w(x): Attenuation function applied to the distance (optional)

Spearman's Rank Correlation Coefficient (Between Two Variables)

$$\rho_s(X,Y) = 1 - \frac{6\sum_{i=1}^{n}\left(R_{X_i} - R_{Y_i}\right)^2}{n(n^2-1)}$$

Where:
- $\rho_s(X, Y)$: Spearman's rank correlation coefficient between variables X and Y
- R_X_i, R_Y_i: Rank of the i-th observation in X and Y, respectively
- n: Number of observations

Moran's I Equation

$$I = \frac{N}{W} \cdot \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} w_{ij}(x_i - \bar{x})\left(x_j - \bar{x}\right)}{\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

Where:
I = Moran's I statistic
N = Number of spatial units indexed by i and j
x_i = Value of the variable at location i
$\bar{x}$ = Mean of the variable
w_{ij} = Spatial weight between unit i and unit j
W = Sum of all spatial weights.

Segment Count per Cell

$$S_i = |E_i|$$

Where:
- S_i: Number of segments in cell c_i
- E_i: Set of segments within cell c_i

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Total Segment Length per Cell:

$$L_i^{\text{total}} = \sum_{e_k \in E_i} L_k$$

Where:
- L_i_total: Total length of segments in cell c_i
- L_k: Length of segment e_k

Mean Segment Length per Cell:

$$\bar{L}_i = \frac{1}{S_i} \sum_{e_k \in E_i} L_k$$

Where:
- $\bar{L}_i$: Mean segment length in cell c_i

Maximum Angle Change per Cell:

$$\Delta\theta_i^{max} = \max_{e_k, e_{k+1} \in E_i} |\theta_{k+1} - \theta_k|$$

Where:
- $\Delta\theta_i$_max: Maximum angle change in cell c_i
- θ_k: Angle of segment e_k

Mean Angle Change per Cell:

$$\overline{\Delta\theta_i} = \frac{1}{|E_i'|} \sum_{e_k, e_{k+1} \in E_i'} |\theta_{k+1} - \theta_k|$$

Where:
- $\overline{\Delta\theta_i}$: Mean angle change in cell c_i
- E_i': Set of connected segment pairs within cell c_i

Node Count per Cell:

$$N_i = \sum_{j=1}^{m} \delta(n_j \in c_i)$$

$\delta(n_j \in c_i)$ =
1, if node $n_j \in$ cell c_i
0, otherwise
Where:
- N_i: Number of nodes in cell c_i
- $\delta(n_j \in c_i)$: Indicator function for whether node n_j lies within cell c_i

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7.3. Appendix C

Table S1. *List of all bird species observed in the study, alongside the habitat types included in the biotope map. For each species–habitat type combination, the table indicates whether the habitat is used for nesting (N), foraging (F), or both (NF). Species are sorted according to the taxonomic order provided by the Swedish Species Information Centre (Artportalen).*

			Habitat type																		
Scientific name	Family	Common English name	Buildings (51)	Artificial surfaces (52)	Roads and railways (53)	Cafés and restaurants (500)	Arable land (3)	Non vegetated open land (41)	Grassland and meadows (42)	Bushes (200)	Trees (201)	Valuable trees (202)	Open wetland (2)	Inland water (61)	Marine water (62)	Cliff beach (441)	Grassland beach (442)	Shaded beach (443)	Reed (444)
Branta canadensis	*Anatidae*	Canada Goose					F		F				F	F	F	N	NF		N
Branta leucopsis	*Anatidae*	Barnacle Goose							F							N	NF		
Anser anser	*Anatidae*	Greylag Goose					F		F				F	F	F	N	NF		N
Anas platyrhynchos	*Anatidae*	Mallard							F					F	F	F	NF	N	N
Bucephala clangula	*Anatidae*	Common Goldeneye												F				N	
Caprimulgus europaeus	*Caprimulgidae*	European Nightjar									N	N							
Apus apus	*Apodidae*	Common Swift	NF	F	F	F	F	F	F	F	F	F	F	F		F	F	F	F
Cuculus canorus	*Cuculidae*	Common Cuckoo							F	NF	NF	NF	F					NF	NF
Streptopelia decaocto	*Columbidae*	Eurasian Collared Dove				F			F	N	N	N						N	
Columba livia	*Columbidae*	Common Pigeon	N	F	F	F			F										
Columba oenas	*Columbidae*	Stock Dove									NF	NF						NF	
Columba palumbus	*Columbidae*	Common Wood Pigeon					F		F		N	NF						N	
Gallinula chloropus	*Rallidae*	Common Moorhen												F			F	N	N
Fulica atra	*Rallidae*	Eurasian Coot												F	F		F	N	N
Haematopus ostralegus	*Haematopodidae*	Eurasian Oystercatcher							F						F	N	F		
Sterna hirundo	*Laridae*	Common Tern												F	F	N			
Chroicocephalus ridibundus	*Laridae*	Black-headed Gull				F			F					F	F	NF	F		N
Larus canus	*Laridae*	Common Gull				F	F		F					F	F	NF	F		
Larus argentatus	*Laridae*	European Herring Gull				F	F		F					F	F	NF	F		
Larus fuscus	*Laridae*	Lesser Black-backed Gull	N			F			F					F	F	NF	F		
Strix aluco	*Strigidae*	Tawny Owl	N	F					F	F	F	NF						N	
Dendrocopos major	*Picidae*	Great Spotted Woodpecker									NF	NF						NF	
Picus viridis	*Picidae*	European Green Woodpecker									NF	NF						NF	
Pica pica	*Corvidae*	Eurasian Magpie				F			F	F	N	N				F	F	N	F
Corvus monedula	*Corvidae*	Western Jackdaw	N			F	F		F	F	F	N				F	F	F	
Corvus cornix	*Corvidae*	Hooded Crow				F			F	F	NF	NF				F	F	NF	
Poecile palustris	*Paridae*	Marsh Tit								F	NF	NF						N	
Cyanistes caeruleus	*Paridae*	Eurasian Blue Tit								F	NF	NF						N	
Parus major	*Paridae*	Great Tit								F	NF	NF						N	
Phylloscopus sibilatrix	*Phylloscopidae*	Wood Warbler								N	NF	NF						N	
Phylloscopus trochilus	*Phylloscopidae*	Willow Warbler								N	NF	NF						N	
Phylloscopus collybita	*Phylloscopidae*	Common Chiffchaff								N	NF	NF						N	
Acrocephalus scirpaceus	*Acrocephalidae*	Common Reed Warbler																F	NF
Acrocephalus palustris	*Acrocephalidae*	Marsh Warbler								NF									
Hippolais icterina	*Acrocephalidae*	Icterine Warbler								N	NF	NF						N	
Sylvia atricapilla	*Sylviidae*	Eurasian Blackcap								N	NF	NF						N	
Sylvia borin	*Sylviidae*	Garden Warbler								N	NF	NF						N	
Curruca curruca	*Sylviidae*	Lesser Whitethroat								NF									
Curruca communis	*Sylviidae*	Common Whitethroat								NF									
Regulus regulus	*Regulidae*	Goldcrest								F	NF	NF						N	
Troglodytes troglodytes	*Troglodytidae*	Eurasian Wren								N	NF	NF						N	
Sitta europaea	*Sittidae*	Eurasian Nuthatch									NF	NF						NF	
Certhia familiaris	*Certhiidae*	Eurasian Treecreeper									NF	NF						NF	
Sturnus vulgaris	*Sturnidae*	Common Starling							F	F	NF	NF				F	F	N	F
Turdus philomelos	*Turdidae*	Song Thrush							F	F	NF	NF					F	N	
Turdus merula	*Turdidae*	Common Blackbird							F	N	NF	NF					F	N	
Turdus pilaris	*Turdidae*	Fieldfare							F	F	NF	NF					F	N	
Erithacus rubecula	*Muscicapidae*	European Robin								F	NF	NF						N	
Ficedula hypoleuca	*Muscicapidae*	European Pied Flycatcher								F	NF	NF						NF	
Phoenicurus ochruros	*Muscicapidae*	Black Redstart	N	F	F					F	F	F							
Phoenicurus phoenicurus	*Muscicapidae*	Common Redstart								F	NF	NF						N	
Passer montanus	*Passeridae*	Eurasian Tree Sparrow	N			F	F			NF	F	F						NF	
Passer domesticus	*Passeridae*	House Sparrow	N	F	F	F	F			NF	F	F						NF	
Motacilla alba	*Motacillidae*	White Wagtail	N	F	F		F		F	F	F	F	F			F	F		
Fringilla coelebs	*Fringillidae*	Chaffinch								NF	NF	NF						NF	
Fringilla montifringilla	*Fringillidae*	Brambling								NF	NF	NF						NF	
Coccothraustes coccothraustes	*Fringillidae*	Hawfinch								NF	NF	NF						NF	
Chloris chloris	*Fringillidae*	European Greenfinch								NF	NF	NF						N	
Acanthis flammea	*Fringillidae*	Redpoll								NF	NF	NF						NF	
Carduelis carduelis	*Fringillidae*	European Goldfinch		F			F	F	F	NF	NF	NF					F	NF	
Spinus spinus	*Fringillidae*	Eurasian Siskin								NF	NF	NF						NF	

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1.1. Appendix D

Table S2. *Description of the attributes used in the dataset.*

Attribute	Description
Required Darwin Core attributes	
occurrenceID	A Universally Unique Identifier (UUID) for the occurrence.
basisOfRecord	The type of the record (i.e., MachineObservation).
scientificName	The full scientific name, with author and date information if known, after reclassifying and excluding records based on the technical validation. The name follows the scientific name currently valid for the taxon according to the Swedish taxonomic database (dyntaxa.se).
eventDate	The date during which the occurrence record was recorded, following the ISO 8601 date-time standard.
Other Darwin Core attributes (not required)	
eventTime	The local time interval during which the event occurred, following the ISO 8601 date-time standard.
decimalLatitude	The latitude (in decimal degrees) of the acoustic recorder's location.
decimalLongitude	The longitude (in decimal degrees) of the acoustic recorder's location.
geodeticDatum	The coordinate reference system used for the location (i.e., EPSG:4326).
country	The name of the country of the occurrence record (i.e., Sweden).
countryCode	A two-letter standard abbreviation for the country of the occurrence record (i.e., SE).
taxonRank	The taxonomic rank of the most specific name in the scientificName (i.e., species).
kingdom	The full scientific name of the kingdom in which the taxon is classified (i.e., Animalia).
phylum	The full scientific name of the phylum or division in which the taxon is classified.

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class	The full scientific name of the class in which the taxon is classified.
order	The full scientific name of the order in which the taxon is classified.
family	The full scientific name of the family in which the taxon is classified.
genus	The full scientific name of the genus in which the taxon is classified.

taxonID	The unique LSID (Life Science Identifier) of the taxon according to the Swedish taxonomic database (dyntaxa.se) provided by the Swedish Species Information Center (Artportalen).
Custom attributes	
globalSortOrder	A taxon-specific attribute provided by the Swedish Species Information Centre (Artportalen). It is an integer value, which can be used to enable a taxonomic sort order of all Swedish taxa handled in the Swedish taxonomic database (dyntaxa.se).
BirdNETClass	The taxon scientific name originally classified by the BirdNET model, prior to the technical validation and reclassification of records.
BirdNETConfidence	The BirdNET built-in confidence score for species detection, ranging from 0 to 1[37]. The dataset includes only species detections with a minimum confidence score of 0.85.
expertValidated	Indicates whether the occurrence record has been validated by an expert ornithologist.
isIsolated	Indicates whether a bird detection is isolated, i.e., not preceded or followed by another detection of the same species within a 9-second window (at a model's detection sensitivity of 1.0, no segment overlap, and a minimum confidence threshold of 0.1).
reclassified	Indicates whether the occurrence record has been reclassified from the original BirdNET classification, following the decision tree shown in Figure 5.

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occurrenceProbability	An estimation of the likelihood of a species occurrence, based on expert validation and model predictions, where: • **occurrenceProbability = 1.00**: For expert-validated records (expertValidated == "Yes") that were confirmed to be correct or reclassified based on a clear suggestion from the ornithologist (reclassified == "Yes"). • **0.5 < occurrenceProbability < 1.00**: For non-validated records (expertValidated == "No"), this value shows the model-predicted probability of occurrence, based on the trained RF classifier.
Other Darwin Core attributes (not required)	
commonNameSwedish	The common Swedish name of the taxon.
commonNameEnglish	The recommended common English name of the taxon according to the Swedish taxonomic database (dyntaxa.se).
detectionDistanceInMeters	The expected radius, in meters, around the acoustic recorder within which sounds were detected. The values (i.e., 20–70) are suggested based on the maximum detection distances for typical sound amplitudes and frequencies observed in playback experiments by Sethi et al.[14].
siteName	The name of the site where the recorder was located.
bcl	The building type surrounding the recorder, as described in Berghauser Pont et al.[24,25], where: • bcl2: Compact low-rise buildings • bcl3: Dense mid-rise buildings • bcl5: Compact mid-rise buildings • ref_bcl6: Reference spacious mid-rise buildings • ref: Reference non-built green space

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