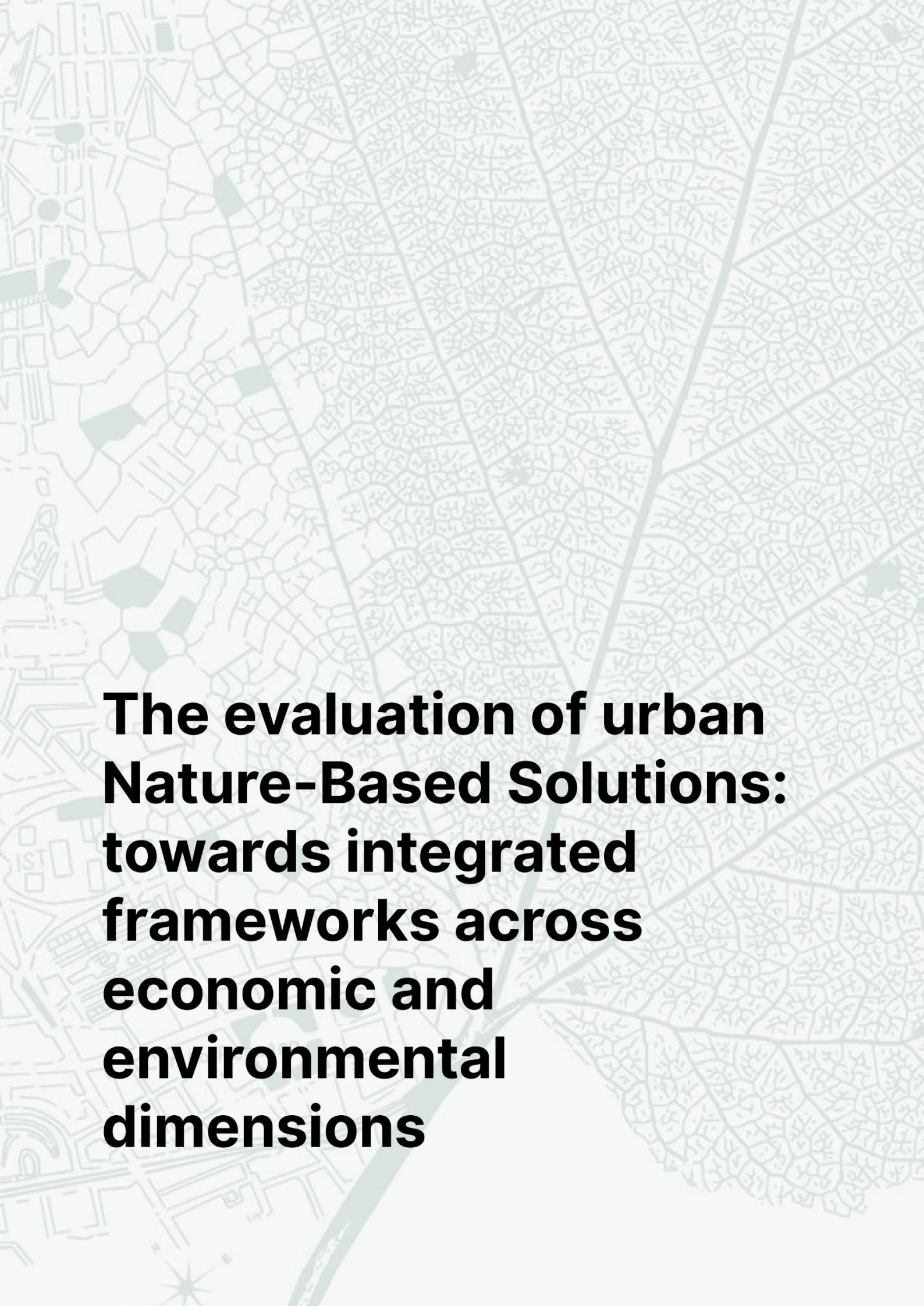


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The evaluation of urban Nature-Based Solutions: towards integrated frameworks across economic and environmental dimensions



**Politecnico
di Torino**

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**The evaluation of urban Nature-
Based Solutions: towards
integrated frameworks across
economic and environmental
dimensions**

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INTRODUCTION

Contemporary cities are increasingly exposed to complex environmental, social and economic challenges. Climate change, rising temperatures, urban heat island effects, soil sealing, biodiversity loss and unequal access to green spaces are progressively affecting the quality, liveability and resilience of urban environments. These issues are particularly relevant in dense urban contexts, where the interaction between built form, environmental vulnerability and socio-economic conditions produces differentiated impacts across neighbourhoods and population groups.

In this context, Nature-Based Solutions have gained increasing attention as integrated strategies capable of addressing multiple urban challenges simultaneously. By working with natural processes and ecosystem functions, NBS can contribute to climate adaptation, heat mitigation, stormwater management, biodiversity enhancement, improvement of public space and citizens' well-being. Their relevance lies in their multifunctional character: unlike conventional grey infrastructure, they are not designed to respond to a single problem, but to generate a plurality of environmental, social and economic benefits.

However, this same multifunctionality also makes their evaluation particularly complex. The effects produced by NBS are heterogeneous, often distributed over different spatial and temporal scales, and not always directly measurable through monetary values. Some benefits, such as temperature reduction or increased vegetation cover, can be estimated through environmental indicators; others, such as perceived well-being, accessibility, social value or willingness to pay, require different forms of assessment. For this reason, traditional evaluation approaches based exclusively on economic efficiency may be insufficient to capture the multidimensional value of NBS interventions.

The literature on NBS evaluation has progressively recognized the need for integrated and multidimensional assessment frameworks. Nevertheless, existing approaches often remain fragmented, highly context-dependent or difficult to operationalize at the preliminary planning stage. In many cases, there is still a gap between theoretical evaluation frameworks and practical decision-support tools able to compare urban areas, prioritize interventions and support public decision-making.

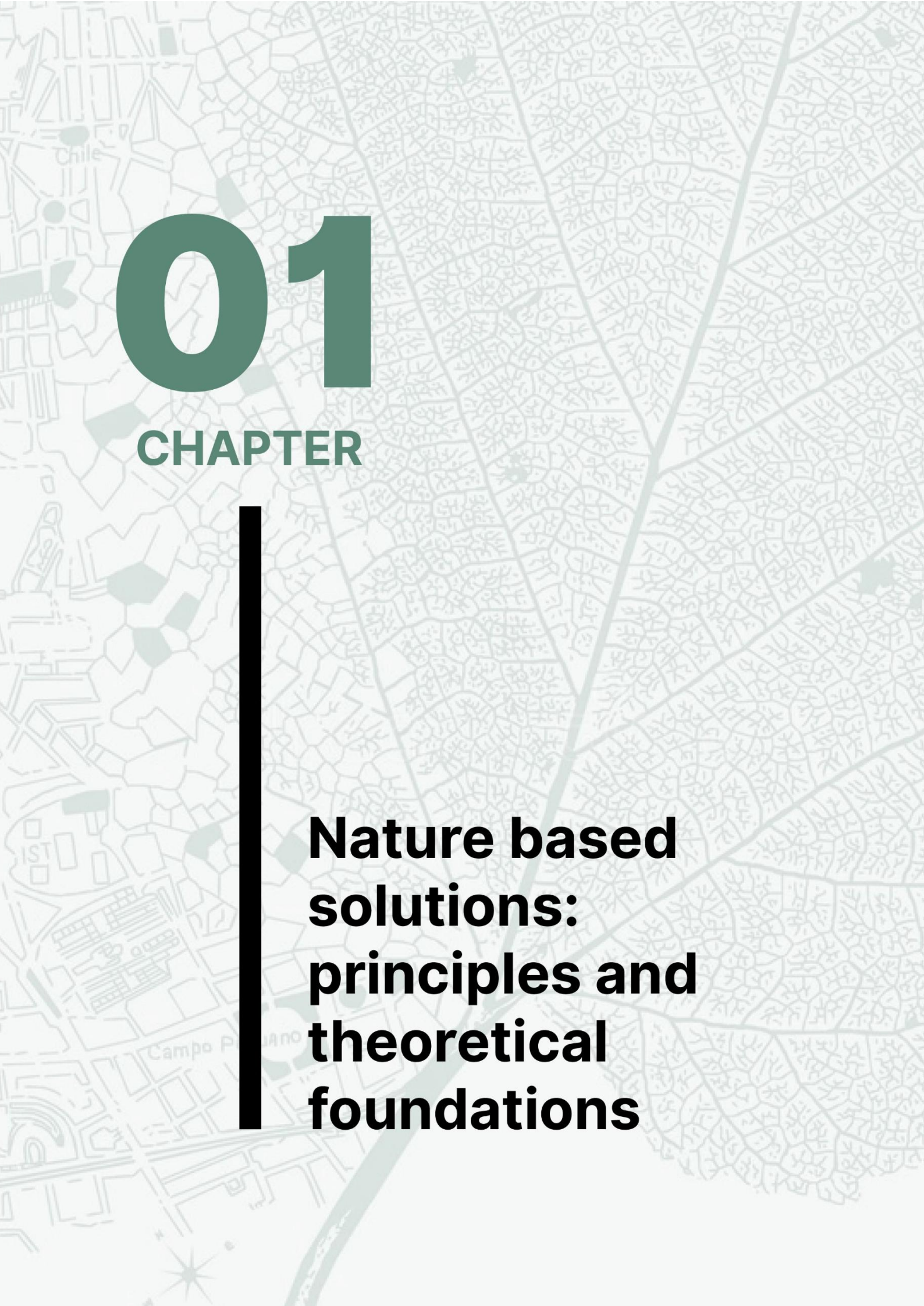
Starting from this background, the present thesis develops a preliminary methodological framework for assessing urban areas in terms of their suitability for future NBS implementation. The objective is not to test the performance of a specific implemented intervention, but to propose an integrated evaluation structure capable of combining environmental, economic and social dimensions within a coherent decision-support process. The framework is conceived as an *ex ante* tool, aimed at supporting the comparison of alternative urban contexts and identifying the conditions under which NBS may generate higher multidimensional value.

The proposed methodology is structured around a sequence of analytical steps. First, the urban context is investigated through GIS-based territorial analysis, considering environmental and spatial indicators such as land surface temperature, vegetation distribution and vulnerability. Second, real estate sub-

market segmentation is used to define comparable urban areas and to connect environmental conditions with market dynamics. Third, a multicriteria evaluation structure is developed through the Analytic Hierarchy Process, integrating environmental, economic and social criteria and sub criteria. Within this framework, measurable, estimated or simulated indicators can be used to describe the performance of each alternative, while pairwise comparisons are used to define the relative importance of the criteria.

The city of Turin is used as the reference context for the development of the framework. Its heterogeneous urban fabric, differentiated real estate sub-markets and environmental conditions make it a suitable case for exploring the relationship between urban morphology, market values and environmental vulnerability. The selected areas are therefore interpreted not as isolated project sites, but as urban contexts in which future NBS implementation could be assessed through a multidimensional and comparable approach.

The thesis is organized into five chapters. Chapter 1 introduces the theoretical background of Nature-Based Solutions and their role within international and European sustainability frameworks. Chapter 2 reviews the main evaluation approaches for NBS, focusing on economic valuation, Cost-Benefit Analysis and Multicriteria Decision Analysis. Chapter 3 presents the proposed methodological framework, including the selection of criteria, indicators and analytical tools. Chapter 4 contextualises the framework within the Turin case study through a preliminary territorial and real estate analysis, clarifying how the selected indicators could support a future comparative assessment of urban suitability for NBS implementation.

The background of the slide features a light gray map of a city, likely Santiago, Chile, with labels for 'Chile' and 'Campo P...'. Overlaid on the map is a large, detailed pattern of a leaf's veins, creating a textured, organic background.

01

CHAPTER

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Nature based solutions: principles and theoretical foundations

1.1. Definitions of Nature Based Solutions (NBS)

The concept of Nature-Based Solutions is relatively recent, emerging in the early 2000s. It is a broad notion closely connected to the rapid economic growth and population increase experienced in recent decades, which have inevitably led to the massive exploitation and consumption of natural resources, global pollution, land degradation, and biodiversity loss.¹

These processes have, in turn, directly affected social equity and the overall well-being of the global population.² Nature-Based Solutions (or NBS, as they will be referred to hereafter) were firstly attempted to be defined by the International Union for Conservation of Nature (IUCN) at its 2016 World Conservation Congress as *“actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, while simultaneously providing human well-being and biodiversity benefits.”*³

Another commonly shared definition is the one of the European Commission as *“actions which are inspired by, supported by or copied from nature. Some involve using and enhancing existing natural solutions to challenges, while others are exploring more novel solutions, for example mimicking how non-human organisms and communities cope with environmental extremes. Nature-based solutions use the features and complex system processes of nature, such as its ability to store carbon and regulate water flow, to achieve desired outcomes,*

¹ Louise McRae et al., *Living Planet Report 2016: Risk and Resilience in a New Era* (World Wildlife Fund Canada, 2016). pp. 10-15

² McRae et al., *Living Planet Report 2016*. p.106

³ United Nations Environment Programme and International Union for Conservation of Nature (2021). *Nature-Based Solutions for Climate Change Mitigation*. Pdf, n.d., accessed November 20, 2025, p. v-vi
<https://wedocs.unep.org/xmlui/bitstream/handle/20.500.11822/37318/NBSCCM.pdf>.

*such as reduced disaster risk, improved human well-being and socially inclusive green growth.”*⁴

Drawing from these two definitions, it is possible to discern a growing concern about the increasing fragility of ecosystems and the urgent need for effective methods to restore, conserve, and rethink how we address emerging environmental and social challenges on a global scale. In a simple way, NBS use ecosystems and the services they provide to address societal challenges such as climate change, food security or natural disasters.⁵

They position themselves precisely as an effective approach capable of responding to these challenges. The concept has spread rapidly largely because its underlying principle of emulating sustainable natural processes, whereby is nature itself provides the solutions, is intuitive and accessible even to non-specialists. Their interdisciplinary relevance, spanning scientific, cultural, and policy domains, has the potential to further facilitate their integration into high-level governmental strategies and global policy agendas.⁶

At the same time, however, it is evident that the definition of NBS remains broad and inherently ambiguous, which is a point that will be explored throughout this thesis. Without appropriate regulation and conceptual refinement, NBS risk appearing overly generic and difficult to implement in practice due to the lack of a precise operational definition.

⁴ *Towards an EU Research and Innovation Policy Agenda for Nature-Based Solutions & Re-Naturing Cities: Final Report of the Horizon 2020 Expert Group on 'Nature Based Solutions and Re Naturing Cities' : (Full Version)* (Publications Office of the European Union, 2015), p. 5 <https://data.europa.eu/doi/10.2777/765301>.

⁵ Cfr. E. Cohen-Shacham et al., eds., “Nature-Based Solutions to Address Global Societal Challenges,” IUCN International Union for Conservation of Nature, August 4, 2016, pp. 16, 19, <https://doi.org/10.2305/IUCN.CH.2016.13.en>.

⁶ Cfr. E. Cohen-Shacham et al., “Core Principles for Successfully Implementing and Upscaling Nature-Based Solutions,” *Environmental Science & Policy* 98 (August 2019): pp. 21–22, <https://doi.org/10.1016/j.envsci.2019.04.014>.

Clear principles, standardized guidelines, and operational frameworks are therefore essential to ensure consistent application and to avoid misinterpretation or unintended consequences.⁷

⁷ Cfr. Barbara Sowińska-Świerkosz and Joan García, “What Are Nature-Based Solutions (NBS)? Setting Core Ideas for Concept Clarification,” *Nature-Based Solutions* 2 (December 2022): pp.1-2
100009, <https://doi.org/10.1016/j.NBSj.2022.100009>.

1.2. Theoretical framework and policy evolutions

1.2.1 Chronological evolution

The recognition of the intrinsic characteristics of ecosystems and their fundamental role in supporting human well-being has always been a central element in human history, rooted in the belief systems of indigenous civilizations that have preserved this understanding for centuries. However, it was only in the 1970s that the idea of environmental or, more precisely, “*ecosystem services*” became widespread and firmly established within modern scientific literature.

By the 1990s, it gradually became clear that a more systematic approach was needed to understand the relationship between people and nature, essentially, a structured description of cause-and-effect dynamics. In this context, the **Convention on Biological Diversity (CBD)** in 1995 formally introduced the “*Ecosystem Approach*,” providing a foundational framework for the development of NBS.⁸

Building on this momentum, the 2005 **Millennium Ecosystem Assessment (MEA)** was launched to further assess and guide the sustainable management of ecosystems. It is an international research initiative launched in 2001 by the UN Secretary-General to assess the consequences of ecosystem change on human well-being, involving more than 1,000 experts. Thanks to this growing awareness, the Assessment became a milestone in the field of NBS, providing a solid scientific foundation for integrating ecosystem conservation, restoration, and management into international policy frameworks, while acknowledging the increasing pressure placed on ecosystems.

The term “**Nature-Based Solutions**” began to appear toward the late 2000s.

⁸ Cfr. The Secretariat of the Convention on Biological Diversity, *The Ecosystem Approach - CBD Guidelines* (The Secretariat of the Convention on Biological Diversity, 2004), p.5.

Although it is just a phrase, its emergence marked a significant and meaningful shift in the way the human–nature relationship was understood. People were no longer seen merely as passive beneficiaries of nature’s resources and opportunities; rather, they became active agents capable of protecting, conserving, managing, and restoring natural or human-modified ecosystems, thereby addressing major societal challenges by learning from and working with natural processes.

The growing relevance and visibility of the NBS concept can be attributed largely to its increasing adoption by international organizations in the fields of environmental science and nature conservation, such as **IUCN and the World Bank** around **2008-2009**. At the time, these organizations were working intensively on identifying solutions to climate change, declining living conditions, and biodiversity loss by promoting interventions that work with ecosystems rather than relying solely on conventional engineering measures, such as artificial barriers or grey infrastructures.⁹ Indeed, in **2011**, the “**Bonn Challenge**” highlighted the need to use ecosystem-based solutions to address environmental degradation, setting the goal of restoring more than 150 million hectares of land by 2020 and over 350 million hectares by 2030.

The **2013 EU Green Infrastructure Strategy** is particularly important, as it marks the first time that NBS were mentioned in an official European policy document and proposed as potential alternatives to traditional grey infrastructure. This initiative represents the starting point of a broader trajectory that would gradually lead to a more comprehensive and integrated consideration of NBS within European environmental governance.

This shift contributed to a wider international reframing in which nature conservation and societal development were no longer perceived as opposing

⁹ Cohen-Shacham et al., “Nature-Based Solutions to Address Global Societal Challenges.” Gland, Switzerland. 2016, pp. 17-18, <https://doi.org/10.2305/IUCN.CH.2016.13.en>

objectives. Instead, they began to be understood as interconnected domains capable of acting synergistically, recognizing both the positive and negative interactions between people and nature, and focusing on enhancing biodiversity and human well-being simultaneously.

A significant milestone in this evolving perspective was the **Paris Agreement (COP21)**. Adopted on **12 December 2015**, it commits signatory states to limiting global temperature rise to well below 2°C, and preferably 1.5°C, above pre-industrial levels.¹⁰ In this context, NBS gained increasing visibility within the global climate debate involving more than 195 participating countries.¹¹

To support the idea that NBS are a relatively recent concept, it is worth noting that before 2015 the term was used mainly in general communication settings, and only from early 2016 did it begin to appear consistently in academic literature and scientific publications.

In **2016**, through the **Horizon 2020** framework, the largest European funding programme for research and innovation, dedicated financial resources were allocated for the implementation of NBS for the first time.¹² The programme, active from 2014 to 2020, supported several projects in which NBS played a central role in addressing social and environmental challenges, enhancing climate resilience, and contributing to urban and architectural planning strategies.¹³

In fact, since 2020 the concept of NBS has gained increasing traction, becoming a key topic in international and global development.

¹⁰ United Nations Framework Convention on Climate Change, *Paris Agreement*, 2015, Article 2, p. 4.

¹¹ E. Cohen-Shacham et al., eds., *Nature-Based Solutions to Address Global Societal Challenges*, Gland, IUCN International Union for Conservation of Nature, 2016, pp. 17–18.

¹² European Commission, “Nature-Based Solutions Research Policy,” accessed June 30, 2026.

¹³ European Commission, “Horizon 2020,” accessed June 30, 2026.

From that year onwards, an increasing number of policies and frameworks not only reference NBS, but also position them as pivotal, placing them at the center of discussions and subsequent reports.

A particularly important milestone is 2020, with the release of the **IUCN Global Standard for Nature-Based Solutions**, the first framework to classify NBS by providing eight criteria and twenty-eight indicators (which will be discussed in more detail in the paragraph 1.2.2).¹⁴

Subsequently, in 2021, the **COP26 Glasgow Climate Pact** marked the moment when NBS officially entered international climate negotiations.¹⁵ In the last few years, NBS have been increasingly integrated into major international and European policies. The **Kunming-Montreal Global Biodiversity Framework (GBF)** aims to halt and reverse biodiversity loss by 2030, with NBS identified as a key strategy to achieve these goals.¹⁶ Similarly, the **EU Biodiversity Strategy for 2030** seeks to protect 30% of European terrestrial and marine areas while restoring degraded ecosystems integrating NBS.¹⁷

This trajectory culminated between 2023 and 2024 with the political agreement and final adoption of the **EU Nature Restoration Regulation**, *the first continent-wide and comprehensive law of its kind*,¹⁸ establishing binding targets for the restoration of degraded ecosystems within the European Union.

¹⁴ IUCN, *IUCN Global Standard for Nature-Based Solutions - A User-Friendly Framework for the Verification, Design and Scaling up of NBS*, no. 1st (Gland, Switzerland, 2020), p.3, <https://doi.org/10.2305/IUCN.CH.2020.08.en>.

¹⁵ United Nations Framework Convention on Climate Change, *Glasgow Climate Pact*, Decision -/CP.26, 2021, pp. 2, 5.

¹⁶ Secretariat of the Convention on Biological Diversity, "Kunming-Montreal Global Biodiversity Framework: 2030 Targets," accessed June 30, 2026, <https://www.cbd.int/gbf/targets>.

¹⁷ European Commission, *EU Biodiversity Strategy for 2030: Bringing Nature Back into Our Lives*, European Union, 2020, pp. 2–3, 9.

¹⁸ European Union, Regulation (EU) 2024/1991 of the European Parliament and of the Council of 24 June 2024 on nature restoration and amending Regulation (EU) 2022/869, Official Journal of the European Union, 29 July 2024; European Commission, "Nature Restoration Regulation," accessed June 30, 2026.

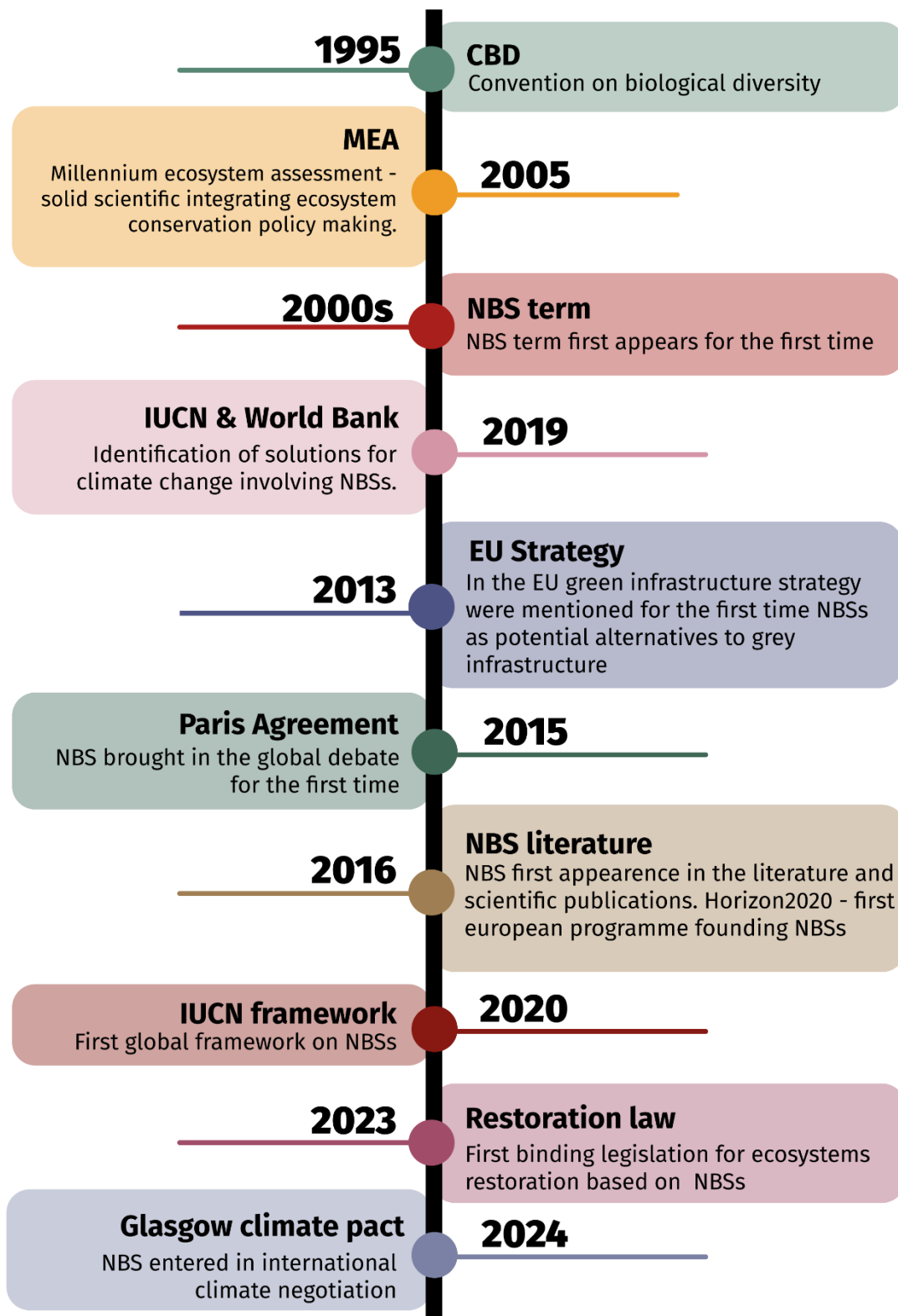


Figure 1 - Evolution of the Nature-Based Solutions concept within international and European policy frameworks.

Author's elaboration.

1.2.2 Regulatory frameworks

The previous section outlined how the concept of NBS emerged by translating the principles of the ecosystem-based approach into practical applications, and how these principles evolved over time to the point that NBS became integrated into both European and global policies and regulations.

The issue that now comes into focus concerns the operational dimension of NBS. In the policy documents referenced above, NBS are generally presented as instruments serving broader strategic goals; they function as *means* to achieve wider environmental, social, or climate-related objectives. Given the growing conceptual and applied relevance of NBS, recent years have seen various European institutions and global organizations develop more structured frameworks that aim to provide clearer operational definitions and more specific guidance for their implementation.

The aim is to provide a brief overview of the most well-known and widely used frameworks, which in this case include:

- a) *IUCN Global Standard for Nature-Based Solutions*, both the 1st and 2nd editions
- b) *EU Framework*, including the official definition, Horizon 2020 contributions, and the Evaluating the Impact of NBS guidance

IUCN Global Standard for Nature-Based Solutions ¹⁹

Recognizing that Nature-based Solutions (NBS) are innovative approaches capable of providing up to 30% of climate mitigation by 2030, the International Union for Conservation of Nature (IUCN) introduced the *Global Standard for NBS in 2020*.

¹⁹ IUCN, *IUCN Global Standard for Nature-Based Solutions - A User-Friendly Framework for the Verification, Design and Scaling up of NbS*.

This standard, revised in 2025, serves as a critical tool to ensure the growing political and social engagement with NBS translates into credible, rigorous, and measurable actions.

The absence of clear criteria thus presents a dual risk: inconsistent application and a consequent erosion of both effectiveness and credibility. The IUCN Standard mitigates this risk by providing a benchmark for quality (defining what constitutes a well-designed NBS) and a framework for continuous improvement, uniting a global network of practitioners. Developed from user feedback, it is intentionally facilitative, eschewing a rigid, compliance-based model with definitive targets.²⁰ Its core function is to enable users to implement NBS, learn from experience, and progressively strengthen the intervention's effectiveness, sustainability, and adaptability.

The Standard has two functions; to help guide the design of an NBS and provide a means to verify that the design meets the requirements of the NBS Standard, in fact, the key features that can be addressed to the design are:²¹

- Design implementation
- Verification of the actual design
- Scaling-up the design

Positioned as a flexible rather than a prescriptive framework, the IUCN Standard is inherently geared towards continuous improvement and the generation of tangible added value.

This design makes it credible and actionable for investors, as it enables the diagnosis of weaknesses through practical application and is adaptable across diverse sectors.

²⁰ IUCN, *IUCN Global Standard for Nature-Based Solutions - A User-Friendly Framework for the Verification, Design and Scaling up of NbS*, pg.2.

²¹ IUCN (2020). *Guidance for using the IUCN Global Standard for Nature-based Solutions. A user-friendly framework for the verification, design and scaling up of Nature-based Solutions*. First edition. Gland, Switzerland: IUCN, p. 11.

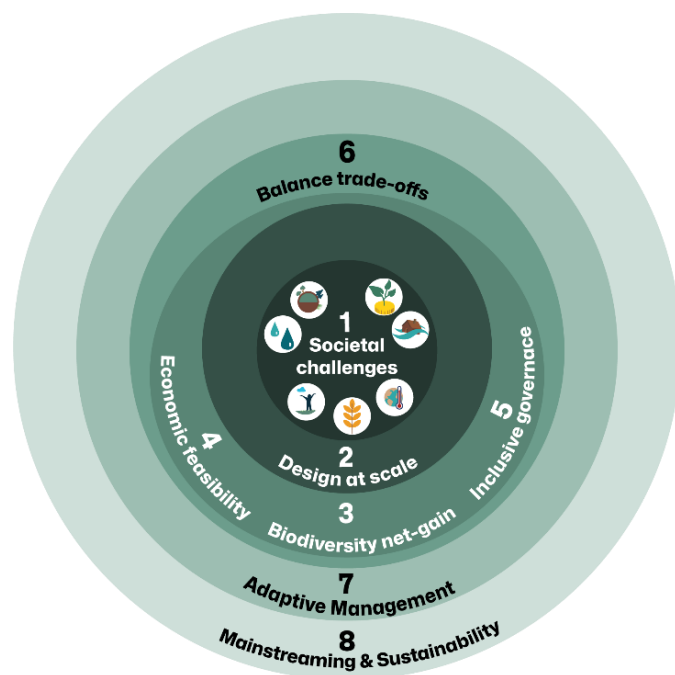
Its scalability is a key feature, making it applicable at both micro levels (e.g., individual financial institutions, small enterprises) and macro levels (e.g., city-wide urban planning, national government policies).

Operationally, the Standard provides a structured framework comprising 8 core criteria and 28 associated indicators for project design and assessment. These criteria encompass:²²

1. Identification of the targeted social challenge
2. Intervention scale and context
3. Environmental sustainability
4. Social equity
5. Economic sustainability
6. Transparent management of trade-offs
7. Adaptive management based on monitoring and learning
8. Policy integration for durable impact

Figure 2 - The eight criteria of the IUCN Global Standard for Nature-Based Solutions.

Author's elaboration based on IUCN, Guidance for using the IUCN Global Standard for Nature-based Solutions: A user-friendly framework for the verification, design and scaling up of Nature-based Solutions, 1st ed., Gland, Switzerland, IUCN, 2020, fig. 6, p. 16.



²² IUCN (2020). Guidance for using the IUCN Global Standard for Nature-based Solutions. A user-friendly framework for the verification, design and scaling up of Nature-based Solutions. First edition. Gland, Switzerland: IUCN, p. 16

As a practical instrument, it is supplemented by comprehensive technical guidance, a user manual with verification resources, and a self-assessment toolkit that scores performance against each criterion. An Excel-based self-assessment tool facilitates the evaluation process, requiring users to rate each indicator's level of adherence on a four-tier scale: Strong (>75%), Adequate (50-75%), Partial (25-50%), or Insufficient (<25%).²³

The results are synthesized into an intuitive “traffic light” visualization, immediately identifying weaknesses and non-conformities.

The methodology incorporates a normalization step to standardize the weight of all eight criteria, culminating in a final, comprehensive percentage score that reflects the project's overall alignment with the Standard. Crucially, a project failing to meet a minimum threshold in *any* of the eight criteria is deemed not to fulfill the IUCN Standard.²⁴

²³ IUCN (2020). Guidance for using the IUCN Global Standard for Nature-based Solutions. A user-friendly framework for the verification, design and scaling up of Nature-based Solutions. First edition. Gland, Switzerland: IUCN, pp.38-39.

²⁴ IUCN, *IUCN Global Standard for Nature-Based Solutions - A User-Friendly Framework for the Verification, Design and Scaling up of NBS*.

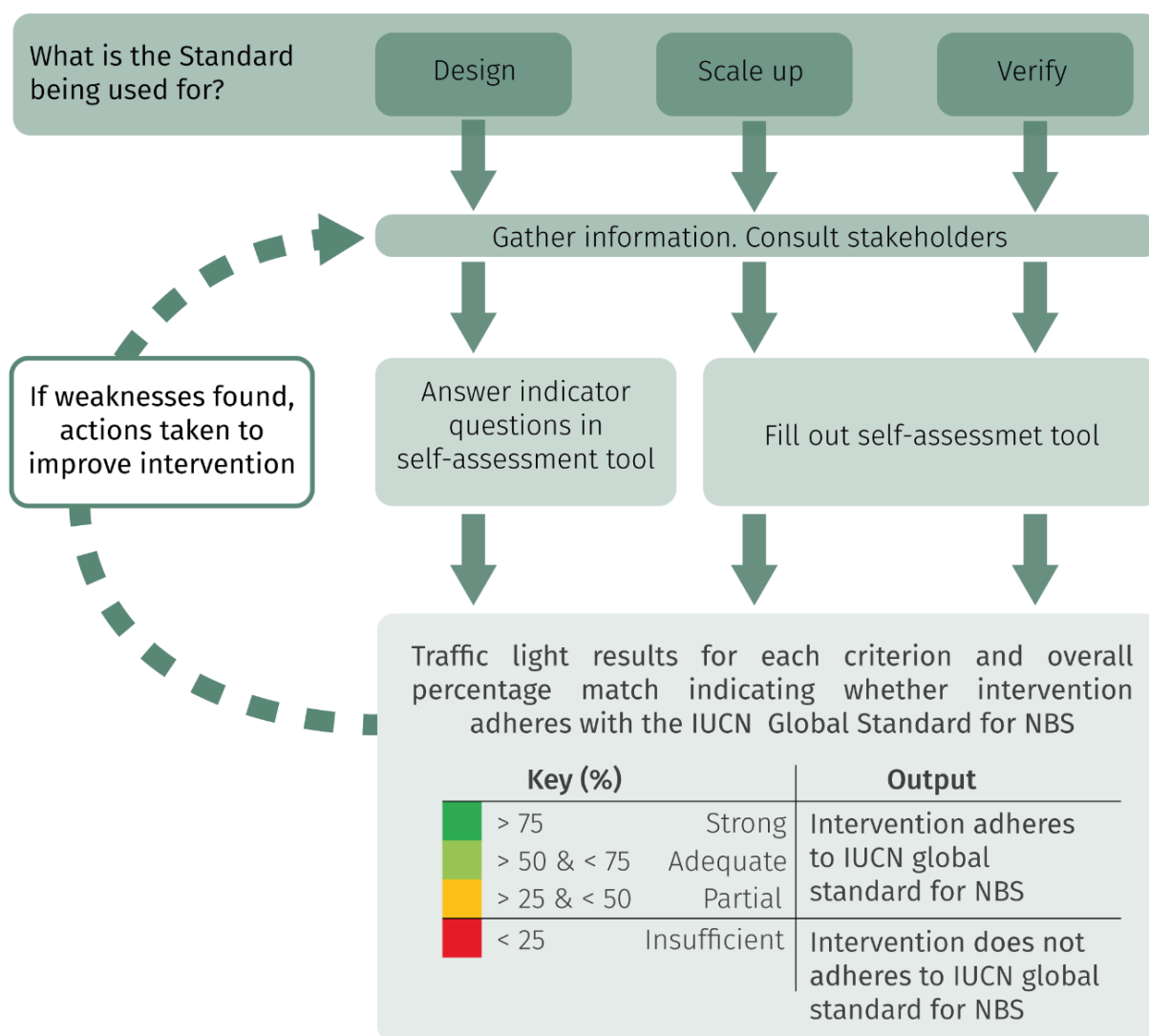


Figure 3 - Use of the IUCN Global Standard for Nature-Based Solutions and its link with the self-assessment process.

Author's elaboration based on IUCN, *Guidance for using the IUCN Global Standard for Nature-based Solutions: A user-friendly framework for the verification, design and scaling up of Nature-based Solutions*, 1st ed., Gland, Switzerland, IUCN, 2020, fig. 7, p. 39.

EU Framework for evaluating NBS

In parallel with the development of the IUCN Global Standard, the European Union has progressively advanced its own conceptual and operational framework for NBS, with a strong emphasis on impact evaluation and performance measurement. A key reference document in this context is *“Evaluating the Impact of Nature-Based Solutions: A Handbook for Practitioners”* (European Commission, 2021), developed within the Horizon 2020 research and innovation agenda.²⁵

While the IUCN Global Standard primarily serves as a quality and verification benchmark, the EU Handbook is conceived as an evaluation-oriented framework, aimed at assessing the effectiveness and impacts of NBS interventions over time.

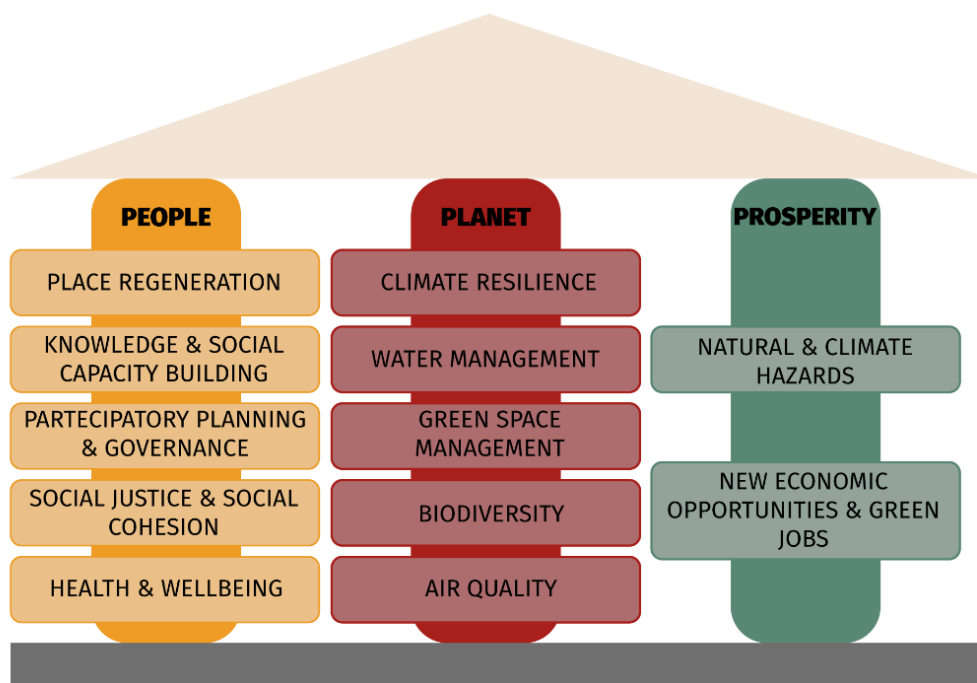


Figure 4 - Conceptual mapping of NBS societal challenge areas within the People, Planet and Prosperity pillars of sustainable development.

Author's elaboration based on European Commission, *Evaluating the Impact of Nature-Based Solutions: A Handbook for Practitioners*, 2021, fig. 4-1, p. 118.

²⁵ European Commission, *Evaluating the Impact of Nature-Based Solutions: A Handbook for Practitioners*, 1st ed. (Publications Office of the European Union, 2021), <https://data.europa.eu/doi/10.2777/244577>.

Rather than defining what qualifies as an NBS, the Handbook focuses on how to systematically measure its outcomes, making it particularly relevant for ex-post and ongoing assessment processes.²⁶

At the core of the EU framework is a structured indicator-based approach, designed to capture the multifunctional character of NBS. Impacts are organized into three main evaluation domains, which reflect the integrated nature of sustainability in urban contexts:

- *Environmental domain*; addressing ecosystem functioning, biodiversity enhancement, climate regulation, and resource efficiency.
- *Social domain*; encompassing human health and well-being, social cohesion, accessibility, and equity.
- *Economic domain*: including cost-effectiveness, long-term economic performance, job creation, and avoided costs.

Each domain is articulated into impact categories, which are further operationalized through specific indicators and metrics. These indicators can be quantitative (e.g., temperature reduction, runoff reduction, economic savings) or qualitative (e.g., perceived well-being, governance quality), depending on data availability and project scale.²⁷

These indicators serve as tools to monitor whether NBS interventions are effective. The framework's structure is flexible, allowing it to be adapted to a wide range of NBS contexts and enabling comparison across different projects.

The aforementioned indicators can be categorized into two broad categories:²⁸

- Recommended indicators
- Additional indicators

²⁶European Commission, *Evaluating the Impact of Nature-Based Solutions*. pp. 6,53,89,115.

²⁷ European Commission, *Evaluating the Impact of Nature-Based Solutions*. pp. 115-120

²⁸ European Commission, *Evaluating the Impact of Nature-Based Solutions*. pp.121-122

The first constitute a core set of indicators that should be applied to all NBS projects, ensuring consistency and comparability. The latter, however, are more specific and applicable to particular objectives and local contexts of targeted interventions. They serve to enrich the evaluation, making it more comprehensive and better aligned with the specific context.

Subsequently, the indicators are further recategorized based on their function within the intervention into three macro-classes: ²⁹

- *Structural indicators* refer to the enabling conditions required for NBS implementation, including governance structures, financial resources, technical capacity, and policy frameworks. These indicators are particularly relevant during the planning phase, as they assess whether the necessary conditions are in place to support successful implementation.
- *Process indicators* evaluate how NBS interventions are co-designed, implemented, and managed, focusing on aspects such as stakeholder engagement, efficiency, inclusiveness, and quality of governance. These indicators are most useful during the implementation and adaptive management phases.
- *Outcome indicators* capture the actual results and impacts of NBS interventions, including changes in environmental performance, social well-being, and economic value, and are therefore central to impact evaluation.

The framework also emphasizes the importance of baseline assessment and temporal monitoring. Indicators should be measured before implementation to establish reference conditions and subsequently during and after implementation to assess changes over time.

²⁹ European Commission, *Evaluating the Impact of Nature-Based Solutions*, pp.121-122

Where possible, comparisons between NBS intervention sites and similar non-intervention areas (control sites) are encouraged to strengthen causal interpretation and isolate NBS-specific effects from broader contextual changes.

In addition, the framework links indicator selection to the typology of NBS proposed by Eggermont et al. (2015), which classifies NBS according to their level of ecosystem intervention and functional objectives.³⁰

- *Type 1 NBS*, involve minimal or no intervention and focus on the protection and enhancement of existing ecosystems, such as conservation areas and natural habitats.
- *Type 2 NBS*, involve active ecosystem management to promote multifunctionality and improve ecosystem service provision, as in sustainable forestry, agriculture, and landscape-scale interventions.
- *Type 3 NBS*, involve the creation or redesign of ecosystems through engineered or hybrid solutions, such as green roofs, urban parks, and constructed wetlands.

This typology supports the selection of appropriate indicators by aligning measurement approaches with the ecological and functional characteristics of different NBS interventions.

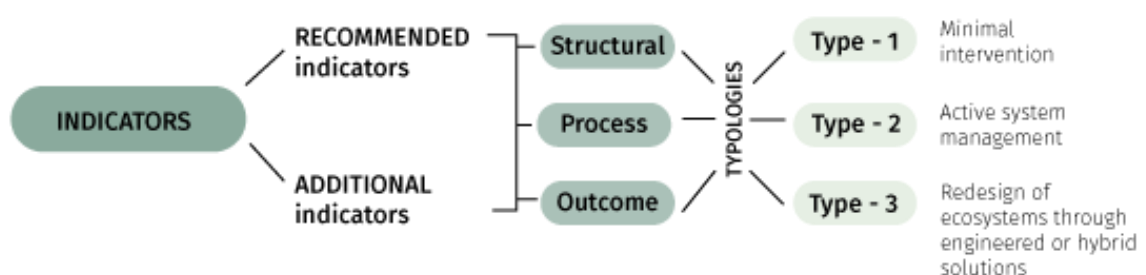


Figure 5 - Indicator typologies interpreted within the proposed evaluation framework.

Author's elaboration based on European Commission, *Evaluating the Impact of Nature-Based Solutions: A Handbook for Practitioners*, 2021, pp. 121-123

³⁰ European Commission, *Evaluating the Impact of Nature-Based Solutions*, pp.121-122

This hierarchical structure:

domain → category → indicator

provides a transparent and modular framework that can be adapted to different urban and regional contexts.

A key feature of the EU Handbook is its flexibility in indicator selection.

Rather than imposing a fixed checklist, the framework encourages practitioners to select the most relevant indicators according to:

- the specific societal challenge addressed,
- the spatial and temporal scale of the intervention,
- local environmental and socio-economic conditions,
- available data and monitoring capacity.

This approach acknowledges the inherent diversity of NBS typologies and avoids one-size-fits-all evaluations, while still maintaining methodological coherence. Importantly, the Handbook emphasizes that indicators should be selected and interpreted in a way that enables comparability and replicability, particularly across EU-funded projects.

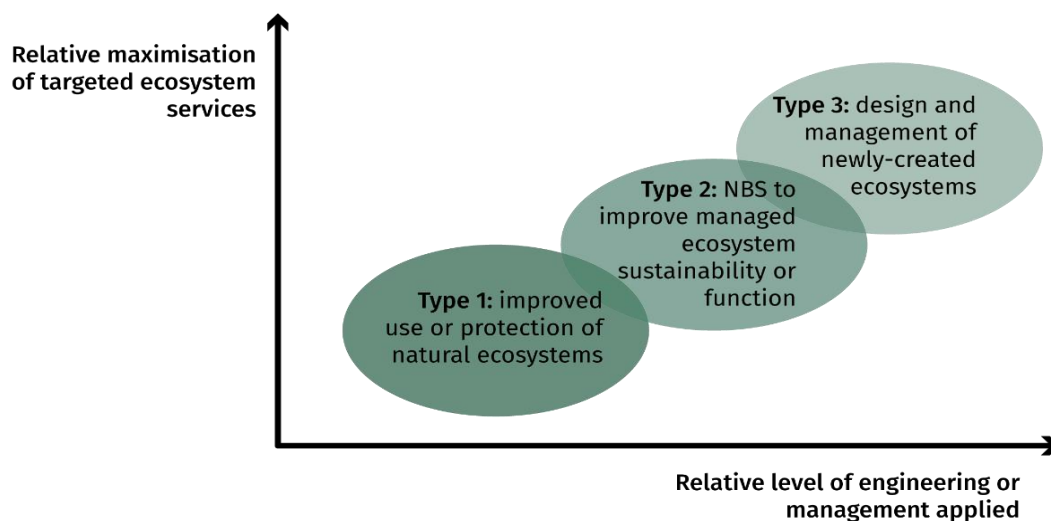


Figure 6 - Typology of Nature-Based Solutions according to the level of ecosystem management and intervention.

Author's elaboration based on European Commission, *Evaluating the Impact of Nature-Based Solutions: A Handbook for Practitioners*, 2021, fig. 4-2, p. 122, adapted from Eggermont et al., 2015.

No.	INDICATOR	UNITS	CLASS	APPLICABILITY OF NBS		
				TYPE 1	TYPE 2	TYPE 3
RECOMMENDED						
1.1	Total carbon removed or stored in vegetation and soil per unit area per unit time	kg/ha/y	O			
1.2	Avoided greenhouse gas emissions from reduced building energy consumption	t CO ₂ e/y	O			
1.3	Monthly mean value of daily maximum temperature (TX _x)	°C	O			
1.4	Monthly mean value of daily minimum temperature (TN _n)	°C	O			

Figure 7 - Example of recommended Climate Resilience indicators classified by unit, indicator class and applicability to different NBS types.

Author's elaboration based on European Commission, *Evaluating the Impact of Nature-Based Solutions: A Handbook for Practitioners*, 1st ed., Luxembourg, Publications Office of the European Union, 2021, table 4-1, p. 127.

From an operational perspective, the EU framework promotes monitoring and evaluation as iterative processes, supporting adaptive management and learning over time.

Evaluation is therefore positioned not merely as an assessment tool, but as a decision-support mechanism that informs project refinement, upscaling strategies, and policy integration.

Unlike the IUCN Global Standard, the EU Handbook does not introduce threshold-based verification or compliance scoring. Instead, it provides a structured yet non-prescriptive analytical framework, designed to support evidence-based decision-making and to strengthen the justification of NBS investments within urban and regional planning processes.

Concluding remarks on NBS frameworks

At this stage, it is necessary to reflect on whether a single, comprehensive, and truly binding operational framework for the implementation of NBS currently exists. In general, the answer is negative. NBS approaches are relatively recent, and none of the existing frameworks holds a binding legal status. The only partial exception is represented by the EU Nature Restoration Law, which applies exclusively to specific restoration interventions within the European context.

While the frameworks discussed provide structured guidance on the design, implementation, monitoring, and management of NBS, they do not constitute an exhaustive, universally adopted, and enforceable operational method. Instead, they function as reference frameworks, offering principles, criteria, and evaluation tools that support informed decision-making without imposing mandatory procedures. This lack of a binding and standardized operational framework highlights the need for complementary evaluation approaches capable of systematically comparing alternative NBS strategies in complex contexts.

The IUCN Global Standard represents the most advanced attempt to define a shared benchmark of quality, introducing minimum criteria, structured indicators, and verification logic. However, its voluntary nature places it within the realm of soft governance, relying on adoption by practitioners, institutions, and funding bodies rather than legal enforcement. Conversely, the EU framework does not seek to establish binding requirements but rather provides a flexible and analytical structure for impact evaluation. Its strength lies in the articulation of domains, categories, and indicators that support evidence-based decision-making and comparison across alternative NBS interventions. Nonetheless, the absence of thresholds or compliance mechanisms prevents it from functioning as a normative standard.

Taken together, these frameworks reveal a fragmented governance landscape in which NBS are guided by complementary but non-binding instruments. The lack of a mandatory framework implies that the effectiveness and credibility of NBS largely depend on local interpretation, contextual adaptation, and the decision-support tools adopted by planners and policymakers.

In this context, multi-criteria decision-making approaches, such as the Analytic Hierarchy Process (AHP), emerge as a critical methodological bridge. By structuring and weighting indicators derived from established frameworks, AHP enables the systematic comparison of alternative NBS scenarios, partially compensating for the absence of a binding evaluative standard. This approach is particularly relevant in complex urban environments, such as the city of Turin, where multiple social, environmental, and economic objectives must be balanced simultaneously as it will be presented in the following chapters.

Framework	Organization/ year	Scope and objectives	Key criteria	Binding Nature	Operational Guidance
IUCN Global Standard for Nature-Based Solutions (1 st edition)	IUCN, 2020	Provides the most comprehensive global definition and quality standard for NBS.	8 criteria and 28 indicators, including: biodiversity net gain, inclusive governance, economic viability, adaptive management.	Non-binding, voluntary standard.	High: offers a structured assessment tool, scoring system, and implementation guidance.
IUCN Global Standard for Nature-Based Solutions (2 nd edition)	IUCN, 2025	Updated global framework with greater scientific rigor and guidance for scaling, social safeguards, and measurable impacts.	Same 8 criteria updated, with more detailed indicators; greater focus on governance and inclusion.	Non-binding	Updated guidelines with case studies and best practices.
EU Framework: Definition + Horizon 2020 / Evaluating the Impact of NBS	European Commission, 2014–2024 (H2020: 2014–2020; Evaluation report: 2020)	Define NBS in the EU context, guide implementation, and monitor environmental, social, and economic impacts of funded projects.	Multi-dimensional impact categories, including environmental performance, climate resilience and adaptation, social impacts (health, well-being, inclusion), economic performance and cost-effectiveness, governance and implementation processes, scalability and long-term sustainability.	Non-binding for definition; binding only when linked to EU legislation such as the Nature Restoration Law	Medium–High: evaluation framework with indicators and European case studies.

Table 1 - NBS framework summary

1.3. NBS typologies

As previously noted, NBS stem from an ecosystem-based approach. Ecosystems provide a diverse range of services upon which many aspects of human life depend; from large-scale benefits such as overall well-being and carbon sequestration to flood control, coastal and slope erosion stabilization, and the provision of clean water, food, fuel, medicine, and genetic resources. While humans continually utilize nature, they must also learn to protect, manage, and restore natural ecosystems.

Introducing the broader category of NBS acknowledges that ecosystem-based approaches are relevant not only in specific fields, such as climate adaptation, water management, or disaster risk reduction, but also play a crucial role in addressing wider social challenges by directly enhancing human well-being and quality of life.



Figure 8 - Nature-Based Solutions as ecosystem-based approaches addressing societal challenges and generating human well-being and biodiversity benefits.

IUCN, IUCN Global Standard for Nature-based Solutions: A User-Friendly Framework for the Verification, Design and Scaling up of NBS, 1st ed., Gland, Switzerland, IUCN, 2020, fig. 1, p. 1.

NBS operationalize this principle through a set of structural and non-structural interventions, while delivering tangible solutions to pressing societal challenges. In accordance with the IUCN framework ³¹, these approaches are strategically designed to address the following priority issues:

- a. *Climate change mitigation*
- b. *Disaster risk reduction*
- c. *Economic and social development*
- d. *Human health*
- e. *Food security*
- f. *Water security*
- g. *Environmental degradation and biodiversity loss*

NBS represent an integrated approach to enhancing urban resilience by harnessing natural systems to deliver infrastructure, services, and holistic responses to growing environmental and societal challenges. By design, these interventions transcend traditional sectoral boundaries, necessitating collaboration across disciplines and stakeholders. Conceptually, NBS can be viewed as an evolutionary synthesis of earlier environmental approaches, consolidated under a unified and strategic framework. As such, NBS serves as an “umbrella concept” that encompasses four key dimensions.³²

1. *The strategic dimension* (e.g., Ecosystem-based Adaptation - EbA, Ecosystem-based Disaster Risk Reduction - Eco-DRR)
2. *The spatial planning dimension* (e.g., Green Infrastructure - GI, Blue Infrastructure - BI, Green-Blue Infrastructure - GBI, Urban Forestry - UF)

³¹ IUCN (2020). Guidance for using the IUCN Global Standard for Nature-based Solutions. A user-friendly framework for the verification, design and scaling up of Nature-based Solutions. First edition. Gland, Switzerland: IUCN. p.4.

³² European Commission, *Evaluating the Impact of Nature-Based Solutions*. pp. 18-20.

3. *The “soft” engineering dimension* (e.g., Ecological Engineering - EE, Sustainable Urban Drainage Systems - SuDS, Water-Sensitive Urban Design - WSUD, Best Management Practices - BMPs, Low-Impact Development – LID, WSUD = water-sensitive urban design)
4. *The Performance dimension* (e.g., ESS = ecosystem services)

The systematic design of nature-based interventions begins with a foundational analysis of the baseline conditions from both ecological and social standpoints.

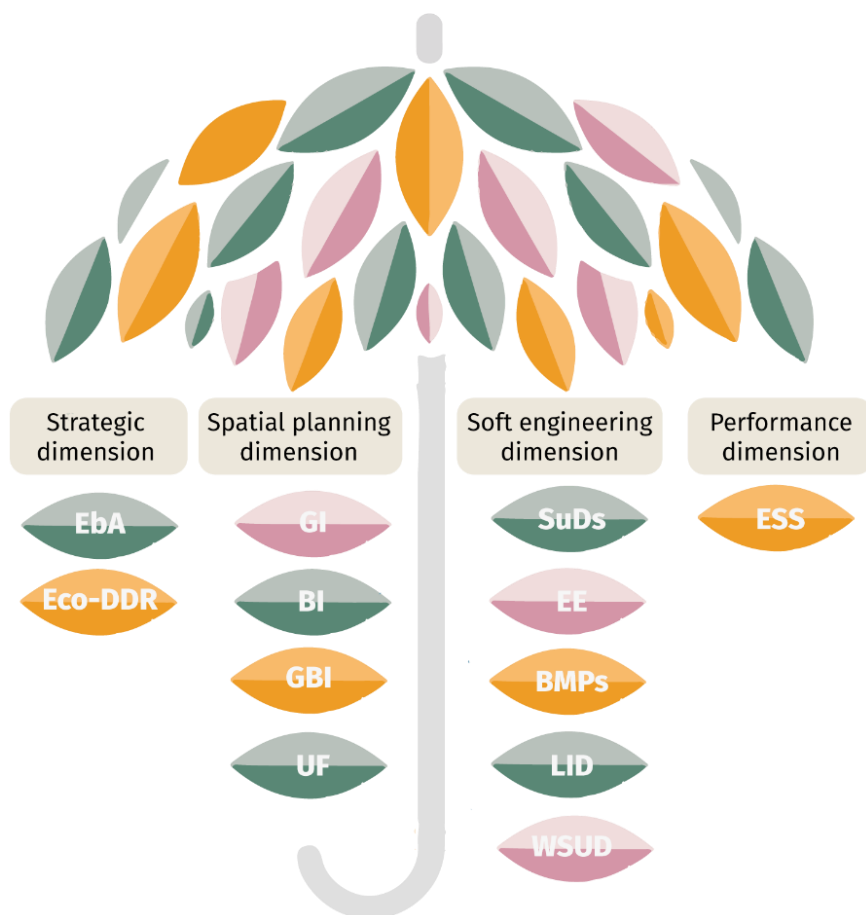


Figure 9 - Nature-based solutions as an umbrella concept and the relation of NBS to key existing concepts.

EbA = ecosystem-based adaptation; Eco-DDR = ecosystem-based disaster risk reduction; GI = green infrastructure; BI = blue infrastructure; GBI = green-blue; UF = urban forestry; SuDS = sustainable urban drainage systems; EE = ecological engineering; BMPs = best management practices; LID = low-impact design; WSUD = water-sensitive urban design; ESS = ecosystem services.

Author's elaboration based on European Commission, Evaluating the Impact of Nature-Based Solutions: A Handbook for Practitioners, 1st ed., Luxembourg, Publications Office of the European Union, 2021, fig. 1-1, p. 19.

This preliminary phase involves a thorough assessment of the existing system; its biophysical characteristics, ecological functions, socio-economic dynamics, and the interdependencies between them. Understanding these baseline conditions and systemic linkages is critical to ensuring that subsequent interventions are appropriately tailored, context-sensitive, and capable of delivering meaningful, long-term benefits.

Following this diagnostic phase, specific ecosystem functions and services are identified and prioritized as targets for enhancement or restoration. Examples include carbon sequestration, flood mitigation, coastal stabilization, waste decomposition, microclimate regulation, and habitat provision. The selection is guided by the site's ecological potential and the social needs identified during the baseline assessment. The ultimate objective of this process is to translate these enhanced ecosystem functions into tangible values and co-benefits for both people and the environment.

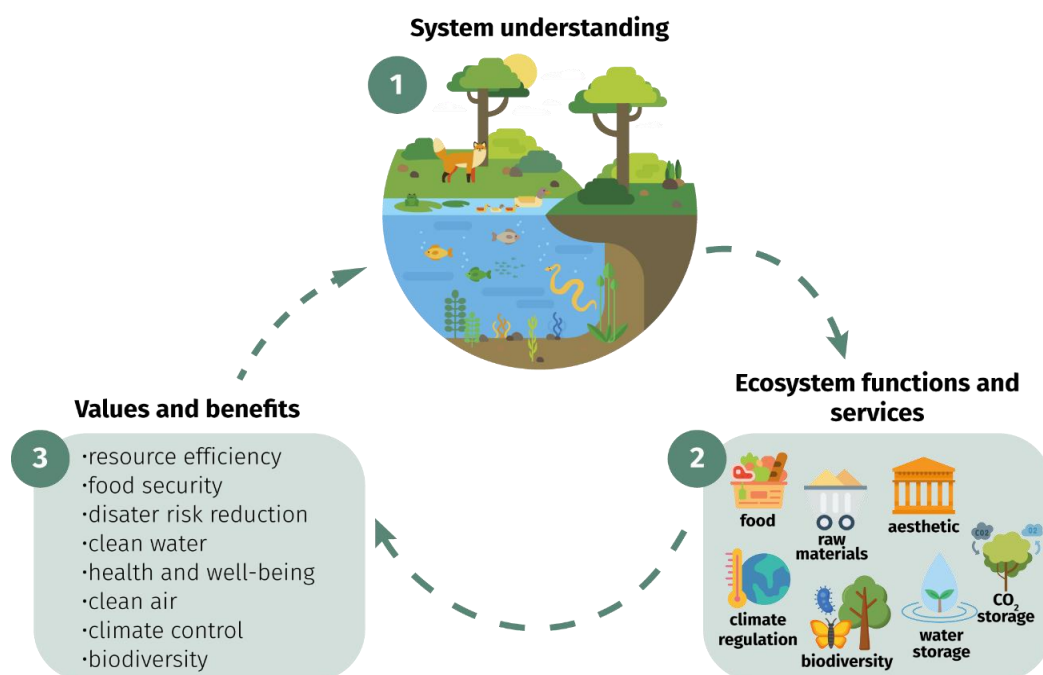


Figure 10 - Conceptual relationship between ecosystem understanding, ecosystem functions and services, and the values and benefits generated by Nature-Based Solutions.

Author's elaboration.

These may include reduced disaster risk, improved air and water quality, climate change mitigation and adaptation, enhanced biodiversity, recreational opportunities, and overall improvements in human health and well-being. We can therefore understand that the field of NBS, drawing inspiration from natural systems and integrating knowledge from multiple scientific disciplines, encompasses an exceptionally wide range of intervention types. Given this breadth, this thesis will focus specifically on those solutions applicable to an urban context, in direct alignment with the selected case study.

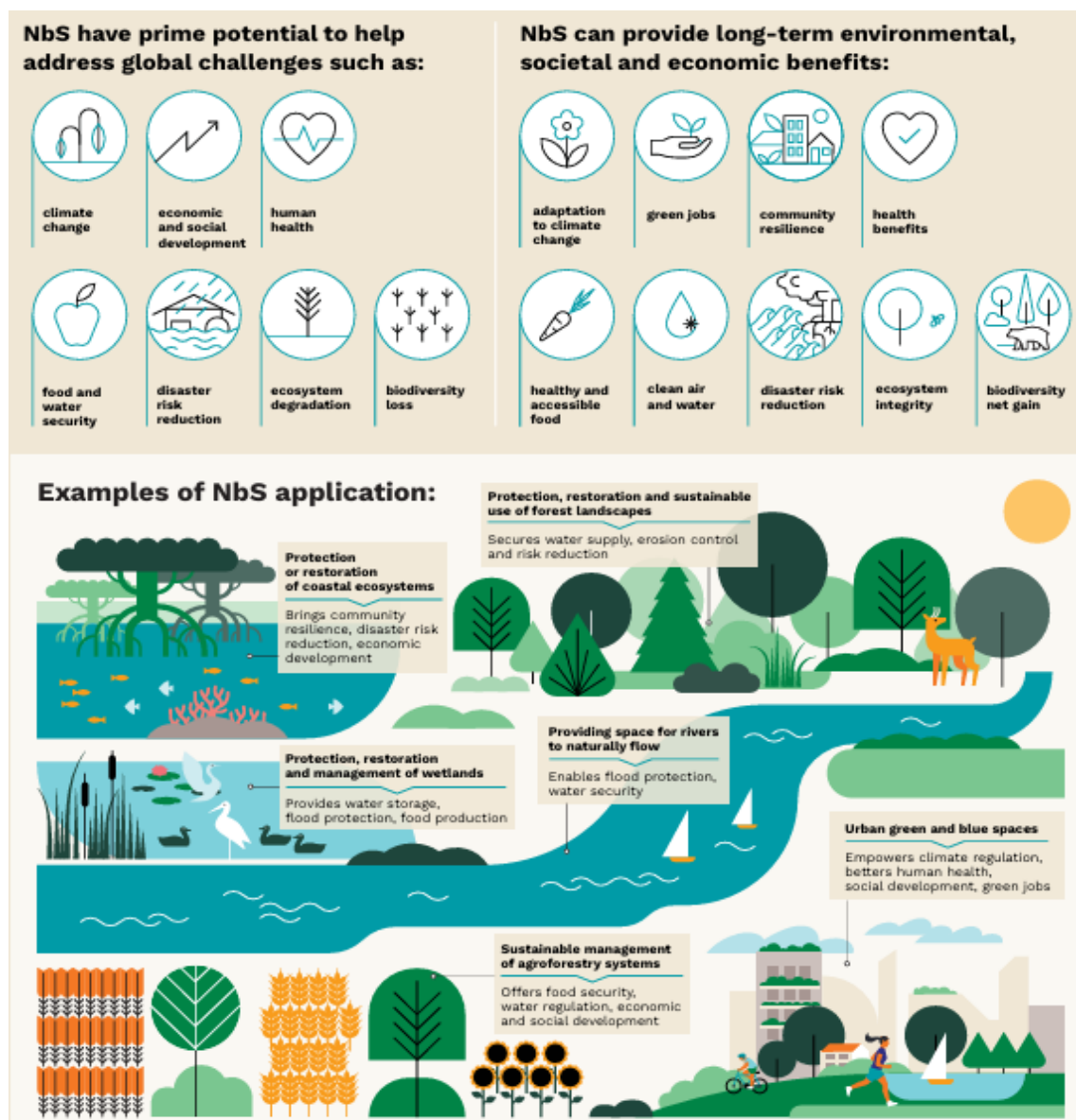


Figure 11 - Nature-Based Solutions: global challenges, long-term benefits and application examples
IUCN, *Nature-Based Solutions infographic*, International Union for Conservation of Nature, 2022.

1.4. NBS in the context of the urban ecosystem

Given the extensive applicability and diversity of solutions encompassed by the concept of NBS, this thesis will now narrow its focus to the urban context.

In Western Europe, the urbanization rate is increasing by 0.2% annually and is projected to reach 89.1% by 2050, up from 79.5% in 2010. Consequently, the protection of these environments must be prioritized. Within urban environments, NBS provide a variety of key benefits. These notably include mitigating the predominant issue of pollution, managing water (including coastal and flood waters as context-dependent), enhancing public health and well-being, and fostering biodiversity.

Another major critical phenomenon that NBS can help counteract is the Urban Heat Island (UHI) effect.

This climatic condition, relative to the size and structure of cities, is caused by multiple factors. These include the high concentration of impervious surfaces like asphalt and concrete in roads and buildings, emissions from high traffic volumes, dense populations, and a scarcity of ventilation, vegetation, and water elements. These factors collectively cause urban temperatures to rise by approximately 1-2°C compared to suburban and rural areas.

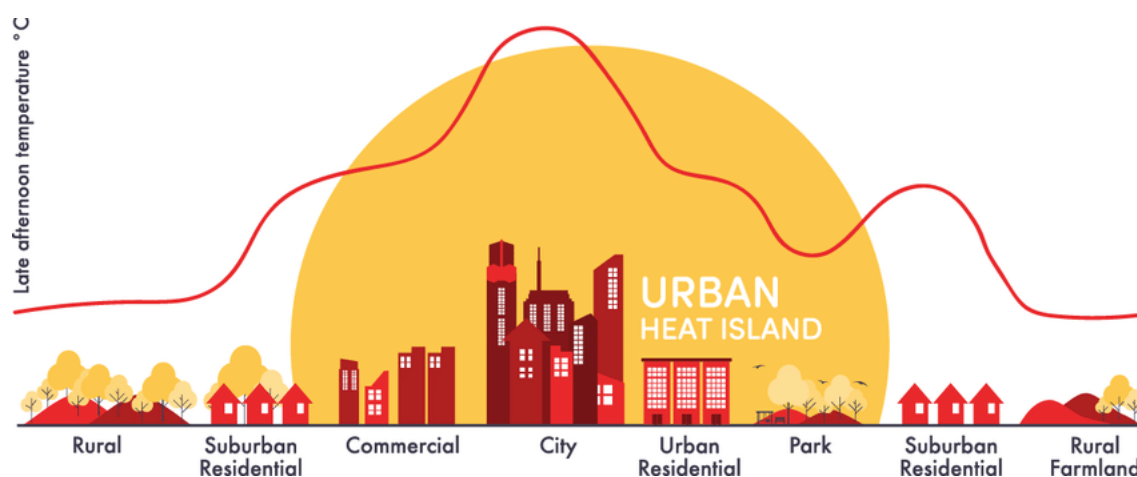


Figure 12 - Graphical representation of the urban heat island effect (UHI)

Cool Parramatta, available in Fuladlu, Riza and Ilkan, "The Effect of Rapid Urbanization on the Physical Modification of Urban Area," conference paper presented at The 5th International Conference on Architecture and Built Environment with AWARDS S.ARCH 2018, Venice, Italy, May 2018, fig. 1.

A significant side-effect of the UHI effect is the increased concentration of air pollutants, which consequently heightens associated public health risks.³³ NBS mitigate this effect through surface cooling and evapotranspiration, while also supporting biodiversity by providing food and habitats for various wildlife species.

At the same time, solutions such as retention ponds, parks, and community gardens play a crucial role in community development, offering a wide range of social, economic, and environmental benefits, as previously mentioned.

In general, green infrastructures (GI) tend to improve mental health and well-being; they also appear to reduce crime rates by fostering social interaction and community cohesion. Furthermore, from an economic perspective, proximity to accessible green spaces enhances property values.

In addition, the construction, maintenance, and operation of such spaces stimulate local economic growth and generate employment.³⁴

While the benefits of NBS within the built-up urban fabric are clear, their full relevance extends beyond the city's immediate boundaries to encompass broader geographical and systemic dimensions.

This importance can be conceptualized across three interconnected spheres:³⁵

- *Within the city*, where NBS are directly implemented to emulate natural processes, delivering concrete co-benefits that counteract key urban

³³ "Urban Heat Islands: Managing Extreme Heat to Keep Cities Cool - Joint Research Centre," December 20, 2024,

https://joint-research-centre.ec.europa.eu/jrc-news-and-updates/urban-heat-islands-managing-extreme-heat-keep-cities-cool-2024-07-22_en.

³⁴ Laura Costadone and Shan Zhang, "Integrated Valuation of the Ecological, Social and Economic Benefits Provided by a Multifunctional Nature-Based Solution," *Nature-Based Solutions* (December 2025), pp. 11-14
100256, <https://doi.org/10.1016/j.nbsj.2025.100256>.

³⁵ Simone Borelli (FAO), et al., "Smart, Sustainable and Resilient Cities: The Power of Nature-Based Solutions," Report, European Commission, 2021. pp.10-12.

challenges such as the heat island effect, air pollution, and stormwater management.

- *Around cities*, in the peri-urban and regional hinterland, where NBS integrate into city-region networks. Here, they create essential ecological buffer zones, contribute to large-scale carbon sequestration, mitigate risks like wildfires, and enhance regional ecosystem services that directly support urban centers.
- *Beyond cities*, reflecting the understanding of a city as an open node within global networks. In these distal territories, the application of NBS principles, through sustainable supply chains, infrastructure development, and resource management, indirectly but fundamentally underpins urban sustainability and resilience by securing the flows of materials and ecosystem services upon which cities depend.

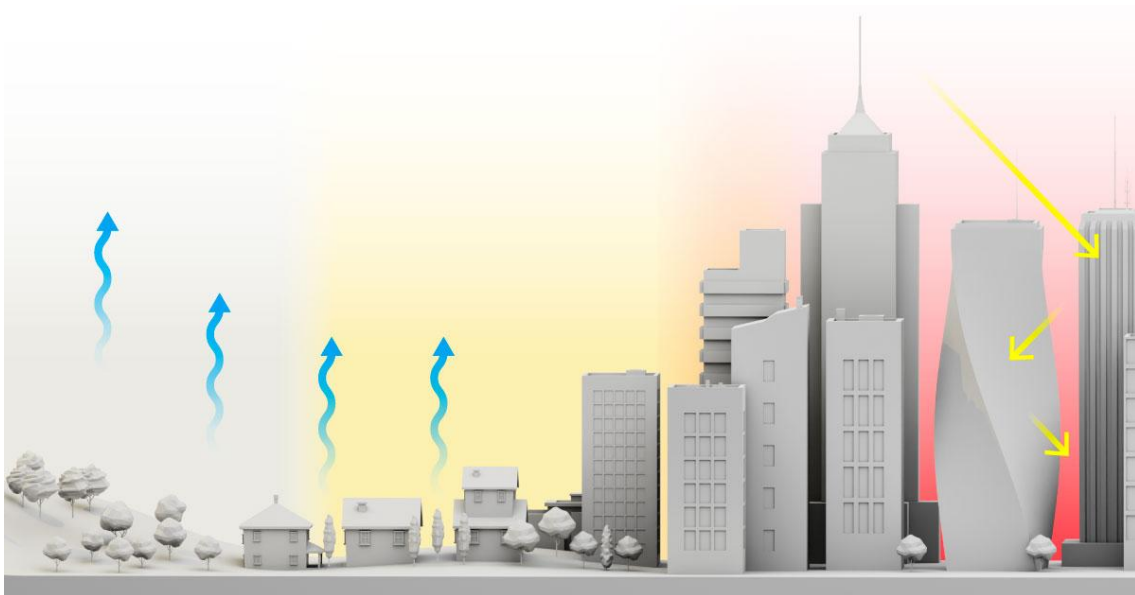


Figure 13 - Schematic representation of the Urban Heat Island (UHI) effect, illustrating heat accumulation and reduced thermal comfort

Source: Reuters Graphics.



Figure 14 - Set of NBS pictures in the urban context

a. Urban forests/Green corridors, b. Urban parks, c. Urban gardens/community gardens, d. Water elements, e. Green facades, f. Green roofs, g. Rain gardens, h. Bioswale

1.4.1 The city scale

At the city scale, NBS encompass strategic interventions designed to complement and reinforce formal land-use planning and integrate with disaster risk management frameworks. The suitability and efficacy of these interventions are fundamentally determined by the city's unique landscape and ecological structure, as well as the specific socio-environmental challenges faced by its population. A comprehensive suite of biophysical and social characteristics (including terrain, climate, hydrology, local ecology, and sociological factors) collectively influences their applicability and design.

These solutions often translate into specific typologies that address systemic urban challenges.³⁶

Representative examples include:

- *Metropolitan green and blue infrastructure networks*: planning and consolidating large-scale ecological systems, including river corridors, peri-urban forests, major parks, and natural reserves, to structure urban growth, ensure landscape continuity, and enhance ecological connectivity across the metropolitan territory.
- *Urban–nature gradient and spatial structuring*: organizing the transition between dense urban fabrics and natural landscapes through open green belts, buffer zones, and multifunctional landscapes that mediate between built areas and ecological systems.
- *Topography-based urban design*: integrating geomorphological features such as valleys, slopes, and elevated terrains into strategic planning through terraced landscapes, re-naturalised stream systems, and large-scale afforestation to increase territorial resilience and landscape stability.

³⁶ World Bank, *A Catalogue of Nature Based Solutions for Urban Resilience* (World Bank Group, 2021).

- *City-scale climate regulation and environmental performance:* expanding urban forests, large parks, and continuous canopy systems to mitigate the urban heat island effect, improve air quality, enhance carbon sequestration, and strengthen long-term climate adaptation capacity at the metropolitan level.

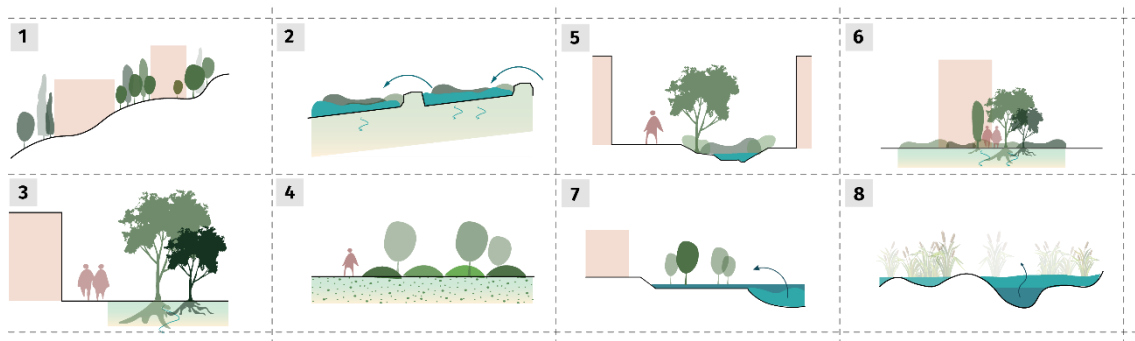


Figure 15- NBS in cities visualization

Author's elaboration based on World Bank, *A Catalogue of Nature-Based Solutions for Urban Resilience*, World Bank Group, 2021, fig.1, p. 10.

1. Urban forest, 2. Terraces and slopes, 3. Stream renaturation, 4. Open green spaces, 5. Green corridors, 6. Urban farming, 7. River floodplain, 8. Natural inland wetlands

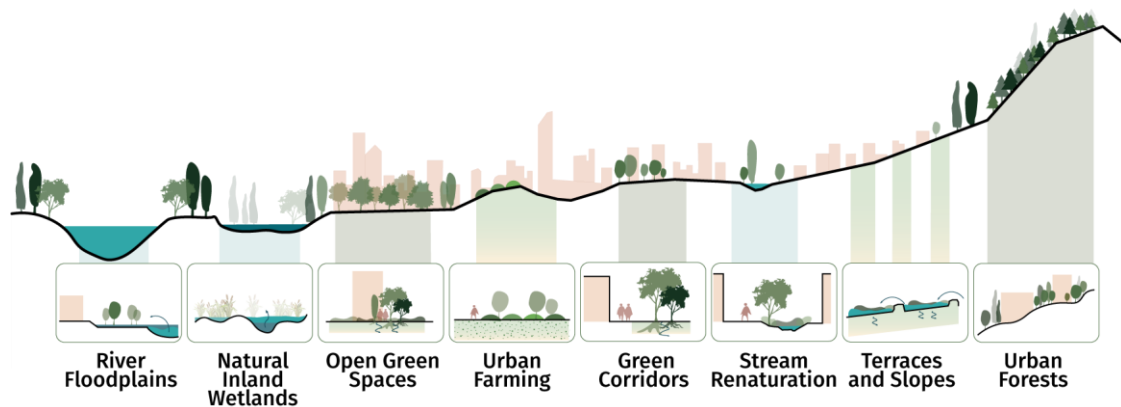


Figure 15- Schematic visualization of Nature-Based Solutions at the city scale.

Author's elaboration based on World Bank, *A Catalogue of Nature-Based Solutions for Urban Resilience*, World Bank Group, 2021, fig. 2-6, p. 24.

1.4.2 The neighborhood scale

At the neighborhood scale, NBS address resilience challenges through highly localized interventions in buildings, streets, and public open spaces. These finer-grained measures function by enhancing stormwater retention and mitigating localized heat islands, thereby building functional clusters of resilience. Their direct benefits include effective rainwater harvesting, the mitigation of air, water, and soil contamination, and the provision of shade to reduce ambient temperatures. Critically, implementing NBS at this scale alleviates pressure on existing grey infrastructure.

A defining feature of neighborhood-level implementation is the necessity of cross-sectoral collaboration. Success depends on forging alliances across the public-private divide, engaging stakeholders including local governments, the private sector, property owners, and resident communities in co-design and stewardship.

Typical NBS applications at this scale include:

- *Building-integrated systems*, such as green roofs, vegetated façades, and private gardens, which synergize with green streets to regulate temperature and store water.

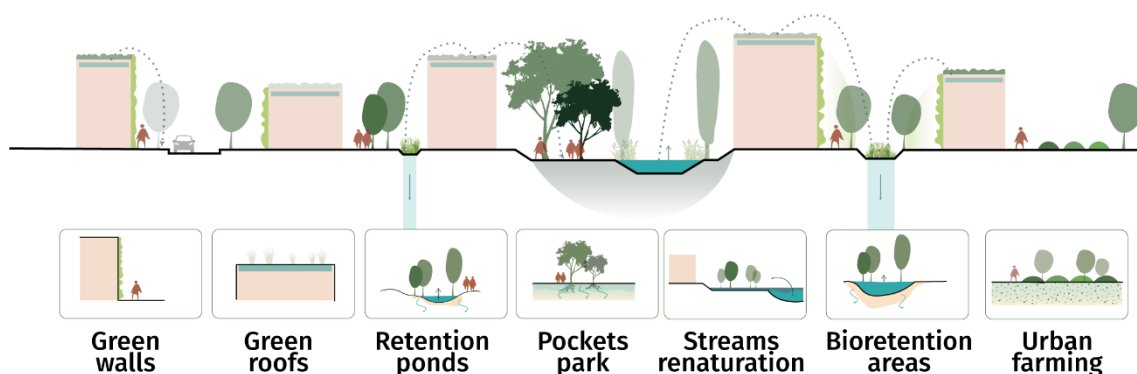


Figure 16 - Schematic visualization of Nature-Based Solutions at the neighbourhood scale.
 Author's elaboration based on World Bank, *A Catalogue of Nature-Based Solutions for Urban Resilience*,
 World Bank Group, 2021, fig. 2-7, p. 25.

- *Pocket parks and everyday green spaces*, small-scale green spaces embedded within residential blocks that provide accessible recreational areas, enhance mental well-being, improve microclimatic comfort, and strengthen neighborhood identity and social cohesion.
- *Tree-shaded streets and active mobility corridors*, street-level NBS integrating vegetation, permeable materials, and shading systems to enhance walkability and cycling comfort, reduce thermal stress, improve environmental quality, and support daily sustainable mobility patterns.
- *Community gardens and productive landscapes*: local food-producing spaces that reconnect residents with nature and food systems, foster social inclusion, support biodiversity, and promote multifunctional use of urban land at the neighborhood scale.
- *Decentralized water retention features*, including retention basins, rainwater ponds, and multi-functional green water squares designed for temporary water storage.
- *Small-scale hydrological interventions*, like bioswales, that manage runoff through filtration and infiltration at the source.

1.4.3 Integrated Systems Approach to NBS

Consequently, the application of NBS in urban settings necessitates an integrated planning approach, grounded in a holistic vision of sustainability.

This systemic methodology for enhancing urban resilience and biodiversity must be context-sensitive, carefully adapted to the specific social, morphological, and political fabric of a given city.

Rather than replacing conventional systems, NBS should function as a complementary tool to strengthen existing risk management frameworks. The objective is not to supersede the ubiquitous 'grey' infrastructure but to work in

synergy with it, thereby creating ‘hybrid’ systems that enhance overall functionality and integrate ecological benefits. This integrative model is essential for embedding NBS into broader urban and territorial planning, risk mitigation, and sustainable maintenance programs.

To optimize their effectiveness, NBS implementation must be guided by a robust understanding of local ecology to ensure scientifically sound outcomes. Equally vital, however, are the socio-collateral benefits: well-designed NBS increase a community’s attractiveness and deliver tangible human well-being. Crucially, the long-term success and longevity of these solutions are inextricably linked to local community support and participatory governance, which ensure ongoing stewardship, maintenance, and the sustained delivery of ecosystem services.³⁷

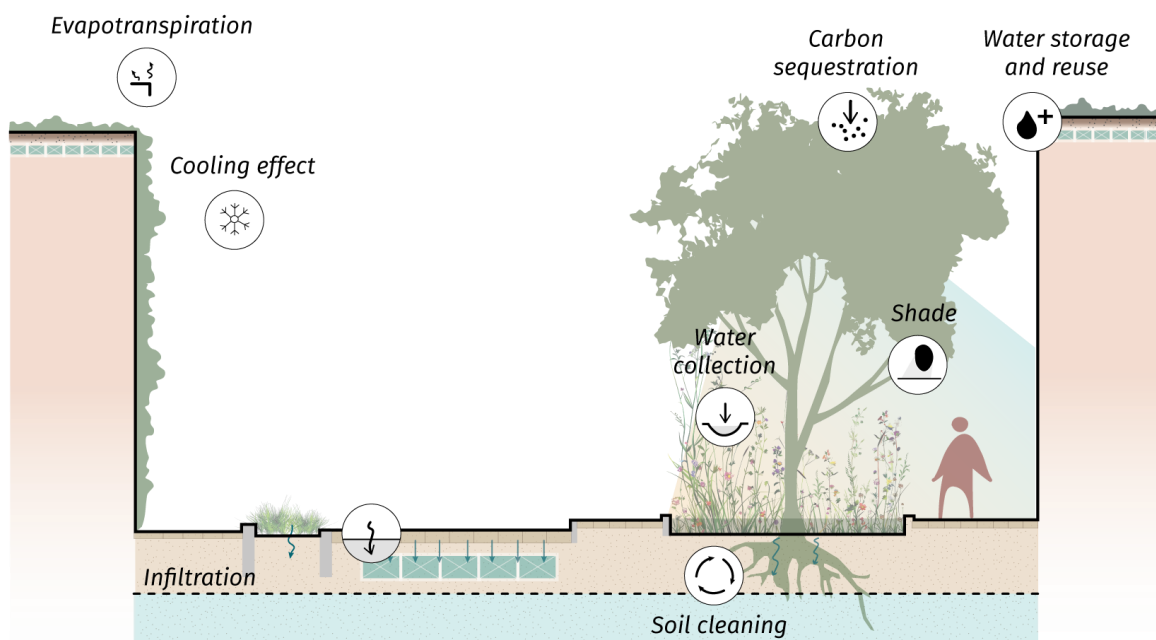


Figure 17 - Example of a hybrid solution integrating green and gray infrastructure
 Author's elaboration based on World Bank, *A Catalogue of Nature-Based Solutions for Urban Resilience*,
 World Bank Group, 2021, fig. 2-2, p. 12.

³⁷ World Bank, *A Catalogue of Nature Based Solutions for Urban Resilience*.

1.4.4 The value proposition of Nature-Based Solutions in urban real estate markets

NBS are fundamentally predicated on the protection, management, and restoration of ecosystems. Within urban contexts, these solutions replicate the function of natural systems, generating a critical flow of ecosystem services that deliver environmental, social, and increasingly, economic value. This economic dimension is of salience to real estate market analysis, where enhancements in environmental quality and neighborhood well-being are frequently capitalized into rising property values. Crucially, this value extends beyond the direct monetary valuation of tangible assets to encompass indirect, option, and non-use values, categories essential for understanding the full contribution of NBS to long-term urban sustainability.

To ground this discussion, consider the implementation of an urban park as a quintessential NBS. As a managed ecosystem integrating vegetation, soil, hydrology, and biodiversity, a park is engineered to address specific urban challenges: climate adaptation, stormwater management, and the promotion of public health and social cohesion. Its establishment generates a suite of interconnected ecosystem services, which can be categorized as follows:

- *Provisioning Services*: these are the tangible, directly utilized outputs, such as recreational space, improved air quality, moderated microclimates, and, in cases incorporating edible landscapes, food production. These services immediately enhance the livability and functional utility of the urban environment for residents.
- *Regulating Services*: these encompass the ecosystem processes that ameliorate environmental conditions. Through evapotranspiration, parks mitigate the urban heat island effect; through infiltration, they manage stormwater and reduce flood risk; and through biological filtration, they improve air quality. These functions collectively elevate environmental

comfort and reduce climate-related vulnerabilities for adjacent neighborhoods.

- *Cultural Services*: this category includes the non-material benefits derived from ecosystem interactions, such as opportunities for recreation, aesthetic enjoyment, mental restoration, and social interaction. Urban parks thereby enhance landscape quality, foster community identity, and contribute to the perceived attractiveness and desirability of residential areas.

The value generated by these ecosystem services is multifaceted. A nuanced economic assessment requires distinguishing between several forms of value:

- *Direct Use Value*: stemming from the immediate, consumptive use of the ecosystem (e.g., walking, sports, leisure). This value is most readily observable in the real estate market, as households demonstrate a willingness to pay a premium for proximate, accessible green space.
- *Indirect Use Value*: derived from the benefits of regulatory functions, such as cooler ambient temperatures, cleaner air, and reduced flood risk. These benefits enhance residential comfort, lower long-term adaptation costs, and are thereby indirectly capitalized into property attractiveness and market value.
- *Option Value*: this represents the value placed on preserving the potential for future use. Property buyers may value the assured permanence of a park as an option for future recreation or as a hedge against environmental risks, thereby increasing the perceived security of their long-term investment.
- *Non-Use Value*: this arises independently of any personal interaction with the ecosystem. It includes **existence value** (the value of knowing the park and its biodiversity are preserved) and **bequest value** (the value of ensuring benefits for future generations). These values, though not

directly traded, contribute to a neighborhood's reputation and long-term societal desirability.³⁸

The translation of these diverse values into market signals is mediated by the economic concept of *externalities*. An externality occurs when an activity, such as the provision of a public park, affects the well-being of third parties without this impact being reflected in market prices or compensated through transaction. The ecosystem services generated by NBS constitute significant *positive externalities*: cleaner air, mitigated flood risk, enhanced microclimate, and improved mental health are benefits enjoyed broadly by the community, not solely by those who directly fund or use the space.

Real estate markets act as a partial mechanism for internalizing these positive externalities, as evidenced by price premiums for properties near high-quality NBS. However, this capitalization is incomplete.

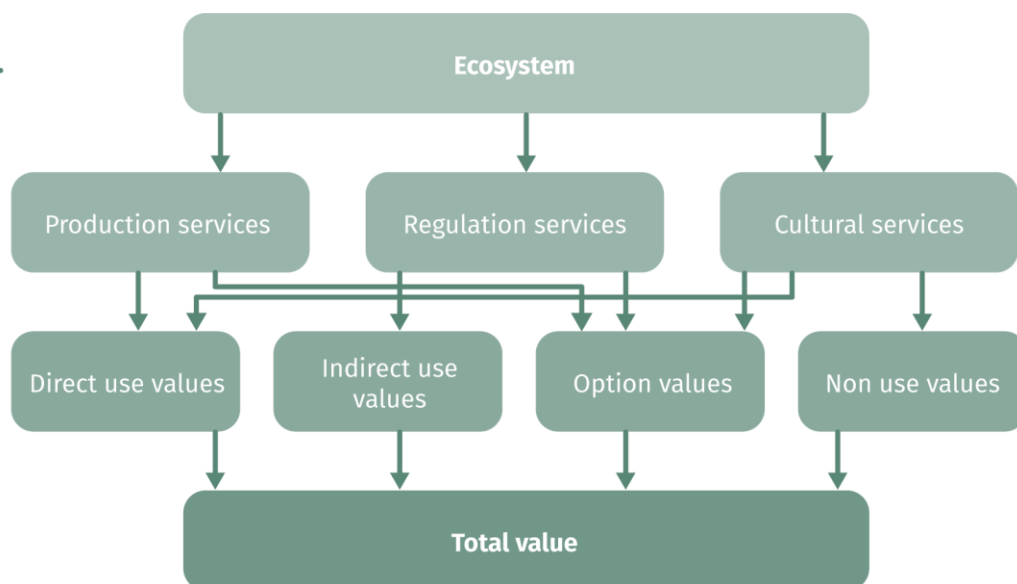


Figure 18 - Connection between ecosystem service types and economic values in value assessments. Author's elaboration based on Hein et al. (2006), cited in Bockarjova and Botzen, *Review of Economic Valuation of Nature-Based Solutions in Urban Areas*, 2017, fig. 1, p. 10.

³⁸ Marija Bockarjova and W. J. Wouter Botzen, *Review of Economic Valuation of Nature Based Solutions in Urban Areas*, 2017, pp. 8-11.

Certain values, particularly non-use values associated with biodiversity conservation and long-term ecological resilience, often remain unpriced in market transactions, despite their fundamental importance to sustainable urban development.

A critical note of caution must be added: the analysis must remain vigilant to the risk of green gentrification, where rising property values can lead to the displacement of vulnerable residents, undermining the social equity goals of sustainable urban development.³⁹

It is this gap between total value creation and market price signals that this thesis seeks to address. Consequently, the primary objective is to develop an evaluation framework that not only deepens the analysis of values reflected in real estate prices but also systematically integrates those that remain unpriced. As elaborated in the following chapters, this necessitates a *multicriteria assessment approach*, designed to holistically capture the full spectrum of environmental, social, and economic factors that constitute value creation through NBS.

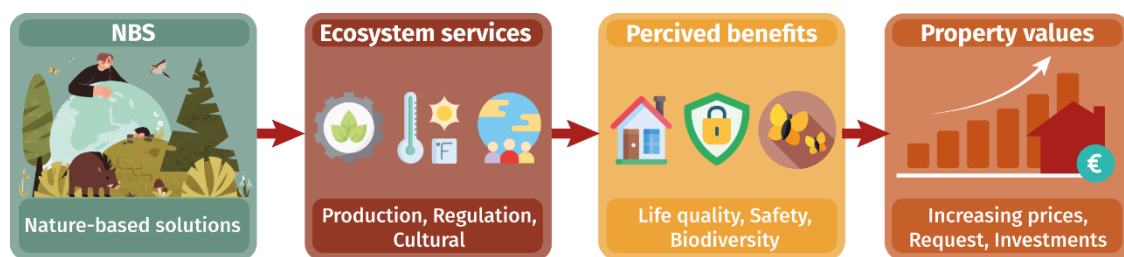
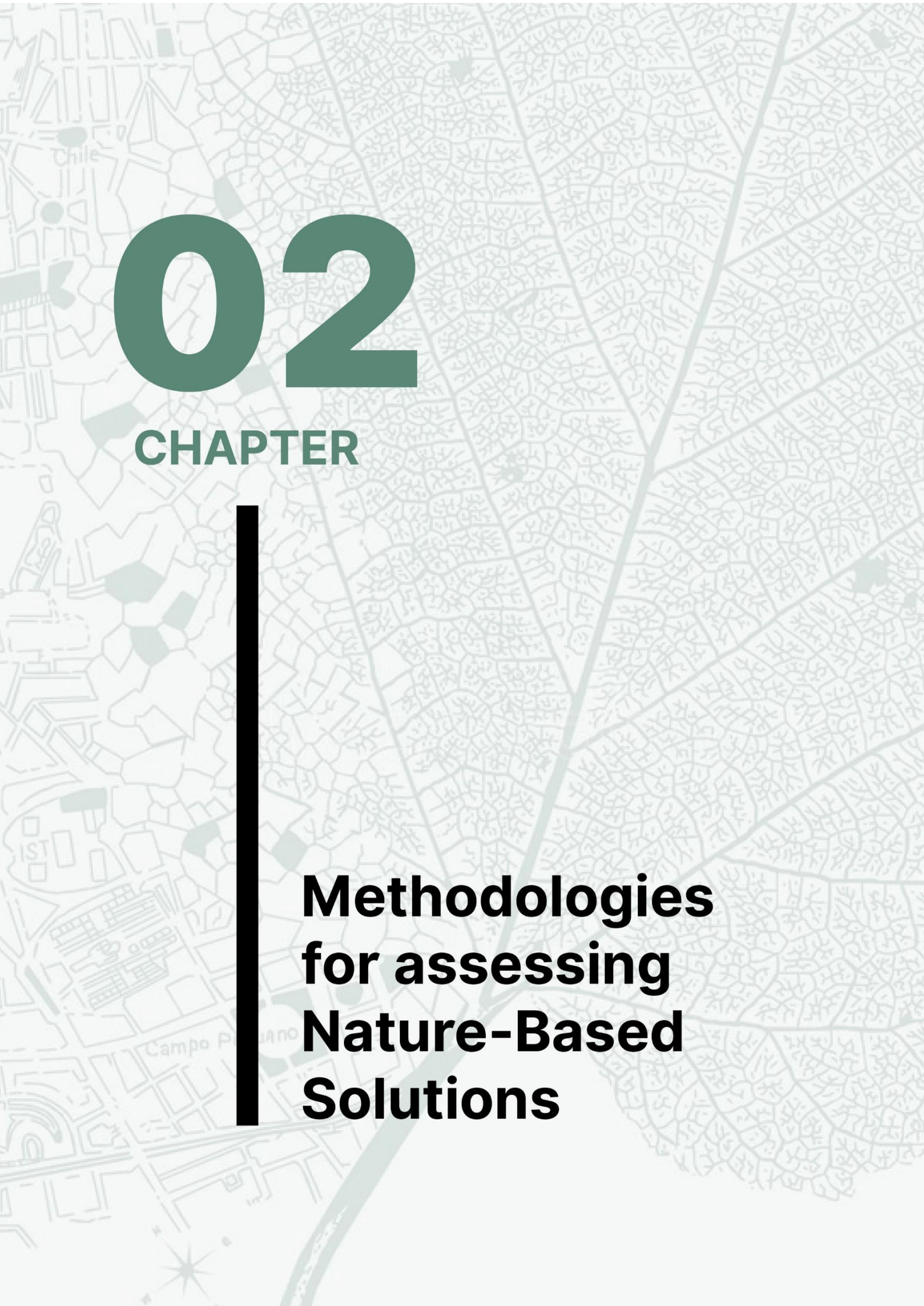


Figure 19 - NBS relation with Real Estate market
Author's elaboration

³⁹ M. Bockarjova et al., "Property Price Effects of Green Interventions in Cities: A Meta-Analysis and Implications for Gentrification," *Environmental Science & Policy* 112 (October 2020): pp. 293–304, <https://doi.org/10.1016/j.envsci.2020.06.024>.



02

CHAPTER



Methodologies for assessing Nature-Based Solutions

2.1. Rationale for evaluating NBS

The rationale for evaluating NBS lies in their capacity to generate multiple environmental, social and economic benefits that are often not directly reflected in market prices.

Similarly to many ecosystem services, NBS generally do not have a direct and explicit market value, since their benefits are not exchanged as standalone goods. Rather, their value is embedded in broader environmental effects, social improvements and economic dynamics, or indirectly reflected in related markets and observable human behaviors.

In this context, the *Total Economic Value (TEV)* framework provides a useful conceptual structure for understanding the overall value of environmental goods and ecosystem services. As outlined by Pearce and Turner,⁴⁰ it distinguishes between use values, related to the direct or indirect benefits derived from ecosystems, and non-use values, which refer to the value attributed to nature regardless of direct use, such as existence or bequest values. The relevance of non-use values is also rooted in Krutilla's contribution,⁴¹ which emphasized that natural resources may hold economic value even when they are preserved rather than directly consumed or used.

However, TEV does not represent a valuation method itself; rather, it defines the range of values that should be considered in the assessment process.

These values must therefore be estimated through specific valuation approaches, which attempt to approximate the economic relevance of NBS despite the absence of explicit market prices. Such approaches may assess, for instance, how proximity to green spaces affects property values, the costs incurred by individuals to access and use urban parks, or the avoided costs

⁴⁰ David W. Pearce and R. Kerry Turner, *Economics of Natural Resources and the Environment*, Baltimore, Johns Hopkins University Press / Harvester Wheatsheaf, 1990.

⁴¹ John V. Krutilla, "Conservation Reconsidered," *The American Economic Review*, vol. 57, no. 4, 1967, pp. 777–786.

associated with flood mitigation, heat reduction or improved environmental quality.

More broadly, they help capture the extent to which NBS influence wider economic activities and contribute to social welfare.

Nevertheless, the reliance on indirect and non-market valuation methods also highlights the need for more comprehensive and integrated assessment frameworks. While monetary valuation can support communication with policymakers and help compare alternative scenarios, it cannot fully capture the multidimensional value of NBS.

For this reason, economic assessment should be integrated with broader environmental and social criteria, allowing NBS to be evaluated not only in terms of monetary benefits, but also in relation to their ecological, spatial and societal impacts.

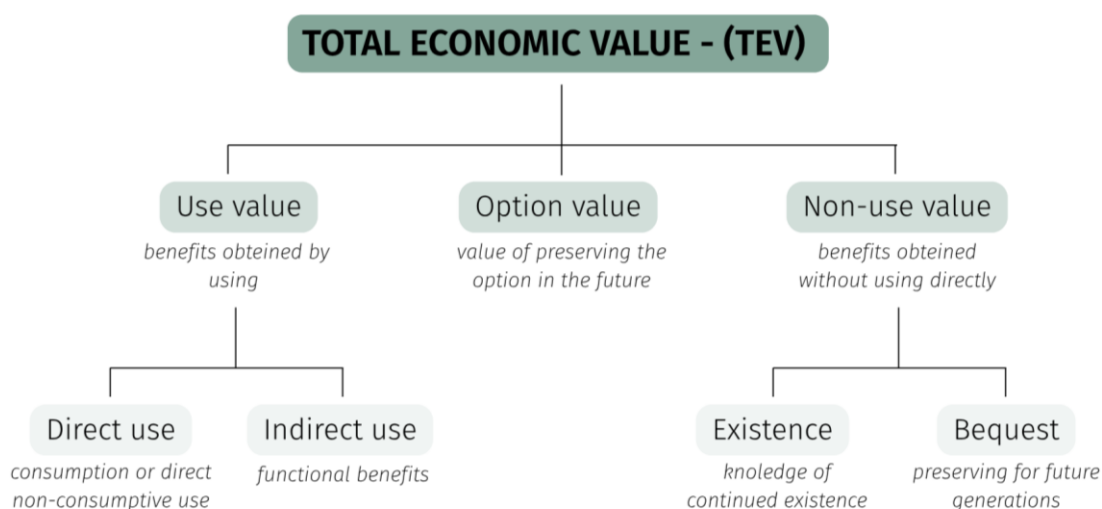


Figure 20 - Total Economic Value (TEV) framework for the valuation of ecosystem services.

Author's elaboration based on Grant et al., "Ecosystem Services of the Southern Ocean: Trade-Offs in Decision-Making," *Antarctic Science* 25, no. 5 (2013): 603–617, fig. 2, p. 609; adapted from Ledoux and Turner (2002), Chee (2004), and Saunders et al. (2010).

2.1.1 Importance of capturing environmental, economic and social benefits

NBS provide multiple and interconnected environmental, economic and social benefits, contributing to the protection, management and restoration of urban ecosystems. Unlike conventional grey infrastructure, whose performance is often assessed through technical efficiency, implementation costs and direct economic returns, NBS operate through the interaction between natural processes and urban systems.

By enhancing blue-green infrastructure networks, they generate a broad range of ecosystem services, including flood mitigation, urban cooling, air quality improvement, biodiversity enhancement, recreation, health and well-being benefits.

Capturing these benefits is essential because many of them are not directly reflected in market prices. Traditional evaluation approaches, including *Cost-benefit analysis* (CBA), tend to be more effective in assessing *quantifiable* and monetizable outcomes, while they often struggle to incorporate *qualitative*, intangible and non-market benefits such as aesthetic value, recreational opportunities, public health improvements, well-being and biodiversity conservation.

As a result, the overall value of NBS may be underestimated, potentially favoring more conventional infrastructure solutions in decision-making processes.

A relevant example of this underestimation is provided by the conversion of a golf course in Virginia Beach, United States, into a multifunctional stormwater park.⁴²

The intervention reduced flood-related structural damages by approximately 50%, while also generating additional co-benefits, including a decrease in air

⁴² Costadone and Zhang, "Integrated Valuation of the Ecological, Social and Economic Benefits Provided by a Multifunctional Nature-Based Solution." (2025) *Nature-Based Solutions* 8 (2025): 100256, p. 1.

temperature of up to 5.6 °C, increased biodiversity and pollinator presence, and a rise in nearby property values of about 2.4%. When these ecosystem services were included in the evaluation, the *Benefit–cost ratio* (BCR), which measures the relationship between project benefits and costs, increased from 1.46 to between 1.6 and 2.1, demonstrating how the exclusion of co-benefits can significantly underestimate the economic viability of NBS.⁴³

Further example is provided by the green cycle belt project in Bruges, Flanders,⁴⁴ a planned green infrastructure investment aimed at connecting the inner city with surrounding municipalities through a cycling route integrated into the landscape.

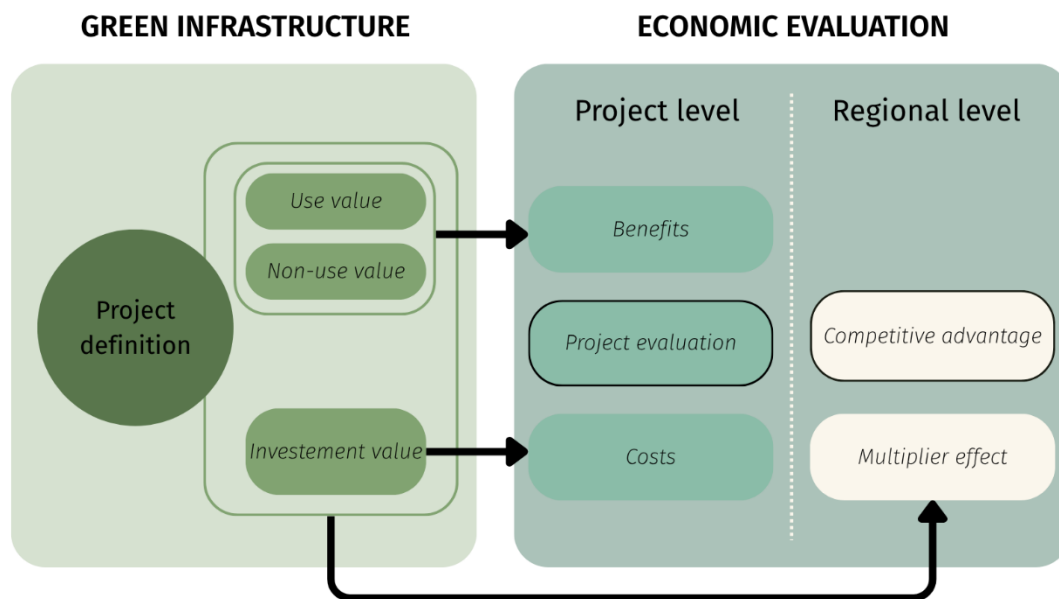


Figure 21 - Conceptual framework for the economic valuation of green infrastructure investments. The framework highlights the relationship between use values, non-use values and investment values, linking project-level cost–benefit evaluation with broader regional economic effects through multiplier analysis.

Author's elaboration based on Vandermeulen et al., "The Use of Economic Valuation to Create Public Support for Green Infrastructure Investments in Urban Areas," *Landscape and Urban Planning* 103, no. 2 (2011): 198–206, fig. 1, p. 199.

⁴³ Costadone and Zhang, "Integrated Valuation of the Ecological, Social and Economic Benefits Provided by a Multifunctional Nature-Based Solution." *Nature-Based Solutions* 8 (2025): 100256, p. 1.

⁴⁴ Valerie Vandermeulen et al., "The Use of Economic Valuation to Create Public Support for Green Infrastructure Investments in Urban Areas," *Landscape and Urban Planning* 103, no. 2 (2011), pp. 198–206, <https://doi.org/10.1016/j.landurbplan.2011.07.010>.

The project was designed not only to improve mobility and recreational accessibility, but also to enhance public health, traffic safety, air quality, and the overall attractiveness of the region.

To capture this broad range of impacts, the evaluation combined the *Total Economic Value (TEV)* framework with *Cost–Benefit Analysis (CBA)* at the project level and *regional economic impact assessment* through multiplier analysis.

A distinctive feature of the approach is the explicit distinction between local project costs and wider regional benefits.

While the CBA assessed whether the direct benefits of the project outweighed its investment and maintenance costs, the regional analysis examined how the investment generated additional economic activity and competitiveness throughout the region. This allowed the evaluation to move beyond a narrow project-based perspective and account for both direct and indirect effects.⁴⁵

The framework incorporated a wide range of value categories, including *direct use values* such as recreation and cycling, *indirect benefits* associated with improved air quality and climate regulation, and *non-use values* linked to ecosystem conservation.

In addition, the analysis considered several co-benefits frequently overlooked in conventional assessments, including avoided costs from reduced car commuting, recreational expenditures, health benefits derived from increased cycling activity, and improvements in traffic safety.

Beyond ecosystem service values, the framework also accounted for the broader economic impacts generated by the investment itself, including construction activities, maintenance expenditures, employment-related benefits, and regional multiplier effects.

⁴⁵ Valerie Vandermeulen et al., “The Use of Economic Valuation to Create Public Support for Green Infrastructure Investments in Urban Areas,” *Landscape and Urban Planning* 103, no. 2 (2011): 198–206.

The case therefore illustrates how integrated valuation methods can provide a more comprehensive representation of the environmental, social, and economic value generated by green infrastructure investments. At the same time, it highlights the role of economic valuation not only as an assessment tool, but also as a communication mechanism capable of making the benefits of NBS more visible and understandable to policymakers, stakeholders, and the wider public, thereby strengthening support for public investment in NBS.

However, the evaluation of NBS should not only focus on aggregate benefits, but also on their distribution across different social groups.⁴⁶ Growing evidence shows that urban greening can generate unintended socio-economic consequences, including *green gentrification*, rising property values, increased living costs and potential displacement of vulnerable communities.⁴⁷

For this reason, comprehensive assessment frameworks should incorporate equity considerations, evaluating not only environmental and economic gains, but also accessibility and affordability.

Therefore, capturing the full value of NBS requires moving beyond narrow evaluation approaches towards more integrated and holistic frameworks.

Such frameworks should be able to assess environmental, economic and social dimensions simultaneously, while also considering long-term impacts, distributional effects and potential trade-offs.

This provides the basis for the following section, which reviews conventional evaluation methods and critically examines their applicability to NBS.

⁴⁶ Marija Bockarjova et al., "Estimating the Social Value of Nature-Based Solutions in European Cities," *Scientific Reports* 12, no. 1 (2022): 19833, p. 6, <https://doi.org/10.1038/s41598-022-23983-3>.

⁴⁷ M. Bockarjova et al., "Property Price Effects of Green Interventions in Cities: A Meta-Analysis and Implications for Gentrification," *Environmental Science & Policy* 112 (2020): 293–304, pp. 293–294, 301–302. <https://doi.org/10.1016/j.envsci.2020.06.024>.

2.2. Conventional evaluation methods

Undertaking monetary valuation of ecosystem services or NBS can serve multiple purposes, and understanding the context in which the valuation is conducted is fundamental.

Typically, valuations are carried out for one or more of the following reasons:

1. **Awareness raising** – to highlight the economic importance of NBS benefits.
2. **Accounting** – to integrate natural capital into national or corporate accounts.
3. **Designing** – to inform the design of NBS interventions and payment schemes.
4. **Calculating economic liability** – to estimate damages or compensation related to ecosystem degradation.
5. **Understanding development dynamics and viability** – to assess whether an NBS is economically sustainable or preferable to alternative solutions.

Consequently, the way co-benefits are framed, synthesized, and integrated becomes centrally important for determining meaningful monetary values. Building on this understanding, the following section provides an overview of conventional evaluation methods for environmental and economic assessment.⁴⁸

⁴⁸ Tom Wild et al., “Valuation of Urban Nature-Based Solutions in Latin American and European Cities,” *Urban Forestry & Urban Greening* 91 (January 2024): 128162, p.2, <https://doi.org/10.1016/j.ufug.2023.128162>.

2.2.1 Overview on conventional evaluation methods for environmental and economic assessment

Several studies in economics value specific items of natural capital like ecosystems, species and resources, however, as above mentioned, in many instances there are no markets for biodiversity or ecosystems services. Therefore, has been necessary to develop other methods to able to measure these non-market values.

Considering that many of additional values of NBS compared to conventional engineered solutions lay in the indirect and non-use values, not including them could lead to serious undervaluation problems.

Within environmental economics, conventional evaluation methods can be divided into three main categories: **Revealed Preference (RP)**, **Stated Preference (SP)**, and **Production Function (PF)**. These approaches differ in terms of the type of data used, the nature of the values they capture, and their degree of applicative complexity.⁴⁹

Revealed Preference methods are based on the observation of actual individual behavior in existing or related markets. The underlying idea is that people's preferences can be indirectly inferred from the choices they make, for example in relation to the costs incurred to access an environmental good or to property prices influenced by environmental characteristics.

Among the most common examples are the *Travel Cost Method*, used to estimate the recreational value of natural areas, and the *Hedonic Pricing Method*, which analyses how environmental attributes (such as air quality or proximity to green spaces) are reflected in property prices.⁵⁰

⁴⁹ Fredrik Carlsson et al., "Valuation of Nature-Based Solutions: Methods, Challenges and Critical Considerations," *Nature-Based Solutions* 8 (December 2025): 100274, pp. 2-3, <https://doi.org/10.1016/j.nbsj.2025.100274>.

⁵⁰ Fredrik Carlsson et al., "Valuation of Nature-Based Solutions: Methods, Challenges and Critical Considerations," *Nature-Based Solutions* 8 (December 2025): 100274, p.3.

However, these methods are limited in that they capture predominantly use values, while neglecting broader dimensions such as existence or option values, not being able to grasp the characteristics which generated the value itself.

To overcome these limitations, *Stated Preference* methods have been developed. These rely on direct surveys through which individuals express their preferences in hypothetical contexts.

In this case, the value is estimated by directly asking individuals about their *Willingness to pay* (WTP) or *Willingness to accept* (WTA) for an environmental change. The two main tools are *Contingent Valuation* (CV), which evaluates a good as a whole, and *Choice Experiments* (CE), which instead allow estimating the value of individual attributes of a good.⁵¹

A fundamental aspect of these methods is their ability to include non-use values, such as the existence value of biodiversity, which cannot be observed through market behavior. Nevertheless, they present critical issues related to the hypothetical nature of the responses, such as the so-called “*hypothetical bias*”, the tendency of individuals to state values different from those they would actually pay in a real context.

Another approach is represented by *Production Function methods* (PFM), which consider the environment as an input within a production process. In this case, the value of an ecosystem service is estimated based on its contribution to the production of marketable goods or services. For example, soil quality or the presence of pollinators can influence agricultural productivity, allowing an indirect economic value to be inferred.

Although this approach is useful for analyzing interactions between the environment and the economy, it requires in-depth knowledge of ecological and production processes, often making it complex to apply.

⁵¹ Fredrik Carlsson et al., “Valuation of Nature-Based Solutions: Methods, Challenges and Critical Considerations,” *Nature-Based Solutions* 8 (December 2025): 100274, p.4.

Overall, each of these methods presents specific strengths and limitations. While Revealed Preference (RP) and Production Function (PF) methods tend to underestimate the total value of ecosystems because they do not include non-use values, Stated Preference (SP) methods, although more comprehensive, raise methodological questions regarding the validity of stated preferences.⁵²

Furthermore, most empirical studies focus on specific components of value, thus providing partial estimates that can hardly be aggregated without the risk of overall overestimation or underestimation.

In light of these critical issues, the need emerges for more integrated and multidimensional approaches capable of simultaneously considering the different value components generated by NBS.

Approach	Basic principle	Common methods	Type of value captured
Revealed Preference	Value is inferred from actual behaviours in existing or related markets	• Travel Cost Method • Hedonic Pricing Method	Mainly use values , such as recreation, accessibility, property value effects, proximity to green spaces.
Stated Preference	Value is estimated through surveys in hypothetical scenarios	• Contingent Valuation • Choice Experiments	Use and non-use values , including WTP/ WTA for conservation, biodiversity, landscape quality or environmental improvement.
Production Function	Ecosystem services are valued according to their contribution to production processes	• Agricultural productivity models • Pollination value; water regulation effects on production	Mainly indirect use values , where nature acts as an input to marketable goods or services.

Table 2 - Summary of traditional methods used to evaluate NBS

⁵² Fredrik Carlsson et al., "Valuation of Nature-Based Solutions: Methods, Challenges and Critical Considerations," Nature-Based Solutions 8 (December 2025): 100274, pp. 5-7

2.2.2 Limitations in addressing non-market and social benefits

The inclusion of variables not directly related to monetary costs in the evaluation of NBS – and, more broadly, of ecosystem services – represents a crucial step toward achieving a more comprehensive and nuanced assessment of their value.

Such variables allow for the consideration of benefits that are often generated by these interventions yet frequently overlooked by conventional economic evaluation methods.

However, the limited inclusion of these aspects is not solely attributable to negligence on the part of evaluators, but rather to a series of structural challenges.

As highlighted in CHAPTER 1, one of the main issues is the **lack of a shared evaluation framework**, which leads to the development of heterogeneous methodologies that are highly *context-dependent*. Consequently, the economic tools employed vary significantly across studies and are often difficult to compare.

For instance, the European Commission handbook framework (see 1.2.2 *Regulatory frameworks*) identifies only two sub-categories economic themes; “*place regeneration*” and “*economic opportunities & green jobs*”.⁵³ These are not sufficiently exhaustive and would benefit from revision or further complementarity to better capture the full range of non-market and social benefits.⁵⁴

In this context, it is also possible to observe a **lack of studies capable of effectively supporting the evaluation of small-scale interventions**.

⁵³ European Commission, *Evaluating the Impact of Nature-Based Solutions*, pp.117-118.

⁵⁴ Wild et al., “Valuation of Urban Nature-Based Solutions in Latin American and European Cities.” *Urban Forestry & Urban Greening* 91 (2024): 128162, p. 2, <https://doi.org/10.1016/j.ufug.2023.128162>

A significant portion of recent research focuses primarily on large-scale projects, such as the regeneration of extensive urban areas or entire neighborhoods.

While these studies may provide a useful basis for applying methods such as *benefit transfer*, which relies on the adaptation of indicators and coefficients derived from similar baseline scenarios, their applicability becomes limited within dense urban contexts.

This limitation is particularly evident in European historical city centers, which are often among the areas most affected by the Urban Heat Island effect (UHI). Due to their compact and densely built urban fabric, these contexts generally offer limited available space for large interventions.

Consequently, opportunities for implementation are frequently fragmented and dispersed, making small-scale solutions such as pocket parks, tree-lined streets, green roofs, and other micro-interventions the most feasible and realistic options.⁵⁵

As a result, there is a significant **lack of representative case studies** addressing the performance and evaluation of these smaller and more localized NBS interventions. This further reduces the **transferability** and **comparability** of existing assessment methodologies, increasing the difficulty of defining standardized evaluation frameworks applicable to dense urban environments.

Furthermore, the role of economic indicators; used to monetize the environmental, social, and economic impacts, and to support decision-making, varies significantly depending on local, political, institutional, and socio-economic contexts. The **type of funding**, whether public (e.g., European PNRR) or private (e.g., bank loans or donor contributions), also influences the strategies

⁵⁵ Cf. Marija Bockarjova et al., “Estimating the Social Value of Nature-Based Solutions in European Cities,” *Scientific Reports* 12, no. 1 (2022): 19833, pp. 1-2 <https://doi.org/10.1038/s41598-022-23983-3>.

applied, highlighting how context-specific conditions shape both the design and assessment of NBS interventions.⁵⁶

Given the significant influence of local, political, institutional, and socio-economic conditions on the choice and application of economic indicators, the situation may sometimes take a different turn. Due to the generally poor assessment of NBS impacts, both in terms of systematic flaws and indicators lacking relevance, innovative accounting approaches may be proposed to capture all benefits, including non-market values.

While these methods can be theoretically robust, their implementation may require substantial investments, new regulations, or complex economic planning processes, which are not yet feasible in many local contexts. NBS multifunctionality can lead to onerous evaluations and impractical data gathering making its positive aspect the most difficult to evaluate.⁵⁷

As a result, a **mismatch** may occur: the growing body of complex research evidence, capable of addressing multidimensional complexity, confronts the **practical limitations of policy decision-making** and local implementation readiness.

Although this discussion stands somewhat separately from the detailed methodological frameworks presented later, understanding these challenges provides important context for the subsequent exploration of the following sections “2.3 Advanced Integrated Approaches – Towards a Holistic Evaluation for NBS”, where more comprehensive and context-sensitive methodologies are introduced.

Beyond the broader constraints related to context, governance, funding and implementation, the assessment of NBS also presents several technical and methodological challenges linked to economic valuation.

⁵⁶ European Commission, *Evaluating the Impact of Nature-Based Solutions*. pp. 6-7.

⁵⁷ European Commission, *Evaluating the Impact of Nature-Based Solutions*. pp. 6-7.

These challenges concern the way benefits are estimated, monetized and compared over time, as well as the assumptions adopted in the evaluation process.

This is particularly important because many NBS benefits are indirect, long-term and not directly reflected in market prices. As a result, their estimated value depends on a series of methodological choices that may significantly affect the reliability, comparability and interpretation of the results.

From an operational perspective, one of the key challenges concerns the definition of the **time horizon**.⁵⁸

As with any project, whether based on traditional grey infrastructure or green infrastructure, the evaluation process requires the prior definition of a temporal framework within which costs and benefits are assessed. This enables the construction of cash flows, the application of appropriate discount rates, and the calculation of economic indicators such as *Net Present Value* (NPV), which represents the difference between discounted benefits and costs over time, and the *Payback Period* (PB), defined as the time required for an investment to recover its initial costs.

In the case of NBS, however, defining an appropriate time horizon becomes particularly complex.

Environmental and social benefits are often assumed to materialize from the earliest stages of the project, which can artificially shorten the estimated payback period and make the intervention appear more economically favorable than it actually is.

In reality, many of the key functions of green infrastructure, such as: air quality improvement, biodiversity enhancement, and pollination capacity, fully develop only in the medium to long term.

⁵⁸ Costadone and Zhang, "Integrated Valuation of the Ecological, Social and Economic Benefits Provided by a Multifunctional Nature-Based Solution." p.10.

During the initial phases, these benefits are inherently limited due to the incomplete growth and maturation of natural components. This temporal mismatch between costs and benefits represents a critical limitation in the evaluation of NBS, highlighting the inadequacy of conventional economic approaches in capturing the dynamic and evolving nature of ecosystem services.

Within the same framework, the selection of an appropriate discount rate is of critical importance. Choosing a discount rate is not merely a financial decision related to risk and portfolio management; it fundamentally shapes how the value of benefits is perceived over time. NBS are typically less immediately remunerative than grey infrastructure, but applying an inappropriate discount rate can significantly bias the assessment of their long-term benefits.

A **low discount rate** assigns future benefits a value close to that of present benefits, thereby emphasizing the long-term impacts of NBS. Conversely, a **high discount rate** gives greater weight to immediate benefits and costs, reducing the present value of benefits that occur in the future.

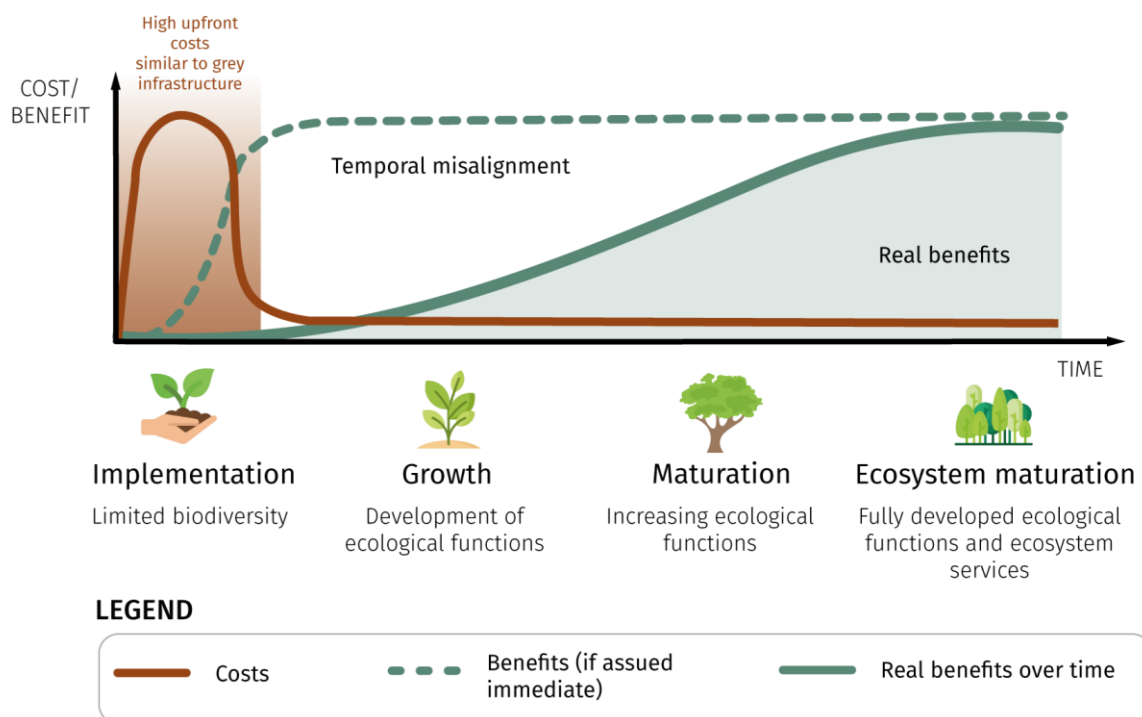


Figure 22 - Temporal misalignment between implementation costs and benefits in Nature-Based Solutions.

Author's elaboration

This consideration becomes even more nuanced when accounting for the socio-economic context, as recommended discount rates vary across countries. For instance, typical ranges used in Cost-Benefit Analysis (CBA) are: Europe 3–8.5%, Asia 4–12%, Latin America 4–6%, North America 2.8–5%, and Africa 3.5%.⁵⁹

Selecting the correct discount rate is thus essential not only for accurate financial evaluation but also for ensuring that the temporal dynamics of ecosystem service benefits are adequately captured, avoiding systematic undervaluation of long-term environmental and social gains.

Double counting is another important issue to consider in the economic evaluation of NBS and Green Infrastructure (GI).

It occurs when the value of a good, service, or benefit is counted more than once within the same evaluation process, leading to an overestimation of the final result. This risk is particularly relevant for NBS, since many of the benefits they generate are closely interconnected. For this reason, evaluating each benefit separately may create overlaps in the estimation process.⁶⁰

The problem of double counting can be found in many of the valuation techniques commonly used for ecosystem interventions, including those discussed in “2.2.1 Overview on conventional evaluation methods for environmental and economic assessment”.

Revealed preference methods – such as *hedonic pricing* and *the travel cost method* – as well as stated preference methods – such as *contingent valuation* – may involve a high risk of overlap when combined within the same multi-method assessment. These techniques are widely used because they are

⁵⁹ Alessia Chelli et al., “Cost-Benefit Analysis of Urban Nature-Based Solutions: A Systematic Review of Approaches and Scales with a Focus on Benefit Valuation,” *Ecosystem Services* 71 (February 2025): 101684, p.7, <https://doi.org/10.1016/j.ecoser.2024.101684>.

⁶⁰ Alexander Whitehouse, “Common Economic Oversights in Green Infrastructure Valuation,” *Landscape Research* 42, no. 2 (2017): 230–34, <https://doi.org/10.1080/01426397.2016.1228860>.

effective in capturing the broad value of NBS. However, difficulties arise when they are used to isolate single benefits that are already included in other estimated values.

A clear example is provided by the *hedonic pricing method*. In the context of NBS evaluation, this method can be used to estimate the value of proximity to an intervention through changes in surrounding property prices.

Property values near green infrastructure often increase because of a combination of benefits associated with the intervention. These may include attractive green views, cleaner air, noise reduction, recreational opportunities, and improvements in physical and mental health. If one attempts to estimate only one of these elements separately, such as green views, part of the measured value may already incorporate the contribution of the other benefits. If those same benefits are then evaluated again through additional methods within the same assessment framework, the risk of double counting becomes very high. For this reason, careful selection of indicators and a clear distinction between different categories of benefits are essential when designing comprehensive evaluation frameworks for NBS.

Another important factor that may hinder the reliability of an evaluation concerns the distinction between the concepts of **economic impact** and **economic value**.⁶¹

Although this distinction is fundamental from a methodological perspective, it is only rarely explored in the literature and even less frequently recognized within commonly used evaluation toolkits.

Economic impact refers to the observable effects that an event, policy, or intervention generates within the economy. It is generally measured through tangible changes in economic indicators such as revenues, value added, profits,

⁶¹ Whitehouse, "Common Economic Oversights in Green Infrastructure Valuation." (2016), pp. 231-232

wages, employment, or property prices. These are therefore concrete and quantifiable effects that can be directly observed within the economic system.

Economic value, by contrast, expresses in monetary terms the overall appreciation that individuals attribute to an event, policy, or intervention. It is often estimated through measures such as willingness to pay (WTP), namely the amount individuals are willing to pay to obtain or preserve a specific good or service.⁶²

Unlike economic impact, economic value also includes intangible dimensions such as personal satisfaction, aesthetic enjoyment, sense of community, or the cultural and symbolic importance of a place or experience.

Although the two concepts may partially overlap, they should not be treated as additive measures. Perceived value is often influenced by expectations regarding economic outcomes, but individuals may have incomplete, limited, or even inaccurate knowledge of the actual economic effects generated by an intervention. As a result, stated valuations do not necessarily correspond to real economic impacts.

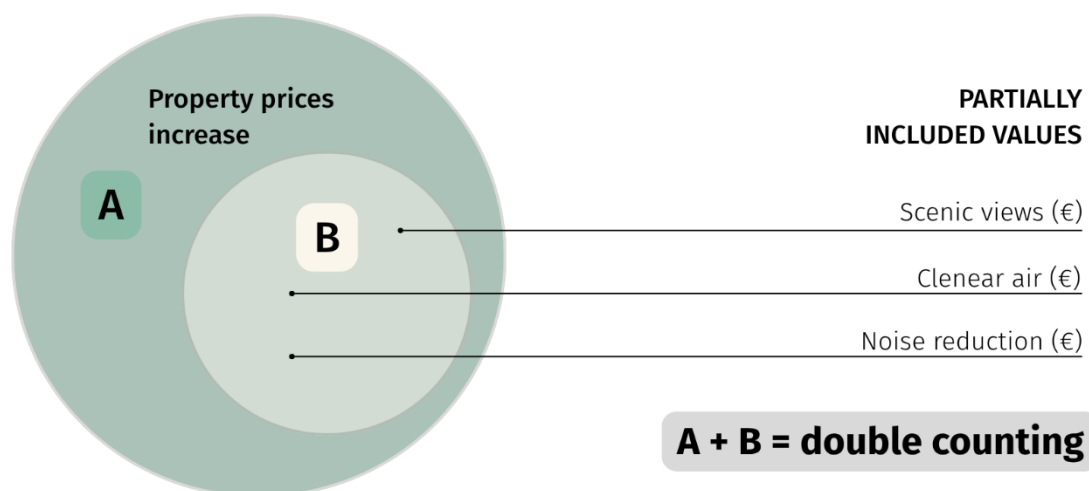


Figure 23 -Simplified representation of double counting risk in NBS valuation
Author's elaboration

⁶² Whitehouse, "Common Economic Oversights in Green Infrastructure Valuation." (2016), pp. 231-232

At the same time, many components of economic value, particularly cultural, aesthetic, and social dimensions, do not produce directly observable effects on standard economic indicators.

For this reason, evaluation toolkits should clearly distinguish between these two macro-dimensions and classify indicators accordingly, rather than aggregating them into a single measure. Summing economic impacts and economic values may lead to misleading results, as it would suggest that all estimated benefits translate into measurable economic outcomes, while part of them instead represent intangible non-market benefits that are not directly reflected in market transactions.

Another important issue that may arise when designing evaluation methods that include non-market values is **additionality**.⁶³

This concept highlights that it is not sufficient to estimate the value generated by NBS alone; rather, it is necessary to assess whether the benefits provided by the intervention represent a genuine improvement compared with the conditions already existing in the surrounding area. The underlying principle is that any intervention should be evaluated in relation to a *baseline scenario*,

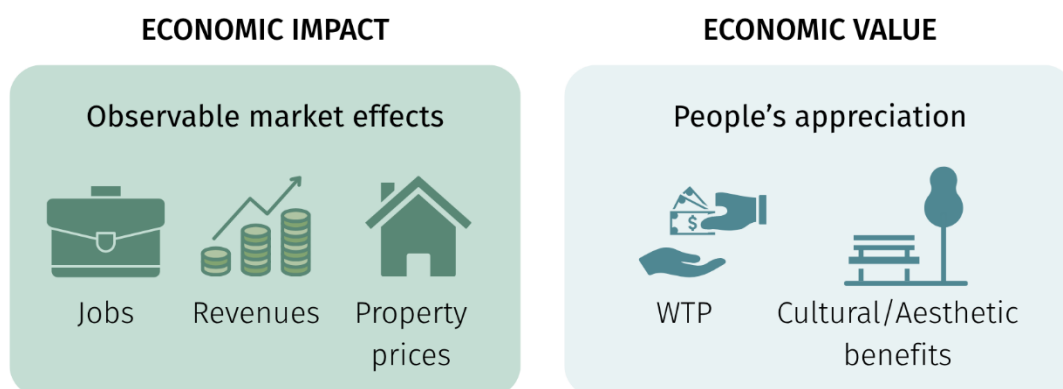


Figure 24 - Distinction between economic impact and economic value in the assessment of Nature-Based Solutions
Author's elaboration

⁶³ Whitehouse, "Common Economic Oversights in Green Infrastructure Valuation." (2016), pp. 232-233.

namely the pre-existing context in which the project is implemented. This requires an assessment of which ecosystem services are already available, whether green spaces are already present, and how many residents currently benefit from parks, trees, cleaner air, shading, or recreational areas.

Through this perspective, it becomes possible to distinguish between projects with high additionality and those with low additionality. *High additionality* typically characterizes areas where the baseline scenario differs substantially from the expected post-intervention condition.

HIGH ADDITIONALITY

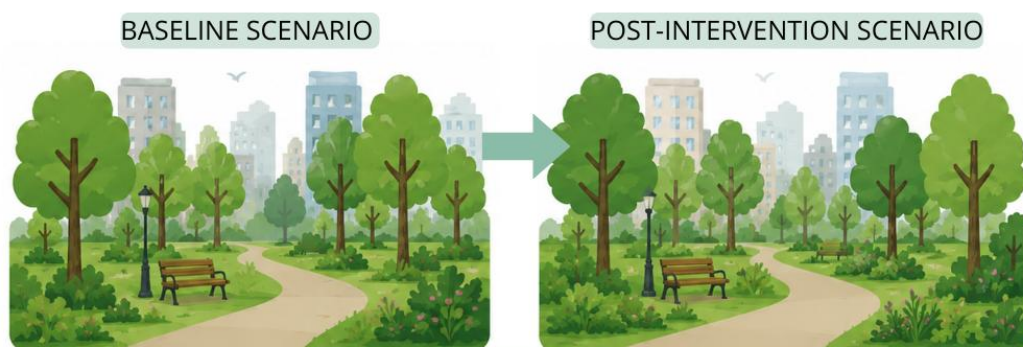
Large gap between baseline and post-intervention scenario



The population perceives and benefits from a significant improvement in quality of life

LOW ADDITIONALITY

Small gap between baseline and post-intervention scenario



New users may be people who shift from existing parks, not new beneficiaries overall.

Figure 25 - Illustration of high and low additionality in Nature-Based Solutions
Author's elaboration

For example, densely populated neighborhoods dominated by asphalt surfaces, with limited vegetation and scarce access to green amenities. In such contexts, the benefits generated by the intervention are likely to be highly valued and widely experienced by the local population. By contrast, *low additionality* refers to areas where parks, gardens, tree-lined streets, and other green amenities are already abundant. In these cases, the introduction of further green infrastructure may still generate benefits, but their marginal value is likely to be lower.⁶⁴

New users may not represent additional beneficiaries overall, but rather individuals shifting from older parks or existing green areas to the newly created one.

This situation is closely linked to the concept of *displacement*, which occurs when a new intervention does not create substantial new benefits, but simply reallocates demand from an existing resource to a new one. In such cases, the project may redistribute the use of green amenities rather than increase total welfare.

The concept of additionality is further complicated by the spatial scale of benefits. Some ecosystem services, such as carbon sequestration, generate benefits at a global level by contributing to climate change mitigation. Others, such as air pollution removal or urban cooling, produce more localized effects. For instance, a tree planted along a highly trafficked road may create greater value than one located in an area where air quality is already good. In this context, monetizing benefits without considering or adjusting for additionality may lead to the estimation of gross figures rather than genuine net benefits, often resulting in overestimated values.

⁶⁴ Whitehouse, "Common Economic Oversights in Green Infrastructure Valuation." (2016), pp. 232-233.

For this reason, careful consideration of baseline conditions and project location is essential when evaluating the real contribution of NBS interventions.⁶⁰

Taken together, the issues discussed above – namely, the definition of an appropriate time horizon, the risk of double counting, the confusion between economic impact and economic value, and the challenge of additionality – reveal significant limitations inherent in many conventional evaluation frameworks applied to NBS.

These limitations not only hinder the comparability and reliability of economic assessments but also risk undermining the credibility of NBS as viable investment options.

In light of these criticalities, a systematic synthesis of existing methodologies and an explicit identification of the most pressing research gaps become essential. This is precisely the objective of the next section, which aims to consolidate the findings presented so far and to outline the directions where further theoretical and empirical work is most urgently needed.

2.2.3 Synthesis and identification of research gaps

The previous sections have shown that evaluating NBS requires approaches capable of capturing a wide range of environmental, economic, and social benefits, many of which are not directly reflected in market prices.

Although the Total Economic Value framework helps conceptualize the different components of value, these dimensions must be estimated using specific valuation methods. Conventional approaches, such as revealed preference, stated preference, and production function methods, provide useful tools for approximating the economic relevance of ecosystem services and NBS benefits. However, each method captures only part of the total value and presents specific limitations related to data availability, applicability, methodological robustness, and the inclusion of non-use or intangible benefits.

Thus, while monetary valuation remains important for supporting decision-making and comparing alternative scenarios, it is not sufficient on its own to fully represent the multidimensional contribution of NBS. This highlights the need to integrate economic assessment with broader environmental, spatial, and social criteria, particularly when evaluating interventions in complex urban contexts.

Nevertheless, despite the increasing volume of research, several critical limitations and methodological challenges continue to emerge when moving from the theoretical recognition of NBS benefits to their practical assessment.

One of the most recurrent issues concerns the absence of shared and standardized evaluation frameworks for NBS. Much of the existing literature remains highly heterogeneous and fragmented, with studies often developed on the basis of context-specific assumptions and methodologies, lacking a common analytical structure or coherent methodological foundation.

In the before mentioned Restoration Law (*see 1.2.1 Chronological evolution*), so the only binding law directly using NBS as practical tool, during the proposal

was highlighted that the monetization of NBS impact remained problematic, due to underestimation of the value of co-benefits.⁶⁵

This fragmentation, combined with the intrinsic complexity and multidimensional nature of NBS, significantly increases the risk of methodological inconsistencies and potential distortions in evaluation processes.

Moreover, despite substantial research dedicated to the development of Nature-Based Solution (NBS) valuation methods, significant gaps remain concerning their practical implementation in urban contexts. In particular, urban-scale and small-scale practical applications remain comparatively underexplored in the literature, as information costs associated with valuations become greater as spatial resolution increases.

This challenge is further amplified in urban settings, where land use and ownership patterns are more fragmented than in other contexts.

Consequently, skepticism persists among local governments and stakeholders regarding both the application of NBS and the use of associated evaluation tools, and this area continues to be largely underexplored.

The complexity with which some methods are described often renders them difficult (if not impossible) to apply in real-world policy and governance settings. These limitations underscore the need for targeted policies to support NBS investment, particularly for retrofitted interventions in existing urban areas.

Moreover, they further exacerbate knowledge gaps at both the micro-scale, among stakeholders within individual cities, and the macro-scale, across different urban areas.

⁶⁵ Wild et al., "Valuation of Urban Nature-Based Solutions in Latin American and European Cities.", p.2.

Such insufficient knowledge exchange ultimately hinders the effective integration of NBS into urban planning and decision-making processes limiting also investment by private financiers.

Beyond theoretical limitations, several systemic errors can arise in practice.

First of all, data availability in urban contexts remains limited, and the quality of available data is sometimes inconsistent. In addition, several systemic issues may arise in practice.

These include, for instance, double-counting phenomena, where the same benefit is unintentionally considered multiple times across different indicators, as well as the adoption of excessively optimistic time horizons, which can artificially inflate the perceived profitability of interventions.

Similarly, insufficient attention to additionality and inadequate analysis of baseline conditions can lead to overestimations of the actual benefits generated by projects, particularly in contexts where ecosystem services or green infrastructures are already partially present.

Another major limitation concerns the inadequate integration of non-market dimensions, particularly environmental and social values, which are closely linked to broader concepts such as equity and sustainability. In many cases, these dimensions remain separate from the economic sphere and are treated as secondary or complementary aspects rather than as integral components of the evaluation process. This issue is partly related to the persistent methodological difficulty in distinguishing between economic impact and economic value, but also to the tendency of conventional approaches to prioritize measurable and monetizable indicators.

However, two opposite yet equally problematic situations can arise.

On the one hand, environmental and social dimensions may be excessively monetized, commodified, or financialized, reducing their intrinsic complexity to simplified financial assets or market-equivalent values.

On the other hand, valuation methods may be so sophisticated that they succeed in capturing non-use values but become too complex to apply in real-world urban contexts. If the first approach risks neglecting localized and context-dependent values by excessive monetization, the second does so by overcomplicating the valuation process; yet both ultimately fail to capture the relational and context-dependent nature of ecosystem services and urban environments.

Consequently, the literature reveals a substantial lack of approaches capable of effectively balancing and integrating both quantitative and qualitative variables within the same assessment framework. While *quantitative* indicators are generally easier to standardize and measure through economic formulas and performance metrics, *qualitative* dimensions – such as well-being, social cohesion, accessibility, perceived environmental quality, equity considerations, preferences, and levels of public satisfaction – remain more difficult to operationalize and are therefore frequently underrepresented in conventional evaluation models.

Furthermore, existing evaluations predominantly focus on large-scale interventions, often involving extensive urban regeneration projects or newly developed green infrastructures. This tendency is likely associated with the greater predictability and controllability of costs, implementation conditions, and expected outcomes characterizing large-scale projects, compared to the uncertainty typically associated with fragmented and localized urban regeneration initiatives.

This consideration leads to two closely interconnected implications.

First, it directly supports one of the main motivations underlying this thesis: the attempt to investigate and evaluate the impacts of small-scale and micro-interventions in dense urban environments characterized by compact urban fabrics, limited spatial availability, and highly fragmented opportunities for intervention. Such contexts, particularly common in European historical city

centres, remain significantly underexplored in the current literature, despite representing some of the urban areas most exposed to environmental and climate-related challenges.

Secondly, the strong context dependency of existing methodologies considerably limits the transferability and comparability of results across different urban settings.

Since many studies rely on highly specific assumptions, indicators, and local conditions, applying existing evaluation methods to other urban environments becomes particularly complex. As a result, the current literature still lacks sufficiently flexible, integrated, and adaptable frameworks capable of supporting decision-making processes across heterogeneous urban scenarios.

In addition to practical and methodological limitations, conceptual critiques point to further research gaps in the economic evaluation of NBS.

Existing approaches often attempt to monetize non-traded goods using market proxies, which results in a limited understanding of the relationship between changes in environmental goods and societal welfare. Quantitative indicators are relatively easy to estimate through existing methods, whereas qualitative data remain more difficult to rationalize within conventional valuation frameworks.

Moreover, economic evaluation may unintentionally financialize natural assets or exacerbate environmental injustices, such as through green gentrification. These gaps underscore the importance of considering NBS not only from a human-centered perspective but also from an *ecocentric* viewpoint, which remains underexplored in current literature.⁶⁵

Taken together, these research gaps highlight the need to move beyond conventional and fragmented evaluation approaches towards more integrated, multidimensional, and context-sensitive assessment frameworks. From this perspective, multi-criteria methodologies certainly represent a promising

direction, for they explicitly allow the simultaneous consideration of heterogeneous environmental, economic, and social variables, while also better accommodating the complexity, uncertainty, and spatial specificity that typically characterize urban NBS.

Hence, economic evaluation should always be used in conjunction with other forms of data and, more generally, within a broader conception of value. In this sense, economic methods properly have a place “alongside” rather than “instead of” other forms of impact assessment.

Finally, this thesis aims to contribute precisely in this direction by exploring whether such methodologies can be effectively adapted to the still under-researched context of small-scale interventions, thereby systematically addressing the fragmentation, context dependency, and methodological imbalances widely identified in the literature.

2.3. Advanced integrated approaches - towards a holistic evaluation for NBS

Building upon the limitations of conventional methods discussed above, a growing number of innovative integrated approaches have emerged in recent years. These have sought, in an experimental manner, to address the biases associated with purely economic market-based evaluations, as well as the difficulties in capturing non-market values and the research gaps previously identified. Methods such as *Life Cycle Costing* (LCC), *Cost-Effectiveness Analysis* (CEA), and *Cost-Benefit Analysis* (CBA) already introduce something more.

LCC (ISO 15686-5:2017)⁶⁶, for instance, still accounts for costs in monetary terms like traditional methods, but it does so over a longer lifespan, the so called “*life-cycle*”, capturing well beyond conventional time horizons.

CEA, on the other hand, works as a ratio, between monetary and non-monetary indicators. Still considers economic costs, yet it introduces physical and social variables using non-monetary units – such as tons of CO₂ sequestered or square meters of green space; thereby including dimensions that pure economic metrics tend to miss.

CBA continues to monetize benefits in economic terms, but it explicitly attempts to go beyond private benefits by evaluating and monetizing also non-private ones, including social and environmental externalities.

Without needing to dive into a full discussion here, these approaches already point towards a more holistic evaluation framework for NBS, while inevitably coming with their own strengths and weaknesses. Importantly, these techniques can be employed to evaluate investment alternatives both across different NBS options and in comparisons between NBS and conventional grey infrastructure.

⁶⁶ International Organization for Standardization, ISO 15686-5:2017, Buildings and Constructed Assets — Service Life Planning — Part 5: Life-Cycle Costing, Geneva, ISO, 2017.

2.3.1 Integrated valuation of public, social and private benefits

The multidimensional nature of NBS benefits discussed in the previous chapter, advanced evaluation approaches increasingly focus on how such benefits can be integrated within more comprehensive assessment processes.

The main challenge is not only to identify environmental, social and economic impacts, but also to translate them into comparable, transparent and decision-relevant evaluation criteria. This requires moving beyond isolated valuation techniques towards approaches capable of combining different forms of evidence, including monetary estimates, qualitative indicators, spatial data and stakeholder preferences.

In this perspective, advanced approaches do not necessarily replace conventional valuation methods but rather adapt and combine them in order to better reflect the complexity of NBS.

Methods such as willingness-to-pay approaches, Cost-Benefit Analysis can therefore be reconsidered as complementary components of broader evaluation frameworks, where different dimensions of value are assessed together rather than separately.

2.3.2 The role of Cost-Benefit Analysis (CBA) in integrated NBS valuation

Cost-Benefit Analysis is one of the most frequently applied techniques for evaluating Ecosystem Services and NBS.

It is a widely used evaluation method that compares the costs and benefits of a project over a defined time horizon, typically by converting them into monetary terms and discounting future values to their present equivalent. In this way, CBA helps determine whether an intervention is economically convenient by assessing whether its expected benefits outweigh its costs.

This central role is largely due to the ability of CBA to translate heterogeneous project effects into a common economic language, making the results relatively accessible to decision-makers, investors and public authorities. For this reason, CBA is frequently used as a *standalone tool* to assess the economic feasibility of an intervention.

However, in the context of NBS, its relevance also depends on its capacity to function as a core component of broader integrated evaluation frameworks. Since NBS generate multiple environmental, social and economic impacts, many of which are not directly monetizable, CBA can be strengthened when combined with complementary approaches, such as non-market valuation methods, willingness-to-pay assessments, social impact evaluation and Multi-Criteria Decision Analysis. In this sense, CBA should not be interpreted only as an isolated method, but also as an economic backbone that can support more comprehensive and multidimensional assessment processes.

According to Chelli et al.,⁶⁷ within the context of environmental projects, a substantial distinction must be made between *private CBA* and *social CBA*. The main difference lies in the perspective adopted.

⁶⁷ Alessia Chelli, Luke Brander and Davide Geneletti, "Cost-Benefit Analysis of Urban Nature-Based Solutions: A Systematic Review of Approaches and Scales with a Focus on Benefit Valuation," *Ecosystem Services* 71 (2025): 101684, pp. 2-3.
<https://doi.org/10.1016/j.ecoser.2024.101684>

Private CBA assesses the economic viability of a project from the investor's point of view, considering only the costs and benefits that they directly incur. This approach is particularly useful for evaluating NBS on private properties, such as the installation of green facades or green roofs, as it can assess the direct profitability for the investor.

Social CBA, on the other hand, includes in the analysis costs and benefits that affect society, and is typically applied to public policies and investments to evaluate their overall impact on the community. It goes beyond mere financial feasibility by also considering the broader environmental and social welfare implications.

These types of evaluations are particularly important because they allow for assessment to be conducted both *ex-ante* – estimating costs, benefits, impacts, and overall convenience before an intervention is carried out – and *ex-post* – quantifying the actual effects produced after implementation and comparing them with predicted outcomes. The latter, in particular, becomes a vital asset for future projects, as it provides empirical data and valuable insights derived from real-world applications.

Of course, the level of complexity in performing the analysis rises considerably, due to the need to identify the groups within society that potentially benefit from or incur costs related to NBS. In addition, both positive externalities – such as recreational opportunities, health improvements, and CO₂ sequestration – and negative externalities – such as pollution emissions, ecosystem losses, and gentrification – must be considered.⁶⁸

⁶⁸ Alessia Chelli, Luke Brander and Davide Geneletti, "Cost-Benefit Analysis of Urban Nature-Based Solutions: A Systematic Review of Approaches and Scales with a Focus on Benefit Valuation," *Ecosystem Services* 71 (2025): 101684, p.7.

These dimensions (private and social) are particularly relevant because they directly influence how NBS benefits are identified, measured, and compared over time.

At the core of both methods lies the definition of benefit, but an even more challenging issue is defining its **spatial scale**. A green roof, for instance, can reduce a building's energy demand; at the district level, it can mitigate the Urban Heat Island effect; and at the global level, it can lower CO₂ emissions. Benefits can therefore be assessed across multiple spatial scales, making the definition of this scale essential.

Equally critical is the **temporal scale**. As already noted in Section "2.2.2 Limitations in addressing non-market and social benefits" ecosystem services vary in their temporal distribution of benefits. The "biological time" of NBS determines when they become fully functional. While an urban park offers immediate recreational and aesthetic benefits, effects on air quality, pollination, and pollutant reduction may take years to materialize, as plants require time to reach full efficiency. This difficulty is further compounded by limitations in the existing literature (see. Figure 23).

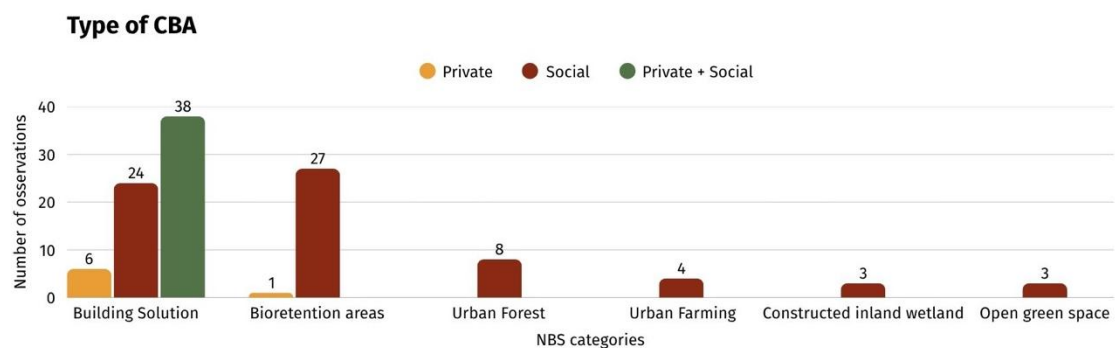


Figure 26 - Distribution of the type of CBA among NBS categories

Author's elaboration based on data reported in Chelli, A., Brander, L., & Geneletti, D. (2025). Cost-Benefit analysis of urban nature-based solutions: A systematic review of approaches and scales with a focus on benefit valuation. *Ecosystem Services*, 71, 101684. Fig.4 p.6.

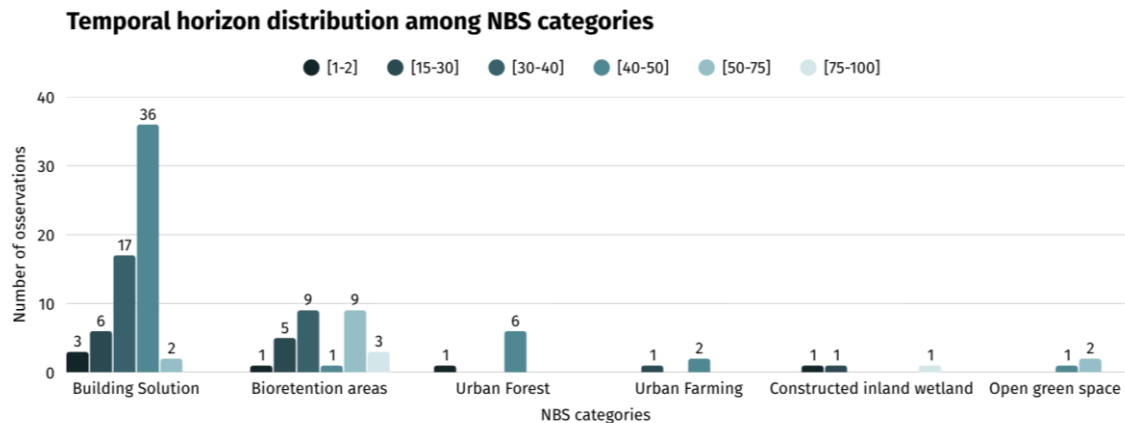


Figure 27 - Temporal horizon distribution among NBS categories

Author's elaboration based on data reported in Chelli, A., Brander, L., & Geneletti, D. (2025). Cost-Benefit analysis of urban nature-based solutions: A systematic review of approaches and scales with a focus on benefit valuation. *Ecosystem Services*, 71, 101684, fig.7, p.8.

Closely related to this temporal consideration is the concept of the **discount rate**. Since many benefits of NBS accrue over the long term, the choice of discount rate becomes crucial. If the discount rate is set too high, future benefits are heavily discounted, potentially hindering project implementation by making long-term benefits less appealing from an economic perspective. Conversely, if the discount rate is too low, it may result in insufficient investment, as future benefits might appear disproportionately valuable relative to upfront costs.

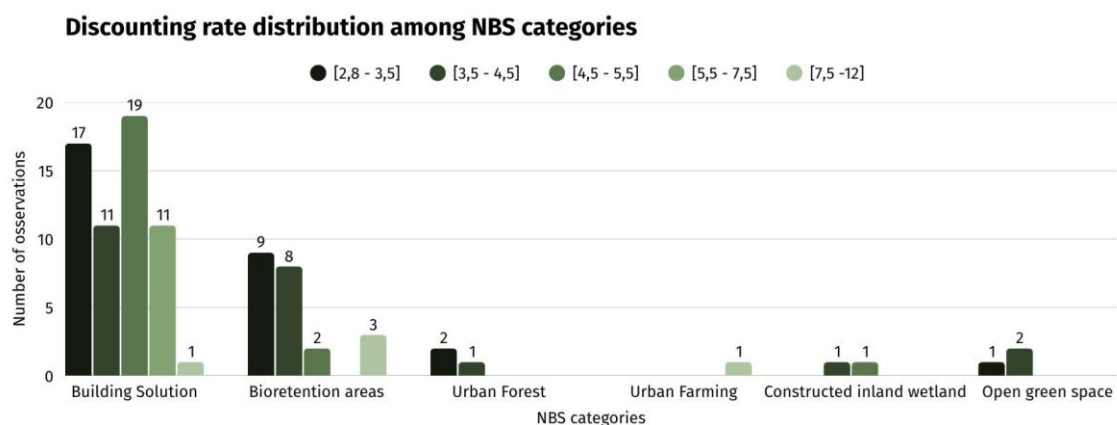


Figure 28 - Discount rate distribution among NBS categories

Author's elaboration based on data reported in Chelli, A., Brander, L., & Geneletti, D. (2025). Cost-Benefit analysis of urban nature-based solutions: A systematic review of approaches and scales with a focus on benefit valuation. *Ecosystem Services*, 71, 101684, fig.6, p.7.

Of course the selection choice is significantly influenced also by socio-economic contexts of the country where the CBA is conducted.⁶⁹

Given this high level of variability – particularly with respect to temporal and discount rate assumptions – and in order to limit uncertainties, it is always recommended that a CBA be performed alongside a **sensitivity analysis**. This approach makes it possible to determine the extent to which the CBA result depends on specific input parameters. The European Commission itself offers a useful benchmark: when a $\pm 1\%$ variation in a variable leads to a 1% change in the Net Present Value (NPV), that variable is to be considered critical.⁷⁰

Despite the limitations discussed above, Cost-Benefit Analysis remains one of the most widely adopted tools for evaluating NBS and environmental projects. Its continued relevance lies not only in its ability to compare costs and benefits within a common monetary framework but also in its flexibility to be combined with complementary valuation approaches.

One of the main strengths of CBA is its capacity to function as an overarching evaluation framework within which different valuation techniques can be integrated according to the specific characteristics of the intervention under assessment.

In the context of NBS, methods such as travel cost, hedonic pricing, contingent valuation, shadow pricing, and benefit transfer can be employed to estimate the monetary value of environmental and social benefits that are not directly traded in markets. Through such combinations, CBA can incorporate a broader range of ecosystem services and externalities than would otherwise be possible through conventional market-based assessments alone.

⁶⁹ Alessia Chelli, Luke Brander and Davide Geneletti, “Cost-Benefit Analysis of Urban Nature-Based Solutions: A Systematic Review of Approaches and Scales with a Focus on Benefit Valuation,” *Ecosystem Services* 71 (2025): 101684, p.7.

⁷⁰ Alessia Chelli, Luke Brander and Davide Geneletti, “Cost-Benefit Analysis of Urban Nature-Based Solutions: A Systematic Review of Approaches and Scales with a Focus on Benefit Valuation,” *Ecosystem Services* 71 (2025): 101684, p.3.

Furthermore, the distinction between private and social CBA should not necessarily be interpreted as an alternative choice between two competing approaches. Rather, the two perspectives can be applied in a *complementary manner* to provide a more comprehensive understanding of an intervention's impacts. While private CBA focuses on the profitability and financial feasibility of an investment from the perspective of individual stakeholders, social CBA expands the analysis to include wider societal costs and benefits – such as public health improvements, environmental enhancement, climate regulation, and recreational opportunities.⁷¹ The combination of these perspectives is particularly useful in the case of NBS, where interventions often generate substantial public benefits that may not be fully captured by private investors. In such cases, integrated assessments can help justify public incentives, subsidies, or policy support aimed at bridging the gap between private profitability and social desirability.

An additional opportunity lies in combining *CBA with non-monetary evaluation* methods. Given the inherent difficulties associated with assigning monetary values to certain ecosystem services and social outcomes, qualitative assessments and multi-criteria approaches can complement economic analysis by incorporating dimensions that would otherwise remain excluded from decision-making processes.

In this way, environmental and social externalities can still be explicitly considered even when reliable monetary estimates are unavailable.

Finally, recent applications have shown that *CBA can also be combined with regional economic assessment tools*, such as multiplier analysis (see Figure 22) allowing the evaluation to move beyond the project scale and capture wider economic effects.

⁷¹ Alessia Chelli, Luke Brander and Davide Geneletti, "Cost-Benefit Analysis of Urban Nature-Based Solutions: A Systematic Review of Approaches and Scales with a Focus on Benefit Valuation," *Ecosystem Services* 71 (2025): 101684, p.2.

These include indirect employment creation, additional income generation, increased local demand, and broader contributions to regional development. Such integrated approaches are particularly relevant for NBS, whose benefits often extend well beyond the immediate boundaries of the intervention itself.

In the same direction, CBA can also be strengthened through its connection with *Life Cycle Assessment* (LCA),⁷² a methodology that evaluates the environmental impacts associated with the different stages of a project's life cycle.⁷³

While the integrations discussed above mainly expand the economic, social, and spatial dimensions of CBA, LCA adds a complementary environmental perspective by considering the burdens generated during the implementation, operation, maintenance, and end-of-life phases of an intervention. This is particularly relevant for NBS, whose evaluation should not only account for the ecosystem services and benefits they generate, but also for the resources, materials, and management processes required to deliver them. In this sense, the combination of CBA and LCA can contribute to a more balanced assessment, in which the economic and social value of NBS is considered alongside their life-cycle environmental performance.⁷⁴

⁷² ISO, ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework, Geneva, International Organization for Standardization, 2006.

⁷³ ISO, ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines, Geneva, International Organization for Standardization, 2006.

⁷⁴ Pyrène Larrey-Lassalle et al., "Life Cycle Assessment Applied to Nature-Based Solutions: Learnings, Methodological Challenges, and Perspectives from a Critical Analysis of the Literature," *Land* 11, no. 5 (2022), article 649, p.1, 4-5, <https://doi.org/10.3390/land11050649>.

2.3.3 Adapted Willingness-to-pay (WTP) approaches

While Willingness to Pay (WTP) has been widely used as a **standalone, traditional economic valuation method** to estimate the perceived value of NBS, recent approaches emphasize integrating such methods within a broader socio-economic framework.

Pandey et al. (2025)⁷⁵ propose an integrated socio-economic assessment methodology in which economic valuation methods, as the beforementioned WTP, are applied prior to Cost–Benefit Analysis to estimate the benefits generated by proposed NBS.

The process starts with Contingent Valuation – (CV) surveys aimed at eliciting local communities' **Willingness to Pay (WTP)** or **Willingness to Contribute (WTC)** for different NBS improvement scenarios. Since the survey also includes perception-based variables related to environmental awareness, perceived problems, and future expectations, *Principal Component Analysis (PCA)* is used to reduce data complexity and identify the main factors influencing respondents' preferences.

A *bivariate probit model* is then applied to estimate the probability of supporting progressively more ambitious intervention scenarios. Only after this valuation phase are the estimated WTP/WTC values translated into monetary benefits and incorporated into an ex-ante CBA, which is used to assess the socio-economic viability of the proposed interventions.

The method is applied to two flood-prone areas in Kolkata: Maheshtala, where a modified “Room for the River” programme is proposed through canal restoration and conservation, and Rabindra Sarovar Lake, where ecological

⁷⁵ Soumit Pandey et al., “Socio-Economic Viability of Nature-Based Solutions: A Case Study in Kolkata,” *Discover Environment* 3, no. 1 (2025): 64, <https://doi.org/10.1007/s44274-025-00251-5>.

restoration and preservation of the lake and park area are assessed. For both sites, three scenarios of increasing intervention intensity are tested.⁷⁶

The results show strong community support and positive economic viability: 71% of respondents in Maheshtala were willing to pay, while 60% of respondents in Rabindra Sarovar were willing to contribute.⁷⁷

The subsequent CBA reports positive NPVs for both projects, suggesting that the proposed NBS interventions may represent viable alternatives to conventional flood-management strategies.

This approach is particularly relevant because it demonstrates that economic valuation can generate benefit estimates before the application of CBA, rather than relying solely on pre-existing market values.

Moreover, using methods such as WTP or WTC can increase **community awareness**, engaging citizens in the decision-making process, fostering interest in environmental improvement, and supporting mitigation of local vulnerabilities. Such engagement can also facilitate **public-private partnerships** and help forecast the funding needed for the implementation and maintenance of NBS.

The choice of **discount rate** is fundamental in this context. For Maheshtala, a relatively low discount rate (2%) is used to ensure that future benefits remain substantial over the project's lifespan, reflecting the long-term value of interventions. In contrast, for Rabindra Sarovar, a higher discount rate (19%) is applied, placing greater emphasis on immediate impacts.⁷⁸

Despite these advantages, the methodology still faces several critical limitations, including small sample sizes, limited survey participation, and

⁷⁶ Pandey et al., "Socio-Economic Viability of Nature-Based Solutions." pp.2-5.

⁷⁷ Pandey et al., "Socio-Economic Viability of Nature-Based Solutions."pp.17-18.

⁷⁸ Pandey et al., "Socio-Economic Viability of Nature-Based Solutions."

difficulties in obtaining accurate cost estimates, which can affect the robustness and generalizability of the results.

Additionally, reliance on stated preferences makes outcomes sensitive to respondents' perceptions, socio-economic characteristics, and the framing of proposed scenarios.

2.3.4 Hybrid approaches involving Multi-Criteria Decision Analysis (MCDA)

In this context, and differently from the conventional evaluation methods previously discussed, Multi-Criteria Decision Analysis (MCDA) represents a relevant approach for the assessment of complex and multidimensional interventions such as NBS.

Rather than relying on a single evaluative perspective, MCDA allows different types of criteria to be considered simultaneously, including environmental, social, economic and spatial dimensions.

It can therefore integrate *quantitative* and *qualitative* information, as well as monetizable and non-monetizable impacts, within a structured decision-support process.

For this reason, multi-criteria approaches are particularly suitable for evaluating NBS, whose benefits are often context-dependent, heterogeneous and difficult to capture through conventional economic methods alone. The methodological structure and possible application of MCDA will be discussed in greater detail in the following chapter.

MCDA as trade-off analysis

A particularly relevant contribution in the definition of criteria and frameworks capable of addressing and evaluating NBS is provided by Chairat and Gheewala (2024)⁷⁹, who propose a quantitative assessment framework explicitly aligned with the criteria of the IUCN Global Standard for NbS. (see 1.2.2 *Regulatory frameworks*).

The framework, as previously described, was developed in response to the growing recognition that the performance of NBS cannot be adequately captured through a single evaluation method, given that these interventions simultaneously generate environmental, social, and economic effects that operate across different spatial and temporal scales.

By adopting the IUCN Standard as a conceptual reference, the authors ensure that the assessment process remains connected not only to the measurement of impacts but also to broader objectives, including addressing societal challenges, enhancing human well-being, ensuring economic feasibility, promoting biodiversity conservation, and supporting long-term sustainability.

To achieve this objective, the framework **combines several complementary assessment tools**, each designed to capture a specific dimension of NBS performance. Specifically, ecosystem service assessment quantifies the benefits generated by natural systems; *Life Cycle Assessment (LCA)* evaluates environmental impacts throughout the intervention's life cycle; *Social Life Cycle Assessment (S-LCA)* focuses on social implications and stakeholder-related effects; and *Cost-Benefit Analysis (CBA)* addresses economic feasibility and the monetary valuation of costs and benefits.⁸⁰

⁷⁹ Sumonrat Chairat and Shabbir H. Gheewala, "The Conceptual Quantitative Assessment Framework for Nature-Based Solutions (NbS)," *Nature-Based Solutions* 6 (December 2024): 100152, <https://doi.org/10.1016/j.nbsj.2024.100152>.

⁸⁰ pp.2-6.

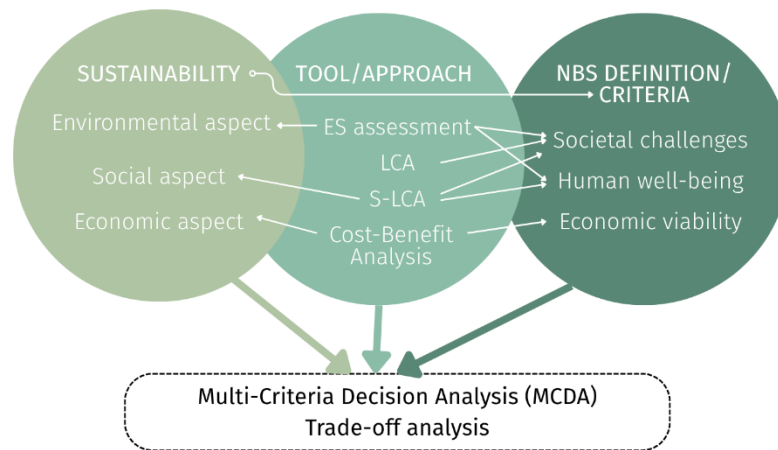


Figure 29 - Conceptual assessment framework for Nature-Based Solutions integrating sustainability dimensions, assessment tools and NBS definition criteria.

Author's elaboration based on Chairat and Gheewala, *The Conceptual Quantitative Assessment Framework for Nature-Based Solutions (NbS)*, *Nature-Based Solutions 6* (2024): 100152, fig. 2, p. 5.

Rather than treating these methods as competing alternatives, the framework views them as **complementary sources** of information that together contribute to a more comprehensive understanding of NBS outcomes.

A particularly innovative aspect of the proposal lies in its recognition that the outputs generated by these tools are often expressed through different indicators, units of measurement, and value systems, which makes direct comparison difficult. To overcome this challenge, the authors introduce a Multi-Criteria Decision-Making (MCDM) component capable of integrating environmental, social, and economic results within a common decision-support structure. In this way, the framework does not attempt to reduce all impacts to a single monetary metric; instead, it acknowledges the multidimensional nature of NbS and provides a **mechanism for analysing trade-offs**, synergies, and conflicting priorities among evaluation criteria.⁸¹

Beyond the integration of multiple assessment methods, the framework is also noteworthy because it is accompanied by a **step-by-step operational guideline**. The proposed procedure guides practitioners through the different stages of

⁸¹ Sumonrat Chairat and Shabbir H. Gheewala, "The Conceptual Quantitative Assessment Framework for Nature-Based Solutions (NbS)," *Nature-Based Solutions 6* (December 2024), p.5

evaluation – from the identification of societal challenges and ecosystem services, through the selection of indicators and assessment tools and data collection, to impact evaluation and final decision-making.

This operational dimension is particularly important, as one of the recurring criticisms identified in the literature concerns the difficulty of translating theoretically robust assessment methods into practical tools that can effectively support planning and policy decisions.⁸²

However, the application of such integrated assessment frameworks raises several methodological challenges. Notably, many of these challenges have already been highlighted in the critique of traditional evaluation methods (see 2.2.2 *Limitations in addressing non-market and social benefits*).

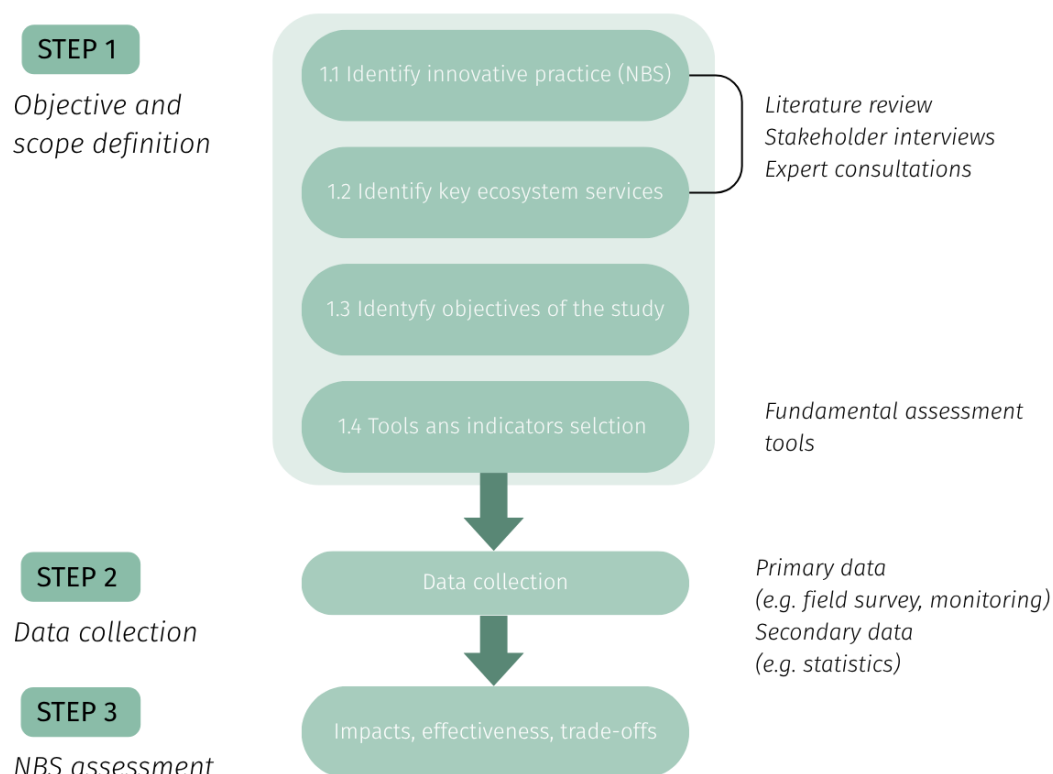


Figure 30 – Step-by-step procedure for Nature-Based Solutions assessment.

Author's elaboration based on Chairat and Gheewala, *The Conceptual Quantitative Assessment Framework for Nature-Based Solutions (NbS)*, *Nature-Based Solutions* 6 (2024): 100152, fig. 3, p. 5.

⁸² Sumonrat Chairat and Shabbir H. Gheewala, "The Conceptual Quantitative Assessment Framework for Nature-Based Solutions (NbS)," *Nature-Based Solutions* 6 (December 2024), p.5

First, the broad and sometimes ambiguous definition of NBS requires clear criteria to classify an intervention as NBS before evaluating its performance. Moreover, indicator selection is strongly influenced by spatial and temporal scales, since ecosystem functions and services emerge at different times and across different territorial levels. These issues directly affect the robustness of multi-criteria assessment, particularly regarding the **definition of the baseline scenario**, data availability and reliability, and indicator choice.

Furthermore, the risk of **double counting** remains critical when ecosystem services are not clearly distinguished. Hence, the framework requires careful methodological calibration, including uncertainty and sensitivity analysis. Although the framework proposed by Chairat and Gheewala represents a useful step forward, its application cannot be universal or automatic. Rather, it should be adapted to the specific ecological, spatial and socio-economic context of each case study.

This aspect is particularly relevant for the present research, where the development of an evaluation framework for urban NbS requires not only the integration of environmental, social and economic dimensions, but also the careful definition of context-specific indicators capable of supporting transparent and replicable trade-off analysis.

For these reasons, the framework proposed represents a particularly valuable reference for the present research. Not only does it demonstrate the feasibility of combining different assessment approaches within a coherent structure, but it also reinforces the idea that NbS evaluation should move beyond fragmented analyses towards integrated frameworks capable of simultaneously accounting for environmental, social, and economic dimensions.

In this respect, the use of multi-criteria methodologies as a mechanism for synthesizing heterogeneous information offers an especially promising direction for the development of holistic and operational assessment frameworks.

MCDA + CBA within the aggregation procedure COSIMA DSS

A particularly relevant technical application of this integrated approach is provided also by Oppio et al. (2024),⁸³ who apply a multimethodological framework *combining Cost-Benefit Analysis (CBA), Multi-Criteria Decision Analysis (MCDA)* and COSIMA-DSS to assess ecosystem services generated by a green roof intervention in Turin.

The relevance of this study is twofold: first, it is developed within the **same urban context of the present research**; second, it adopts a methodological structure based on the integration of economic, environmental and socio-cultural dimensions, which makes it a useful reference for the evaluation of NBS in dense urban environments.

The application compares two scenarios: T_0 , corresponding to the existing condition of the Lingotto rooftop without intervention, and T_1 , representing the implementation of a new green roof.⁸⁴

The evaluation is structured into two main components.

The first is a *cost-based assessment*, developed through CBA, in which ecosystem service benefits are estimated using the *SimulSoil software* (existing computer-based tool, result of *LIFE + programme 2007-2013* developed by Politecnico di Torino). This tool allows the quantification of both biophysical and monetary variations associated with land-use change, including services such as carbon sequestration, habitat quality, sediment retention, water yield, crop production and timber production.⁸⁵

⁸³ Alessandra Oppio et al., "Assessing Ecosystem Services through a Multimethodological Approach Based on Multicriteria Analysis and Cost-Benefits Analysis: A Case Study in Turin (Italy)," *Journal of Cleaner Production* 472 (September 2024): 143472, <https://doi.org/10.1016/j.jclepro.2024.143472>.

⁸⁴ Alessandra Oppio et al., "Assessing Ecosystem Services through a Multimethodological Approach Based on Multicriteria Analysis and Cost-Benefits Analysis: A Case Study in Turin (Italy)," *Journal of Cleaner Production* 472 (September 2024): 143472, pp.4-5.

⁸⁵ Alessandra Oppio et al., "Assessing Ecosystem Services through a Multimethodological Approach Based on Multicriteria Analysis and Cost-Benefits Analysis: A Case Study in Turin (Italy)," *Journal of Cleaner Production* 472 (September 2024): 143472, pp.4-5.

Construction and maintenance costs are then estimated through synthetic and analytical procedures over a 30-year time horizon, using a 3% discount rate.

The second component is a *value-based assessment*, developed through MCDA and, more specifically, through *Multi-Attribute Value Theory*.⁸⁶

This part allows the inclusion of socio-cultural criteria that are difficult to monetize, such as outdoor activities, educational opportunities, aesthetic perception, project relevance, biodiversity-related indicators, social attractiveness, accessibility, job opportunities and contribution to the SDGs.

The performances of T_0 and T_1 are standardized on a 0–1 scale and then aggregated through a weighted-sum model. In this phase, the method also becomes relevant for **stakeholder dialogue**, since different weighting scenarios are developed according to the perspectives of citizens, the client, the

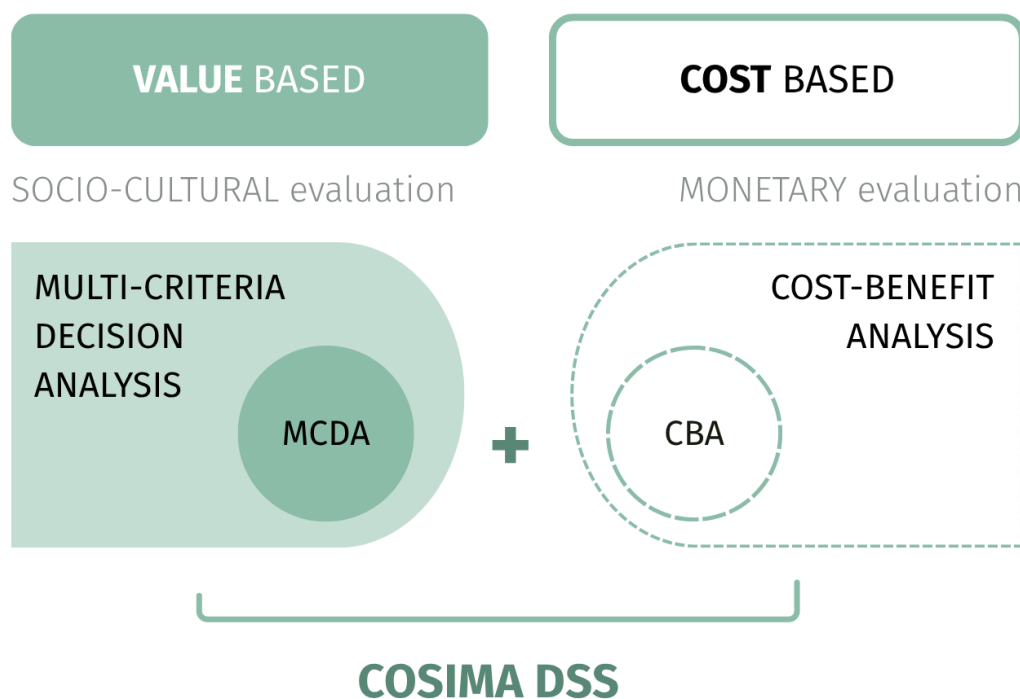


Figure 31 - COSIMA DSS methodological model combining value-based MCDA and cost-based CBA. Author's elaboration based on Barfod, Salling and Leleur, "Composite Decision Support by Combining Cost-Benefit and Multi-Criteria Decision Analysis," *Decision Support Systems* 51, no. 1 (2011): 167–175, fig. 1.

⁸⁶ Oppio et al., "Assessing Ecosystem Services through a Multimethodological Approach Based on Multicriteria Analysis and Cost-Benefits Analysis."

municipality and the project studio. In this way, the framework does not only measure project performance but also makes explicit how different actors assign importance to different dimensions of value.

The CBA and MCDA outputs are finally combined through **COSIMA-DSS**, (*Composite Model for Integrated Sustainability Assessment – Decision Support System*), a decision-support model designed to integrate monetary and non-monetary impacts within a single evaluative framework and to produce a synthetic indicators, as the **Total Rate of Return**.

The functioning of COSIMA-DSS is based on a specific aggregation formula, which can be synthetically interpreted as a mechanism for converting MCDA scores into monetary-equivalent values.⁸⁷

$$TRR(A_k) = \frac{TV(A_k)}{C_k} = \frac{1}{C_k} \left(\sum_{(i=1)}^I V_i(X_{ik}) + \alpha \cdot \left(\sum_{(j=1)}^J w_j \cdot VF_j(Y_{jk}) \right) \right) \quad (1)$$

Where A_k is alternative k ; C_k is the total costs k ; X_{ik} is the quantity of the CBA impact i for alternative k ; $V_i(X_{ik})$ is the value in monetary units for the CBA impact i for alternative k ; w_j is a weight which reflects the influence of MCDA criterion j ; Y_{jk} is a parameter value for MCDA criterion j for alternative k ; $VF_j(Y_{jk})$ is a value score for alternative k under criterion j .

Through this formula, the α -indicator (which works as a percentage) acts as a calibration factor that converts MCDA scores into monetary-equivalent values, making them comparable with the monetary outputs of CBA. In this way, the non-monetary component is not simply added as a qualitative consideration but is formally incorporated into the calculation of the Total Rate of Return.

⁸⁷ Formula adapted from Oppio et al., "Assessing Ecosystem Services through a Multimethodological Approach Based on Multicriteria Analysis and Cost-Benefits Analysis," p. 3, formula (1).

A low α value limits the influence of social, environmental and stakeholder-related benefits, while a higher α value increases their contribution to the final result. In previous applications, α values are usually considered within a range of approximately 10–40%, although the choice ultimately depends on the decision-maker's preferences and on the relative importance assigned to intangible impacts.

Therefore, COSIMA-DSS makes it possible to observe how the overall attractiveness and ranking of alternatives change when greater importance is assigned to intangible and socio-cultural values.

This is particularly important because the project appears less attractive if assessed only from a strictly financial perspective, whereas its performance improves significantly when environmental, social and stakeholder-related benefits are incorporated.

Therefore, the study demonstrates how COSIMA can expand the role of CBA within a broader integrated framework, allowing economic feasibility, ecosystem service provision and socio-cultural value to be assessed together.

Beyond the technical integration of CBA and MCDA, the relevance of the framework also lies in its capacity to **support a more pluralistic perspective** in ecosystem service evaluation.

As *Oppio et al. (2024)* underline, **MCDA makes it possible to account for the plurality of values embedded in ecosystem services, including ecological, cultural and socio-cultural dimensions that cannot be fully expressed through monetary valuation alone.** In this sense, the integration of cost-based and value-based components is fundamental for avoiding a purely financial interpretation of the project and for producing a more comprehensive assessment of its environmental, social and economic contribution.

Another important aspect concerns **the replicability and transferability of the proposed methodology.** Although the application is developed in relation to the

Lingotto green roof in Turin, the COSIMA-DSS framework is presented as an adaptive decision-support model that can be transferred to other contexts, provided that the criteria and indicators are carefully tailored to the specific decision problem.

This is particularly relevant for the present research, as it suggests that a similar integrated evaluation structure could be adapted to other urban areas of Turin or to different NBS case studies, while still allowing comparison between alternatives through a structured and transparent assessment process.

For this reason, the study represents not only a relevant precedent in the same geographical context, but also a methodological reference for developing an integrated and replicable evaluation framework for NBS, capable of combining economic feasibility, ecosystem service performance, socio-cultural values and stakeholder perspectives within a single decision-support process.

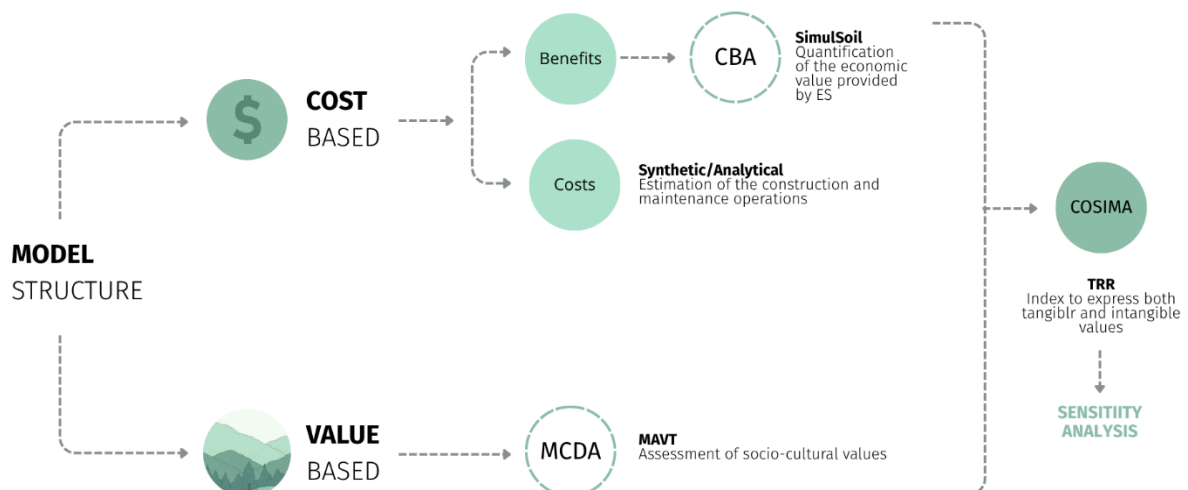


Figure 32 - Multimethodological model for assessing ecosystem services through CBA, MCDA and COSIMA.

Author's elaboration based on Oppio et al., "Assessing Ecosystem Services through a Multimethodological Approach Based on Multicriteria Analysis and Cost-Benefits Analysis: A Case Study in Turin (Italy)," *Journal of Cleaner Production* 472 (2024): 143472, fig. 4, p. 6.

MCA + CBA: the joint MAGICA model

A relevant study, deepening the same concepts but with another focus, is evaluation framework proposed by Teotónio et al. (2023),⁸⁸ where *Cost-Benefit Analysis* (CBA) and *Multi-Criteria Analysis* (MCA) are combined through MAGICA framework to capture both monetized and non-monetized impacts of green infrastructure, enabling a broader assessment than conventional economic analysis alone.

The rationale behind this approach is that MCA can complement traditional CBA by incorporating multiple types of information, including both quantitative and qualitative data. While CBA provides a monetary assessment of project costs and benefits, MCA supports the comparison of alternatives across different dimensions and facilitates the identification of solutions that best reflect the objectives and preferences of decision-makers and stakeholders. As a result, the combined approach is particularly suitable for evaluating complex interventions such as NBS, where relevant impacts often extend beyond purely economic considerations.

MAGICA, an acronym for *Modeling the Attractiveness of Green Infrastructure through a Combined Approach*, addresses this challenge by distinguishing between monetizable and non-monetizable impacts.

The framework is structured around three complementary dimensions of value: a *financial* dimension, which reflects the perspective of the investor and focuses on project profitability; an *economic* dimension, which evaluates impacts on the local economy and broader welfare generation; and a *socio-environmental* dimension, which captures environmental and social effects that cannot be adequately represented through monetary indicators alone.

⁸⁸ Inês Teotónio et al., "Bridging CBA and MCA for Evaluating Green Infrastructure: Proposal of a New Evaluation Model (MAGICA)," *Socio-Economic Planning Sciences* 85 (2023): 101446, <https://doi.org/10.1016/j.seps.2022.101446>.

Depending on the decision-making context, these dimensions may include different categories of benefits and indicators, allowing the framework to be adapted to specific evaluation objectives.

MAGICA adopts different approaches depending on the characteristics of the project, the type of impacts considered and the availability of monetizable information. The framework includes three evaluation models:

- **Simple MAGICA**, which is particularly suitable for more straightforward decision problems, when all relevant impacts can be expressed in monetary terms and the analysis relies exclusively on CBA;
- **2-step MAGICA**, which is applied when some impacts cannot be monetized. In this case, CBA and MCA are both performed, but their results remain separate and are compared through distinct rankings;
- **Joint MAGICA**, the most integrated and complex model, where CBA and MCA outputs are combined into a single measure of project attractiveness through a procedure inspired by COSIMA-DSS.⁸⁹

The first model, Simple MAGICA, is applicable when all relevant project impacts can be expressed in monetary terms. In this case, the analysis relies exclusively on CBA, allowing the calculation of traditional economic indicators such as Net Present Value (NPV), Internal Rate of Return (IRR) and Cost-Benefit Ratio (CBR). While this approach provides clear and directly interpretable economic results, it may overlook relevant environmental and social impacts that cannot be readily monetized.

⁸⁹ Inês Teotónio et al., "Bridging CBA and MCA for Evaluating Green Infrastructure: Proposal of a New Evaluation Model (MAGICA)," *Socio-Economic Planning Sciences* 85 (February 2023): 101446, pp.3-4

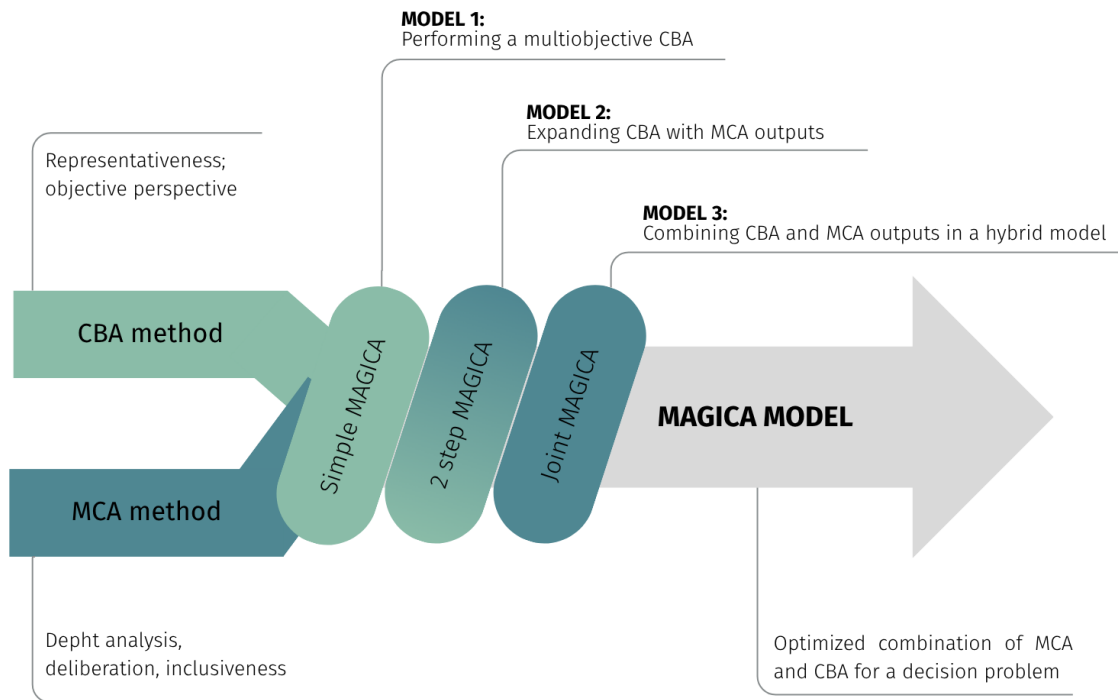


Figure 33 - MAGICA evaluation models integrating CBA and MCA methods.

Author's elaboration based on Teotônio et al., "Bridging CBA and MCA for Evaluating Green Infrastructure: Proposal of a New Evaluation Model (MAGICA)," *Socio-Economic Planning Sciences* 85 (2023): 101446, fig. 2, p. 3.

In situations where some impacts cannot be monetized, 2-step MAGICA combines CBA and MCA while keeping their results separate. Monetary impacts are evaluated through CBA, whereas non-monetary impacts are assessed through MCA using performance indicators, value functions and stakeholder-derived weights. The outputs of the two analyses are not aggregated into a single indicator, but rather compared through separate rankings. This allows decision-makers to explicitly evaluate trade-offs between economic feasibility and socio-environmental performance.

However, when the results of CBA and MCA are highly contrasting, the interpretation of separate rankings may become difficult.

For example, one alternative may be economically feasible but weak in socio-environmental terms, while another may provide relevant non-market benefits but perform poorly from a financial perspective.

In this case, the framework proposes a third model, Joint MAGICA, which combines CBA and MCA into a single measure of project attractiveness. The basic rationale is expressed as:

$$f_{(Joint\ MAGICA)} = f_{(CBA)} + f_{(MCA)} \quad (2)$$

In Joint MAGICA, MCA scores are converted into monetary-equivalent values using a calibration factor known as the α -indicator, following the logic of the COSIMA methodology.

The aim is not to directly add monetary values and dimensionless scores, but to transform the MCA component into a comparable monetary-equivalent measure. The α -indicator expresses the relative importance assigned to non-monetary impacts within the overall assessment. In simplified terms, it defines the share of the total combined value that should be attributed to the MCA component:

$$\alpha: 100 = MCA: (MCA + CBA) \text{ [\%]} \quad (3)$$

From this relation, the monetary-equivalent value of the MCA component can be derived as:

$$MCA_{eq} = \frac{\alpha}{1 - \alpha} * (CBA) \text{ [decimal]} \quad (4)$$

where α is expressed in decimal terms. This means that, once the importance of non-monetary impacts has been defined, the model estimates the corresponding monetary-equivalent value of the MCA component in relation to the positive impacts considered in the CBA.

Once this overall monetary-equivalent value of MCA has been established, it is distributed across the different MCA criteria through the use of unit prices. The unit price (UP_j) represents the monetary-equivalent value associated with one

unit of performance of criterion (j). It is obtained by combining the relative weight assigned to the criterion with a common monetary conversion factor (P):

$$UP_j = w_j \cdot P \quad [€] \quad (5)$$

where (w_j) is the weight assigned to criterion (j), while (P) is a calibrated conversion factor derived from the α -based valuation of the MCA component. Consequently, (UP_j) should not be interpreted as a real market price, but rather as a conversion coefficient used to express dimensionless MCA scores in monetary-equivalent terms.

In this way, it becomes possible to calculate combined indicators such as the Total Value (TV):⁹⁰

$$TV(k) = \sum_{i=1}^I V_{ik} + \sum_{j=1}^J VF_{jk} * UP_j \quad (6)$$

Where,

TV(k) – total value of alternative k in monetary units

V_{ik} – value of alternative k for the CBA impact i in monetary units

V_{jk} – value of alternative k for the MCA impact j

UP_j – “unit price” of MCA impact j.

Although this procedure allows the aggregation of CBA and MCA results into a single indicator, the resulting monetary-equivalent values do **not correspond to actual market prices**. Rather, they depend on the selected α value and on the weighting structure adopted within the MCA.

⁹⁰ Formula adapted from Inês Teotónio et al., “Bridging CBA and MCA for Evaluating Green Infrastructure: Proposal of a New Evaluation Model (MAGICA),” *Socio-Economic Planning Sciences* 85 (2023): 101446, eq. 5, p. 6.

Consequently, the final Total Value and Total Rate of Return should be interpreted as measures of overall project attractiveness rather than as purely economic indicators.

The case study presented by Teotónio et al. applies the framework to sixteen alternative green roof configurations in Lisbon. In this application, the CBA component is calculated by comparing the *life-cycle costs* of each solution with the monetized benefits that could be directly estimated from empirical data. Costs include installation, maintenance, and vegetation replacement, while benefits primarily concern stormwater management—specifically reduced drainage costs and flood risk mitigation. Other potential benefits, such as thermal insulation, were not monetized when they were irrelevant to the specific building context or when reliable data were unavailable.

The MCA component, in turn, is used to evaluate impacts considered relevant but difficult to monetize. Three main non-monetary criteria are included: aesthetic quality, accessibility of the roof space, and the use of recycled construction and demolition materials in the substrate.

These criteria are assessed through stakeholder surveys and processed using the *Analytic Hierarchy Process (AHP)*.

Each alternative receives a score for every criterion, and these scores are then weighted according to the relative importance assigned by respondents. In this way, the CBA captures the measurable economic and hydrological performance of the alternatives, while the MCA incorporates broader qualitative, social, and environmental dimensions that would otherwise remain outside the assessment.

The application of MAGICA thus demonstrates the potential of combining CBA and MCA to achieve a more comprehensive evaluation of green infrastructure. At the same time, it also highlights several methodological and practical challenges.

Implementing the MCA component requires **extensive stakeholder engagement**, preference elicitation, and consistency checks, making the process time-consuming and difficult to replicate in routine planning contexts. Moreover, the final results are **strongly influenced by subjective choices** regarding criteria selection, weighting procedures, and the calibration factor α . In the case study, an α value of 90% is adopted to increase the influence of non-monetary benefits—considerably above the values commonly suggested in previous applications. This raises concerns about the robustness, transparency, and transferability of the results. More broadly, although MAGICA represents an important attempt to bridge economic and non-economic dimensions within a single evaluation framework, its complexity may limit its practical applicability for decision-makers and public authorities.

The need to identify, measure, weight, and aggregate heterogeneous indicators requires considerable technical expertise and data availability.

Method	Main function	Treatment of CBA and MCA	Main strength	Main limitation
COSIMA	Combines monetary and non-monetary values into a single integrated indicator	MCDA scores are converted into monetary-equivalent values through the α -indicator	Allows CBA and MCDA outputs to be formally aggregated	Strong dependence on α and risk of pseudo-monetization
Simple MAGICA	Applies a conventional CBA when all impacts can be monetized	Only CBA is performed	Clear economic indicators such as NPV, IRR and CBR	Excludes non-monetizable environmental and social benefits
MAGICA 2-step	Evaluates monetized and non-monetized impacts through two parallel analyses	CBA and MCA remain separate and are compared through rankings	Preserves transparency and avoids forced aggregation	Final decision can be difficult when rankings conflict
Joint MAGICA	Produces a single measure of project attractiveness	MCA scores are converted into monetary-equivalent values and added to CBA outputs	Provides one final ranking of alternatives	May flatten multidimensional impacts and depends heavily on α

Table 3 - Summary of Hybrid MCDA methods

Furthermore, in Joint MAGICA, converting MCA scores into monetary-equivalent values introduces an additional layer of uncertainty, as these values do not correspond to actual market prices or revealed preferences. For this reason, the resulting Total Value and Total Rate of Return should not be interpreted as purely economic indicators, but rather as synthetic measures of overall project attractiveness.

2.3.5 Challenges in measuring multi-dimensional impact

Advanced evaluation frameworks for NBS offer theoretically comprehensive tools for integrating environmental, social, and economic impacts, but several practical and methodological challenges remain. Limited data availability, context-specific variability, and the complexity of stakeholder engagement, weighting procedures, and sensitivity analyses can make these methods difficult to implement in real-world urban settings.

Moreover, assumptions regarding time horizons, discount rates, and baseline scenarios, inherited from conventional methods, can influence outcomes and, if not carefully calibrated, lead to misinterpretation. For example, as illustrated in the case of *Willingness-to-Pay (WTP) surveys combined with ex-ante CBA in flood-prone areas in Kolkata*, both the choice of discount rate and the survey-based estimation of benefits influenced the assessment of long-term versus immediate impacts. Such cases highlight how methodological complexity and context-specific assumptions can challenge the practical applicability of theoretically robust approaches.

Insufficient knowledge exchange between local stakeholders and across cities further complicates the integration of NBS into urban planning and policy-making.

Overall, hybrid frameworks such as MAGICA and COSIMA represent an important methodological advancement in the evaluation of NBS, as they explicitly

recognize that economic, environmental and social impacts cannot be fully captured through conventional monetary assessment alone.

In particular, the COSIMA method provides one of the conceptual bases for combining CBA and MCA, translating multicriteria scores into monetary-equivalent values through calibration procedures. MAGICA builds on this logic by proposing different levels of integration between the two approaches, from separate rankings to a fully combined indicator.

However, the review of these more complex approaches also shows that the integration of multidimensional impacts remains only partially resolved. In some cases, as in 2-step MAGICA, CBA and MCA are kept separate and compared through parallel rankings. In other cases, as in Joint MAGICA, the different dimensions are aggregated into a single synthetic indicator by converting MCA scores into monetary-equivalent values. While this allows a more immediate comparison between alternatives, it may also flatten the complexity of the evaluation process. By reducing economic, environmental and social variables to one final score or indicator, important trade-offs may become less visible: an alternative may appear preferable without clearly showing whether this result depends on economic efficiency, environmental performance, social acceptability or stakeholder priorities.

A further concern is the potential risk of double counting. This may occur when the same benefit is partially monetized within the CBA and then indirectly reconsidered as a separate criterion within the MCA. In the context of NBS, this risk is particularly relevant because many ecosystem services are interconnected: for example, improved thermal comfort, public health, recreational value and property-value effects may overlap if not carefully defined. Therefore, even highly structured hybrid models require a clear separation of indicators and a transparent explanation of what each criterion actually measures.

Another limitation concerns the way non-monetary impacts are converted into monetary-equivalent values. In approaches such as COSIMA and Joint MAGICA, these values do not necessarily correspond to actual market prices, willingness-to-pay estimates or revealed preferences, but depend on calibration factors and weighting assumptions. For this reason, indicators such as Total Value or Total Rate of Return should be interpreted as measures of overall project attractiveness rather than as purely economic indicators.

This also raises the issue of **apparent objectivity**. By producing numerical outputs such as Total Value or Total Rate of Return, COSIMA and Joint MAGICA may give the impression of a highly objective and technically neutral evaluation. However, the final result depends heavily on the choice of the α -indicator, which determines the relative importance assigned to non-monetary impacts compared to the CBA component. Since α is not derived from market evidence, revealed preferences or direct willingness-to-pay estimates, but from a calibration choice, even small variations in its value can significantly affect the final ranking of alternatives. This dependence may compromise the robustness of the whole evaluative system, as the apparent precision of the final indicator can mask the subjectivity embedded in the calibration process.

At the same time, this does not mean that CBA should be dismissed. On the contrary, CBA remains a valuable and robust tool for assessing economic feasibility, especially when costs and benefits can be reliably monetized. However, in the context of NBS, it may be more appropriate to apply CBA after a broader and more holistic multicriteria assessment has first been carried out. In this way, environmental, social and economic dimensions can initially be placed on the same evaluative level, weighted according to the objectives of the decision-making process, and only afterwards examined through a more strictly economic feasibility lens.

Beyond methodological issues, these frameworks also raise a practical concern. Although they are theoretically comprehensive, their complexity may limit their application in everyday planning and policy-making contexts.

The need for extensive data collection, stakeholder engagement, weighting procedures, calibration factors and sensitivity analyses can make them difficult to implement for local administrations or practitioners with limited time, expertise and resources. This may unintentionally reinforce the preference for conventional grey infrastructure, which is often easier to evaluate through standardized economic and technical metrics, even when it provides fewer co-benefits than NBS.

This review also highlights a relevant gap in the literature. **Economic values are rarely incorporated directly within the MCA structure as one criterion among others.** Instead, most approaches tend to keep economic evaluation and multicriteria assessment as separate modules, integrating their outputs only at a later stage through rankings, weighting procedures or monetary-equivalent conversions.

This tendency may reflect the historical dominance of CBA in infrastructure appraisal and the perceived difficulty of comparing monetary indicators with heterogeneous environmental and social criteria. Nevertheless, maintaining the economic dimension outside the multicriteria structure often increases methodological complexity and may introduce further inconsistencies.

For this reason, future methodological developments should further explore the possibility of incorporating economic valuation outputs directly into transparent multicriteria frameworks, rather than combining CBA and MCA ex post through increasingly complex hybrid procedures. Such an approach could preserve the multidimensional nature of NBS evaluation while reducing the risks of double counting, excessive aggregation and loss of transparency in the interpretation of trade-offs.

In light of these limitations, the present thesis moves towards a different methodological direction. Instead of assigning conventional monetary-equivalent values to non-monetary impacts through a subjective calibration factor, the economic dimension is estimated through consolidated economic valuation methods, such as Hedonic Pricing and Willingness-to-Pay approaches.

These economic outputs are then maintained as a specific criterion within the multicriteria structure, alongside environmental and social criteria.

In this way, the proposed framework seeks to preserve the multidimensional nature of NBS evaluation, while avoiding the need to monetize non-market impacts and reducing the risk of double counting.

03

CHAPTER



Economic evaluation and decision-making tools

3.1. Economic valuation framework

The economic assessment of NBS requires a framework capable of organizing the different forms of value they generate and relating them to appropriate valuation approaches. This section therefore introduces the conceptual and methodological foundations adopted in this research thesis, distinguishing between the classification of environmental value and the tools used to represent or estimate its different components.

The following subsections first present the Total Economic Value as the overarching conceptual reference and subsequently examine the valuation approaches relevant to the proposed framework. These approaches are treated as complementary components of a broader multicriteria assessment rather than as instruments for the complete monetization of NBS benefits.

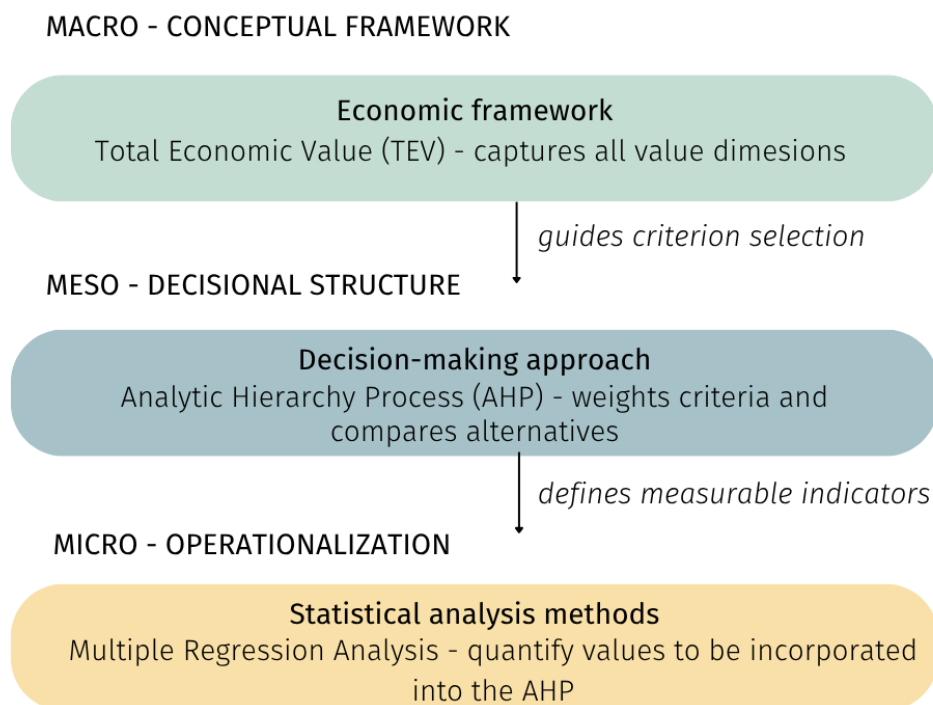


Figure 34 - Conceptual structure of the proposed evaluation framework, linking the Total Economic Value framework, the Analytic Hierarchy Process and the statistical and valuation methods used for operationalization.

Author's elaboration

3.1.1 Total economic value - TEV

Building on the general rationale for the economic evaluation of NBS, the **Total Economic Value** (TEV) provides a conceptual structure for identifying the different forms of value associated with environmental goods and ecosystem services. Rather than constituting a valuation technique, TEV provides a conceptual taxonomy distinguishing between **use values** and **non-use values**⁹¹. It is therefore used in this research as a conceptual reference, rather than as a means of fully monetizing the benefits generated by NBS.

The TEV framework is therefore particularly relevant to the assessment of NBS, whose benefits are multiple, interconnected and expressed through different mechanisms. Some may be observed through market behavior, others through individuals' stated preferences, while others remain more appropriately represented through environmental, social or spatial indicators.

The indicators and valuation tools adopted, which will be described in detail in the following chapter, are not intended to correspond directly or exclusively to individual TEV components. Instead, when considered together as part of the six-indicator structure, they aim to capture the broadest possible range of use and non-use values, including direct, indirect, option, bequest and existence values. Their combined application is therefore intended to produce an assessment that is coherent with the TEV framework, while recognizing that the different forms of value generated by NBS are often interconnected and cannot always be isolated through a one-to-one correspondence between values, indicators and methods. In this sense, TEV provides the shared conceptual foundation underlying the overall evaluation framework.

⁹¹ David W. Pearce and R. Kerry Turner, *Economics of Natural Resources and the Environment* (Baltimore, MD: Johns Hopkins University Press, 1990).

3.2. Multi-criteria assessment framework

The multicriteria approach originally emerged within the field of regional science and was later developed within **Decision Theory**, drawing on a wide range of disciplines, including economics, psychology, and mathematics.

Broadly speaking, it comprises a **family of evaluation techniques** designed to serve different analytical and decision-making purposes. Multicriteria analysis aims to simplify complex problems by structuring them around a set of selected criteria and by providing a rational basis for comparing alternative courses of action.

Within a social and territorial context, objectives-whether related to urban regeneration projects, public policies, or labour-market interventions are generally characterised by a **multidimensional profile**. This plurality of dimensions can be represented through a vector W , composed of the different attributes and indicators required for a comprehensive assessment of the objective.

These may include:

- economic indicators, W_e ;
- social indicators, W_s ;
- physical and spatial indicators, W_f ;
- environmental indicators, W_a ;
- cultural indicators, W_c .

Accordingly, the multidimensional evaluation vector can be expressed as:

$$W = (W_e, W_s, W_f, W_a, W_c) \quad (7)$$

This formulation highlights that the overall assessment of an objective cannot be reduced to a single dimension, in contrast with the economic cost concept,

but results from the combined consideration, not just a simple sum, of several heterogeneous components. The need to account for such heterogeneity has become particularly relevant in the evaluation of environmental and territorial projects.⁹²

As Roscelli⁹³ observes, the increasing centrality of environmental issues has encouraged the adoption of integrated approaches capable of representing the complexity of economic, physical and social factors, including components that are difficult to measure or quantify.

Although quantitative, and especially financial, assessments are often perceived as more reliable than qualitative ones, the evaluation of qualitative attributes and the definition of the criteria through which they are expressed have progressively become established and methodologically mature fields, particularly in relation to complex territorial transformation projects.

From this perspective, MCDA provides a structured framework for combining quantitative and qualitative information without requiring all project effects to be converted into a single monetary unit.

HIERARCHY

Two main approaches can be distinguished for defining the criteria that form a multidimensional decision vector:

- Deductive approach:

General problem → Dimensions → Criteria → Indicators

- Inductive approach:

Alternatives → Observable effects → Common criteria

⁹² Riccardo Roscelli, ed., *Misurare nell'incertezza. Analisi, stime, valutazioni* (Turin: CELID, 1990), 34–51.

⁹³ Riccardo Roscelli, *Misurare nell'incertezza*, 2nd ed., pp. 28–29.

A fundamental assumption underlying MCDA structures is that the different elements of a decision problem can be organized hierarchically. The purpose of this process is to translate multidimensional complexity into progressively simpler and more comparable components. Each level of the hierarchy further specifies and clarifies the elements positioned at the preceding level:

Overall objective → Criteria → Subcriteria or indicators → Alternatives

The definition of criteria and their corresponding indicators therefore represents a central stage of any multidimensional evaluation. Criteria can be understood as measurable aspects of judgement that represent a specific dimension of the decision problem.

Their identification should make it possible to:

- provide a comprehensive description of the problem;
- distinguish effectively between the alternatives;
- express the objectives of the evaluation;
- rely on information that is understandable and available.

CRITERIA and INDICATORS

In the construction of an MCDA framework, criterion definition is particularly important because it determines the nature of the information included in the evaluation structure.

Criteria may differ according to the type of information they express.

They can be **quantitative or qualitative, direct or proxy-based, monetary or non-monetary**, and **cardinal or ordinal**. This distinction is relevant because it determines how each criterion can be measured, compared, normalized and integrated within the multicriteria assessment.

MATRICES

In general terms, the process is based on two main data inputs, which are organized into two matrices: the **evaluation or impact matrix (E)** and the **priority matrix (W)**.

The **impact matrix** records the performance of each alternative with respect to each criterion, thereby describing how the alternatives behave across the different dimensions of the decision problem. Each element of the matrix represents the performance or impact of a specific alternative in relation to a given criterion and may be expressed through quantitative, qualitative, cardinal or ordinal data, depending on the nature of the indicator considered.

		ALTERNATIVE				
		1	...	i	...	I
CRITERIA	.	e (i, j) Matrix (I*J)				
	j					
	.					
	J					

Table 4 - Impact matrix

The **priority matrix or vector**, by contrast, contains the relative weights assigned to the criteria and expresses their importance with respect to the overall objective. It is particularly useful when there is no dominant alternative compared to the others. If the proposed framework works within one scenario the matrix would be just a vector, as:

$$W=(w_1,w_2,...,w_n) \quad (8)$$

$$\sum_{j=1}^n w_j = 1 \quad (9)$$

Instead, if the evaluation needs to identify priorities within the criteria for different possible scenarios, the matrix would look like:

		CRITERIA				
SCENARIOS	1	...	j		J	
	.					
	n	w (j, n)				
	.					
	N	Matrix (J*N)				

Table 5 - Priority matrix

The priority matrix therefore represents the extent to which each criterion contributes to the final decision.

The **assessment matrix** combines the performance values contained in (E) with the criterion weights defined in (W), producing the overall score and final ranking of the alternatives. Each element expresses the overall performance of a given alternative under a specific set of priorities.

		ALTERNATIVES			
SCENARIOS	1	...	i		I
	.				
	n	s (i, n)			
	.				
	N	Matrix (I*N)			

Table 6 - Assessment matrix

The aggregation of the impact and priority matrices may be carried out through different evaluation procedures, depending on the nature of the data, the

measurement scales adopted and the multicriteria method applied. When only one decision scenario is considered, the matrix (S) is reduced to a single vector containing the overall scores of the alternatives.

More specifically:

- the **impact matrix (E)** contains the performance values of each alternative with respect to the selected criteria;
- the **priority matrix (W)** contains the preferences or weights assigned to those criteria;
- the **assessment matrix (S)** is obtained by combining the information contained in (E) and (W).

The determination of criterion weights represents a central stage of MCDA, and different **weighting procedures** are often associated with different methodological approaches. The main methods include:

- direct expression of preferences;
- ranking of criteria;
- allocation of scores;
- behavioural analysis;
- pairwise comparison methods;
- scenario-based methods or approaches relying on hypothetical preferences.

APPROACH CLASSIFICATION

Except from the weighting technique, multicriteria methods may be classified also according to the structure of the decision problem and the amount of alternatives into **discrete and continuous**. Discrete methods are used when the alternatives are finite and predefined, while continuous methods apply when the set of possible solutions is very large or theoretically unlimited.

A further classification depends on the **nature of the data** used in the evaluation. **Hard** methods rely mainly on quantitative indicators and numerical weights, usually requiring normalization. **Soft** methods are based on qualitative judgements, rankings or categories, while **mixed** methods combine quantitative data with expert or stakeholder-based assessments.

It should be emphasized that no multicriteria technique is universally suitable for every decision problem. The selection of the most appropriate method must therefore be assessed on a case-by-case basis, taking into account the characteristics of the problem, the nature of the available data and the objectives of the evaluation.

The results should also be presented in a clear and transparent manner to the intended users. This requires explicitly reporting the methodology adopted, the criteria considered, the weighting or priority structure applied, and any assumptions, simplifications or approximations introduced during the analysis.⁹⁴

⁹⁴ Silvia Gazzera, "Valutazione della sostenibilità economica dei progetti: un'applicazione congiunta dell'approccio Life Cycle" (Politecnico di Torino, 2019), p.25.

3.2.1 Analytic Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP), developed by Thomas Saaty (1980),⁹⁵ is a **structured decision-making method** designed to support the evaluation of complex problems where multiple interdependent factors, conflicting objectives and different stakeholder perspectives must be considered simultaneously.

Such problems cannot be adequately understood by isolating their individual components, since environmental, economic, social and political dimensions interact within dynamic networks of reciprocal relationships.

In this context, the AHP adopts a systemic approach: **it decomposes complexity into a hierarchical structure, makes priorities and value judgements explicit, and supports the identification of a satisfactory compromise among alternative courses of action.**

Rather than seeking a single objectively correct solution, the method provides a transparent framework for organizing available knowledge and comparing alternatives according to the objectives and preferences involved in the decision process.

Within the broader family of MCDA methods, **the Analytic Hierarchy Process can be classified as a discrete, hierarchical, cardinal method.** It is designed to evaluate a finite set of alternatives by decomposing the decision problem into successive levels, typically including the overall goal, criteria, sub criteria and alternatives.

Its main characteristics lie in its ability to represent a complex decision problem by decomposing it into elementary components and **subsequently comparing these components in pairs**, until a priority scale among the alternatives is established at each level of the hierarchy.

⁹⁵ Thomas L. Saaty, *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*, New York, McGraw-Hill, 1980.

Moreover, the method can simultaneously incorporate both **numerical assessments and purely qualitative judgements**. At each level of the decision process, it also provides measures for **evaluating the consistency** of the judgements expressed.

The AHP is based on three fundamental principles:

- a. the principle of decomposition;
- b. the principle of comparative judgements;
- c. the synthesis of priorities.

a. DECOMPOSITION

The process begins with the decomposition of a complex decision problem into its elementary components. These components are grouped into homogeneous sets and organized into successive levels, thereby forming a hierarchical structure.

The decomposition proceeds from the top to the bottom of the hierarchy. The overall goal is placed at the first level, followed by the evaluation criteria, which may be further divided into sub criteria.

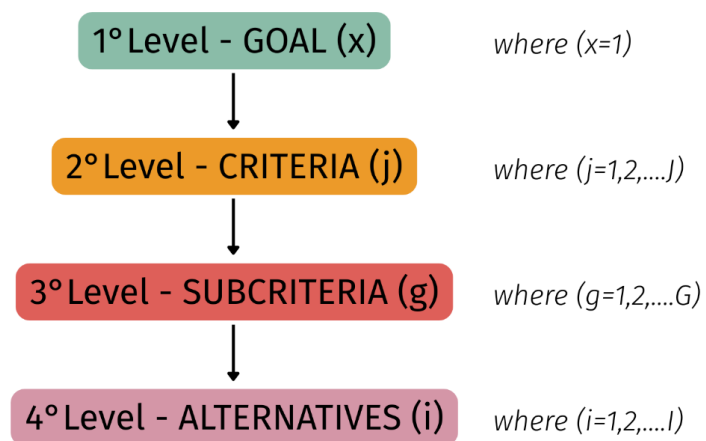


Figure 35 - General hierarchical structure of the Analytic Hierarchy Process (AHP), composed of the overall goal, criteria, sub-criteria and alternatives.

Author's elaboration

The most specific elements of the decision problem - the alternatives - are positioned at the lowest level of the hierarchy.

The hierarchy is generally constructed according to a deductive, top-down approach, starting from the overall objective and progressively breaking it down into more specific components, but it may also be developed inductively.

b. COMPARATIVE JUDGEMENTS

Pairwise comparison is the measurement procedure used to establish the relative priorities of the elements at each level of the hierarchy and constitutes the core of the AHP methodology. The elements belonging to the same hierarchical level are compared two at a time with respect to each element located at the immediately higher level. Each element of the upper level therefore acts as a reference criterion, or parent element, for assessing the relative importance of the elements placed below it.

The comparison is based on the following question:

Which of the two elements is more important with respect to the criterion considered, and to what extent?

A binary preference relationship is thus established between each pair of elements. The intensity of this preference is expressed through a positive numerical value selected from Saaty's nine-point Fundamental Scale. The resulting judgements are subsequently entered into a pairwise comparison matrix.

Both quantitative data and qualitative judgements can be incorporated into this procedure. Regardless of their original nature or unit of measurement, the elements are evaluated in relative terms and expressed through the same comparison scale. In this way, the AHP makes it possible to compare and assign relative weights to criteria that may initially appear heterogeneous or incommensurable.

Saaty's fundamental scale therefore acts as a common measurement framework for translating verbal judgements into numerical values.

It ranges from 1, indicating equal importance, to 9, indicating extreme importance of one element over another. Intermediate values represent progressively increasing levels of preference, while reciprocal values are used when the second element is preferred to the first. The scale is generally considered sufficiently broad to distinguish among different intensities of preference, while remaining cognitively manageable for the decision-maker.

INTENSITY OF IMPORTANCE	DEFINITION	EXPLANATION
1	Equal importance	Two activities contribute equally on the objective
3	Moderate Importance	Experience and judgment slightly favor one activity over another
5	Strong Importance	Experience and judgment strongly favor one activity over another
7	Very strong	An activity is favored very strongly over another
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

Table 7 – Saaty's fundamental scale for pairwise comparison judgments in the AHP method.

This table is used to determine the numerical values to be entered into the square pairwise comparison matrices constructed at each level of the hierarchy, starting from the second level onwards. If n denotes the number of elements composing the level of the objects to be evaluated, namely the alternatives, and

m denotes the number of elements belonging to the immediately higher hierarchical level, namely the criteria, then m pairwise comparison matrices of order $n \times n$ are constructed for that specific level. Let:

$n = \text{number of alternatives to be evaluated}$

$m = \text{number of criteria belonging to the immediately higher hierarchical level}$

For each criterion, a pairwise comparison matrix including all n alternatives is constructed. Since the alternatives are represented both in the rows and in the columns, each matrix has dimensions:

$$n \times n$$

Therefore, as the number of criteria is m , the evaluation of that hierarchical level requires the construction of:

m pairwise comparison matrices of order $n \times n$

In other words, each of the m criteria is associated with a separate $n \times n$ matrix, in which the n alternatives are compared pairwise with respect to the criterion under consideration.

$j(n)$	i_1	.	.	.	I
i_1	1				
.		1			Reciprocal values
.			1		
.	Judgments			1	
I					1

Table 8 - General structure of a pairwise comparison matrix in the AHP method. Judgments are entered in one triangular part of the matrix, while the opposite triangular part contains the corresponding reciprocal values

All pairwise comparison matrices share three main characteristics:

- the elements on the main diagonal are equal to one, since each element is compared with itself,

- the matrix satisfies the **reciprocity property**,
- all the elements of the matrix are **positive**

Reciprocity is a fundamental feature of the AHP analytic procedure. Once a value between 1 and 9 is assigned to express the preference of element (i) over element (i') with respect to criterion (j), the reciprocal value is automatically assigned to the opposite comparison, that is, to element (i') when compared with element (i).

For example, if alternative (A) is judged to be three times more important than alternative (B) with respect to a given criterion, the corresponding value in the matrix will be (3). Conversely, when (B) is compared with (A), the value will be (1/3). Therefore, it is sufficient to complete only one triangular half of the matrix, as the remaining values are obtained through reciprocity.

The data contained in the pairwise comparison matrices are then used to derive priority scales, or priority vectors, among the alternatives of the considered level. These priority values make it possible to compare the relative contribution of each alternative to the achievement of the overall objective.

c. Synthesis of priorities

In order to extract the priority scale, or weights, from the pairwise comparison matrix, the principal eigenvector of the matrix is computed and subsequently normalized. From a mathematical point of view, this process is based on the properties of eigenvalues and eigenvectors.

$$[A] * w = \lambda_{\max} * w$$

where [A] is the pairwise comparison matrix, (w) is the priority vector, and ($\lambda_{\max}$) is the maximum eigenvalue of the matrix.

In the AHP, eigenvalue and eigenvector theory can be applied because pairwise comparison matrices are **square, positive and reciprocal matrices**.

If the matrix is perfectly consistent, all judgements are mutually compatible. For example, if C1 is twice as important as C2, and C2 is three times as important as C3, then C1 must be six times as important as C3.

In mathematical terms, this consistency condition implies that the entire comparison matrix can be reconstructed from the ratios between the weights. In this case, multiplying the matrix A by the priority vector w gives:

$$Aw = nw$$

where n is the order of the matrix, that is, the number of elements compared. This equation corresponds to the general definition of an eigenvector:

$$Aw = \lambda w$$

Consequently, in a perfectly consistent matrix, the priority vector w is an eigenvector of the judgement matrix, and the corresponding eigenvalue is equal to:

$$\lambda = n$$

However, the judgements expressed by the decision-maker are almost never perfectly consistent. For this reason, the AHP uses the **principal eigenvector**, namely the eigenvector associated with the maximum eigenvalue of the matrix:

$$\lambda_{\max}$$

This eigenvector represents the best approximation of the system of weights implicitly contained in the pairwise comparisons. Moreover, the value of $\lambda_{\max}$ makes it possible to measure the consistency of the judgements. In the case of perfect consistency:

$$\lambda_{\max} = n$$

whereas, when inconsistencies are present:

$$\lambda_{\max} > n$$

When inconsistencies are present, due to perturbations in the pairwise comparisons between elements, the absolute or cardinal scale is no longer

perfectly preserved. For instance, if C_1 is considered twice as important as C_2 , and C_2 three times as important as C_3 , then C_1 should theoretically be six times as important as C_3 . However, the decision-maker may assign a value of five instead. In this case, the comparison matrix is affected by inconsistency, and the ideal relation $A \cdot w = n \cdot w$ no longer holds. The distance between $\lambda_{\max}$ and n is therefore used to calculate the Consistency Index:

$$CI = \frac{\lambda_{\max} - n}{n - 1} \quad (10)$$

The **Consistency Ratio** is then obtained by comparing the Consistency Index with a reference value, known as the **Random Index**:

$$CR = \frac{CI}{RI}, \quad (CR \leq 0.10) \quad (11)$$

where RI is the Random Index, namely a reference value associated with the size of the matrix.

The Random Index was calculated by Saaty, the developer of the method, by generating 500 random square, positive and reciprocal matrices for each matrix order n , from 1 to 10 elements. In these matrices, the entries were randomly selected from the possible values of Saaty's Fundamental Scale and their corresponding reciprocals.

N	1	2	3	4	5	6	7	8	9	10
R.I.	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

Table 9 – Random Index (RI) values according to the order (N) of the pairwise comparison matrix.

3.3. Statistical analysis

3.3.1 Multiple regression analysis (MRA)

Regression analysis is one of the most widely used techniques for analyzing multifactorial data. Historically, regression emerged from the mathematical framework of the least squares method, developed in the nineteenth century to estimate unknown parameters in the presence of observational errors. From a statistical perspective, the concept of regression is commonly associated with Francis Galton,⁹⁶ who observed that extreme values tend to regress towards the mean.

This intuition subsequently evolved into a broader statistical approach for studying relationships between variables.

Linear regression analysis is a statistical technique used to investigate and model the relationship between a dependent variable and one or more independent variables.

In its simplest form, **simple regression analysis** estimates how the expected value of a response variable changes as a function of a single explanatory variable. In its multiple form, **multiple regression analysis** allows several predictors to be included simultaneously, making it possible to estimate the individual contribution of each variable to the outcome.⁹⁷

The regression model makes it possible to statistically formalize the relationship between a population, a sample extracted from it, and the variables observed within that sample.

As P. Morano explains “once a population and a set of characteristics, or phenomena, of its elements have been identified, and assuming that a

⁹⁶ Galton, F. (1886) — “*Regression towards Mediocrity in Hereditary Stature*”, Journal of the Anthropological Institute

⁹⁷ Douglas C. Montgomery, Elizabeth A. Peck, and G. Geoffrey Vining, *Introduction to Linear Regression Analysis*, 5th ed. Hoboken, NJ: Wiley, 2012.

relationship exists among them, the aim is to express this relationship through a functional relation based on the information obtained from a randomly selected sample of the population".⁹⁸

Within regression models, the variables considered are generally expressed in quantitative terms. The phenomenon *to be explained* is represented by the **dependent variable**, also referred to as the response or *explained variable*, while the factors used to describe or predict its variation are represented by one or more **independent variables**, also called *explanatory or descriptive variables*.

Therefore, regression analysis aims to identify the functional relationship linking the dependent variable y to a set of independent variables x_i . This relationship can be expressed as:

$$y = f(x_1, x_2, \dots, x_n) \quad (12)$$

The random sample, after having detected the characters of k elements (of the population) will be:

$$\begin{aligned} &(y_1, x_{11}, x_{12}, \dots, x_{1n}) \\ &(y_2, x_{21}, x_{22}, \dots, x_{2n}) \\ &(y_3, x_{31}, x_{32}, \dots, x_{3n}) \\ &\text{-----} \\ &(y_k, x_{k1}, x_{k2}, \dots, x_{kn}) \end{aligned} \quad (13)$$

Where $(y_k, x_{k1}, x_{k2}, \dots, x_{kn})$ refers to the k element of the sample, y_k is the dependent variable, and $x_{k1}, x_{k2}, \dots, x_{kn}$ are the independent variables.

⁹⁸ P. Morano, (2002) L'analisi di regressione per le valutazioni di ordine estimativo, Celid Torino, p. 9.

SIMPLE REGRESSION ANALYSIS (SRA)

Although the objective of this section is to introduce multiple regression analysis, the simple regression model represents a necessary preliminary step. It allows the basic logic of regression to be explained in a clearer way, both analytically and graphically, through the relationship between one dependent variable and one independent variable.

Simple regression translates into a mathematical function $f(.)$ that represents the relationship between x and y , based on a sample of collected observations.⁹⁹

Fundamentally:

$$y = f(x)$$

(14)

The observation of only two variables implies that a generic sample, consisting of k observations, will be characterized by the following properties:

$$(y_1, x_1);$$

$$(y_2, x_2);$$

$$(y_3, x_3);$$

$$(y_k, x_k).$$

The **deterministic model** presents certain limitations inherent to its structure.

It is well known that, in real-world cases, a hypothetical dependent variable cannot depend solely on a single independent variable; rather, it is far more likely that multiple factors contribute to explaining a given phenomenon.

⁹⁹ Lorenzo Castagnaro, *Valutazione dell'influenza della classe energetica sui prezzi degli immobili residenziali nella città di Torino*, Tesi di Laurea Magistrale, Corso di Laurea Magistrale in Architettura per il Progetto Sostenibile, Politecnico di Torino, rel. Prof.ssa Elena Fregonara, co-rel. Prof. Valerio Lo Verso e Arch. Alice Barreca.

Furthermore, in practical applications, it is much more probable that one will identify not a single exact result, but rather an interval within which the outcomes are expected to fall.

For this reason, the deterministic model proves inadequate for statistical inference, as it relies on representative samples, involves unpredictable individual decisions, simplifies a complex reality, suffers from measurement errors, and often uses second-hand data.

A **probabilistic model** is certainly more reliable, as it accounts for the random aspects that may affect the representation of the phenomenon through the model.

The probabilistic model takes the following form:

$$y = f(x) + \varepsilon \quad (15)$$

This formulation identifies y as the dependent variable, whilst x is decomposed into a **non-random element** $f(x)$ and a **stochastic error** ε – the component that accounts for the deviation from a mathematically deterministic relationship. The probabilistic model set out in ((15)) must be expressible across all k observations in the sample; consequently:

$$y_1 = f(x_1) + \varepsilon_1 ;$$

$$y_2 = f(x_2) + \varepsilon_2 ;$$

$$Y_k = f(x_k) + \varepsilon_k ;$$

Conducting a regression analysis requires two fundamental operations:

- reconstructing the deterministic part $f(x)$ of the phenomenon under study;
- and establishing hypotheses regarding the probabilistic distribution of the random errors ε_k .

In the most recurrent scenario, it is assumed that $f(x)$ can be expressed as a linear combination of the unknown parameters:

$$f(x) = \beta_0 + \beta_1 x$$

The function $f(x)$ is given by the sum of a constant parameter β_0 and the product of another constant parameter β_1 with the variable x . If we therefore incorporate the probabilistic component, the function takes the following form:

$$f(x) = \beta_0 + \beta_1 x + \varepsilon$$

For each of the k random observations that make up the sample, the above expression translates into the following form:

$$\begin{aligned} y_1 &= \beta_0 + \beta_1 x_1 + \varepsilon_1; \\ y_2 &= \beta_0 + \beta_1 x_2 + \varepsilon_2; \\ &\text{-----} \\ y_k &= \beta_0 + \beta_1 x_k + \varepsilon_k; \end{aligned}$$

Finally, the model can be represented as follows:

$$y_j = \beta_0 + \beta_1 x_j + \varepsilon_j; \text{ with } j = 1, 2, \dots, k.$$

(16)

In the previous relationships, the known terms are represented by the variables x_j and y_j , derived from the sample observations, whereas the parameters β_0 and β_1 are the unknowns of the model.

If we now consider the simple linear regression model, it is easy to recognize that it establishes a relationship between x and y typical of a straight line in the Cartesian plane.

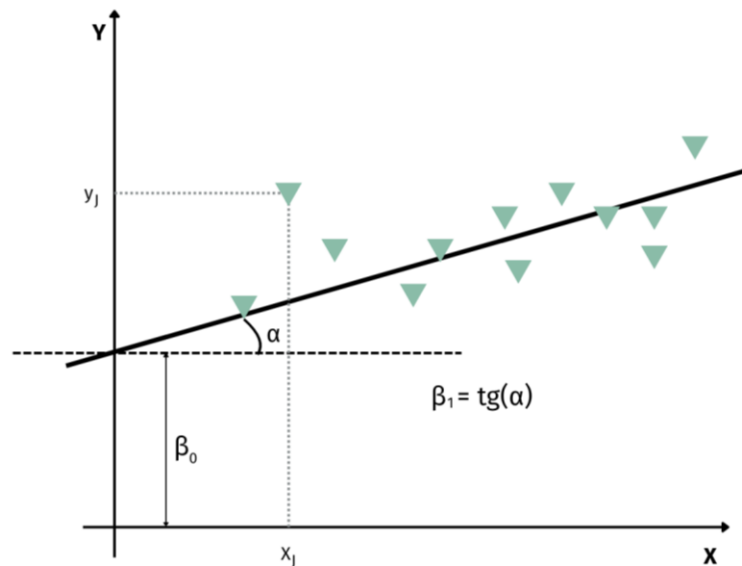


Figure 36 - Graphical representation of the simple linear regression model

Source: Author's elaboration based on Morano, P. (2002), *L'analisi di regressione per le valutazioni di ordine estimativo*, Torino: CELID, p. 26.

Indeed, the equation $y = \beta_0 + \beta_1 x$ represents a line whose intercept is β_0 and whose slope is β_1 .

Hence, the determination of the best line requires a rule to derive the values of β_0 and β_1 . This rule, which serves precisely to calculate those coefficients, is referred to as the "ordinary least squares" method (OLS).

Least squares is an optimization method used to find a mathematical function that best fits a collection of data points, without the constraint of passing exactly through each of them-unlike interpolation.

The function selected is the one that minimizes the total sum of the squared deviations between the fitted curve and the actual data points.

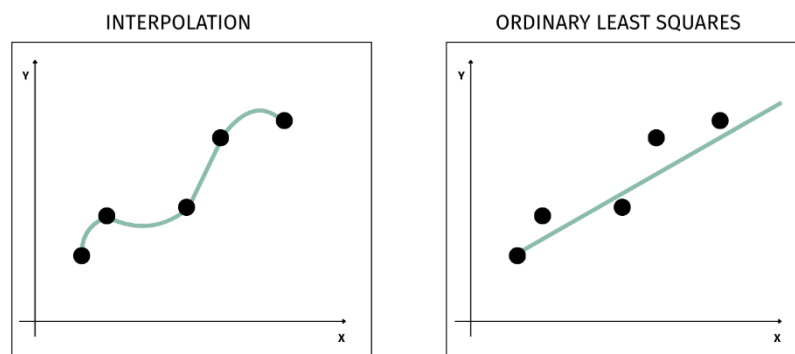


Figure 37 - Difference between interpolation and Ordinary Least Squares (OLS).

Author's elaboration

Once we have found the regression line $y = \beta_0 + \beta_1 x$ that best fits the data, we can graphically compare each observed data point (x_j, y_j) with its corresponding predicted point on the line. This predicted point shares the same x_j coordinate, while its y -coordinate is:

$$\underline{y}_j = \beta_0 + \beta_1 x_j,$$

computed directly from the regression equation.

The vertical gap between the observed value y_j and the fitted value $\underline{y}_j$, defined as:

$$\varepsilon_j = y_j - \underline{y}_j,$$

(17)

is referred to as the residual. This residual captures the random error specific to the j -th observation.

Clearly, the better the regression line fits the observed data, i.e., the closer it passes to the points, the smaller the residuals will be, and the more reliable the estimated line becomes.

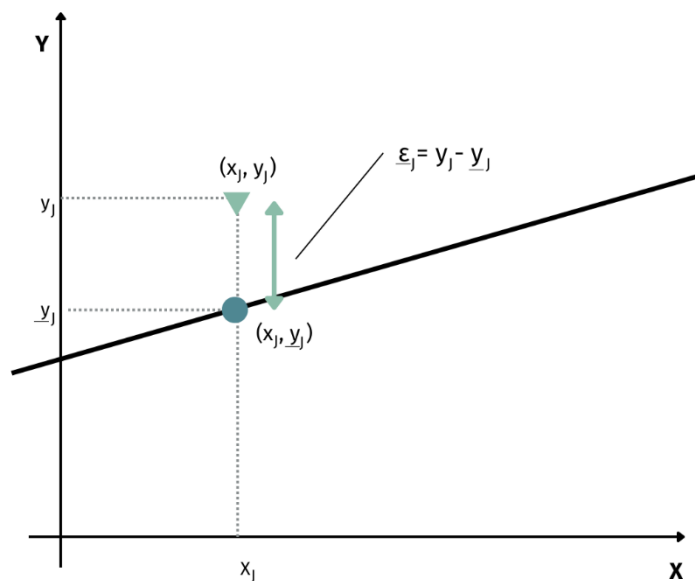


Figure 38 - Residuals in the Ordinary Least Squares (OLS) method.

Author's elaboration based on Morano, P. (2002), *L'analisi di regressione per le valutazioni di ordine estimativo*, Torino: CELID, p.32.

By assuming the optimal regression line, we can effectively filter out the random disturbances, leading to progressively more precise estimates.

The least squares method provides a way to carry out this procedure. According to this principle, the best-fitting line is the one that minimizes the sum of the squared vertical distances between the observed values and the corresponding fitted values on the line:

$$\sum_j (y_j - \hat{y}_j)^2 = \min \quad (18)$$

Given that we have already defined the relationship as:

$$y_j = \beta_0 + \beta_1 x_j + \varepsilon_j$$

we can substitute y_j with its expression $\beta_0 + \beta_1 x_j$, leading to:

$$\sum_j (y_j - \beta_0 - \beta_1 x_j)^2 = \min \quad (19)$$

By expanding this expression and solving for the two unknown parameters β_0 and β_1 , we obtain the following closed-form solutions:

$$\beta_0 = \frac{\sum_j y_j - \beta_1 \sum_j x_j}{k} \quad (20)$$

$$\beta_1 = \frac{k \sum_j x_j y_j - \left(\sum_j x_j \right) \left(\sum_j y_j \right)}{k \sum_j x_j^2 - \left(\sum_j x_j \right)^2} \quad (21)$$

Through these two formulas, it is possible to compute the parameters β_0 and β_1 , which were initially unknown, and which allow us to represent the regression line on the Cartesian plane.

After estimating the coefficients β_0 and β_1 , it is crucial to determine whether they carry statistical meaning or whether they are simply the outcome of a mathematical calculation that offers no insight into the model's validity. Essentially, we must test whether x truly contributes to explaining y .

This verification process can be broken down into two main steps, which involve measuring:

- How well the regression line fits the observed data points in the sample;
- Whether the estimated coefficients β_0 and β_1 are statistically significant.

Coefficient of determination

The coefficient of determination, R^2 , is used to evaluate how well the regression model explains the variability of the dependent variable. Its calculation is based on the comparison between the total variability of the observed values and the variability that remains unexplained by the model.

The total deviation of each observed value from the mean can be decomposed into two components:

$$(y_j - \bar{y}) = (\underline{y}_j - \bar{y}) + (y_j - \underline{y}_j)$$

where y_j is the observed value, $\bar{y}$ is the mean of the observed values, and $\underline{y}_j$ is the value estimated by the regression model line.

The **Total Sum of Squares (TSS)** measures the overall variability of the observed values around their mean:

$$TSS = \sum_j (y_j - \bar{y})^2$$

The **Residual Sum of Squares (RSS)** measures the part of variability that is not explained by the regression model, namely the distance between observed and estimated values:

$$RSS = \sum_j (y_j - \hat{y}_j)^2$$

Based on these two quantities, the coefficient of determination can be expressed as:

$$R^2 = 1 - \frac{RSS}{TSS}$$

(22)

Therefore, R^2 ranges from 0 to 1:

- An R^2 value of 0 indicates that the regression model explains none of the variability in the relationship between x and y . In this scenario, the fitted regression line is flat, running parallel to the horizontal axis.
- An R^2 value of 1 indicates that the model provides a perfect explanation of the relationship between the sample observations—that is, between

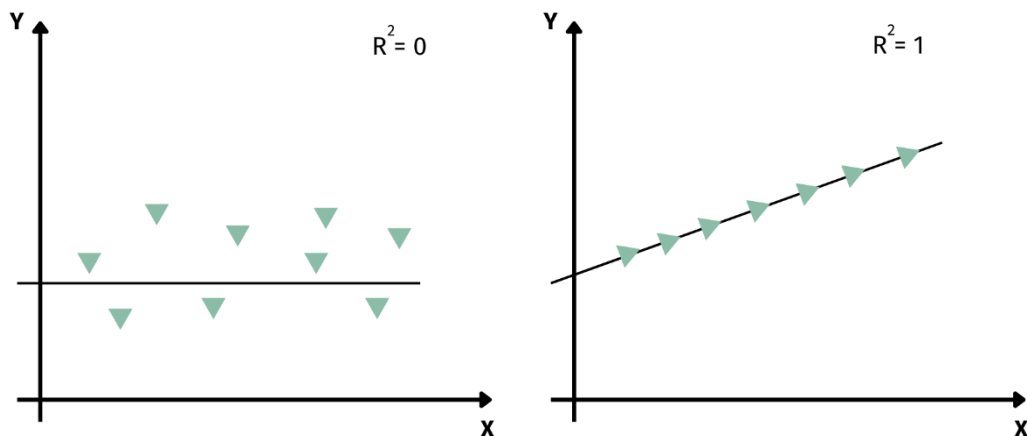


Figure 39 - Interpretation of R^2 in linear regression

Author's elaboration based on Morano, P. (2002), *L'analisi di regressione per le valutazioni di ordine estimativo*, Torino: CELID, pp. 34-36.

the y 's and the x 's. In this ideal case, every observed data point falls precisely on the regression line.

Standard Error

A further indicator useful for assessing the reliability of a model is the standard error of the estimate (SE), defined as the square root of the ratio between the residual deviance and the degrees of freedom of the system g .

The degrees of freedom are computed as:

$$g = k - n$$

where k is the total number of observations and n is the number of regression parameters to be estimated (e.g., with $k = 50$ observations and two parameters β_0 and β_1 : $g = 50 - 2 = 48$).

Once the degrees of freedom are defined, the standard error is calculated as:

$$SE = \sqrt{\frac{\sum_j (y_j - \hat{y}_j)^2}{g}} \quad (23)$$

The ratio between the standard error and the mean of the dependent variable is referred to as the percentage error, and expresses the deviation between observed values and model predictions:

$$e = \frac{SE}{\bar{y}} \quad (24)$$

When performing random sampling, it may occur that the sample is not fully representative, and that the application of the least squares criterion produces estimates that do not correctly identify the true regression line. To verify the significance of the parameters β_0 and β_1 , it is possible to perform tests based on the Student's t-distribution, using the standard error of the parameters.

These tests are useful to determine whether an explanatory variable is statistically significant, and therefore whether it should be included in or excluded from the regression model.

Test on β_0

The test on β_0 verifies the null hypothesis H_0 , according to which the regression line possesses a non-zero intercept, against the alternative hypothesis H_1 , which assumes a line passing through the origin. The test is performed by calculating:

$$t_{\beta_0} = \frac{\beta_0}{S_{\beta_0}} \quad (25)$$

where S_{β_0} is the standard error of parameter β_0 , derived from:

$$S_{\beta_0} = \sqrt{SE^2 \cdot \frac{\sum_j x_j^2}{k \sum_j (x_j - \bar{x})^2}} \quad (26)$$

The calculated value is then compared with the critical value read from Student's t-distribution tables, corresponding to the system's degrees of freedom and the chosen significance level.

Test on β_1

Similarly, the test on β_1 verifies the null hypothesis H_0 , according to which the explanatory variable x is statistically significant in explaining the dependent variable y - identified by the slope coefficient β_1 - against the alternative hypothesis H_1 , for which x has no statistical significance, characterized by a slope coefficient $\beta_1 = 0$. The same procedure applies:

$$t_{\beta_1} = \frac{\beta_1}{S_{\beta_1}} \quad (27)$$

where S_{β_1} is the standard error of parameter β_1 , derived from:

$$S_{\beta_1} = \sqrt{\frac{SE^2}{\sum_j (x_j - \bar{x})^2}} \quad (28)$$

As before, the calculated t-value is compared with the critical value from Student's t-distribution tables, given the degrees of freedom and the chosen significance level.

From the t-statistic to the p-value

While the t-statistic allows for a direct comparison against a critical value from statistical tables at a fixed significance level (e.g., 5%), the p-value offers a more informative and continuous measure of significance. Rather than simply indicating whether a coefficient is significant at a chosen threshold, the p-value expresses the exact probability of observing a t-statistic as extreme as, or more extreme than, the one calculated, under the assumption that the null hypothesis is true:

$$p = P(|T| > |t_{\beta_1}|) \quad (29)$$

where T follows a Student's t-distribution with g degrees of freedom.

A low p-value (conventionally $p < 0.05$) indicates that such an extreme result would be highly unlikely if the variable had no real effect, leading to the rejection of H_0 and the conclusion that the coefficient is statistically significant. Conversely, a high p-value suggests that the observed coefficient cannot be reliably distinguished from zero, and the variable may be excluded from the model without a substantial loss of explanatory power.

In modern statistical software, the p-value is computed directly and is generally preferred to manual table lookup, as it provides an exact significance level rather than a binary accept/reject outcome at a fixed threshold.

MULTIPLE REGRESSION ANALYSIS (MRA)

In the realm of economic and social phenomena, it is rather uncommon for a single explanatory factor to adequately describe the behavior of a dependent variable, as assumed by the simple regression model. Far more frequently, the variable under study is influenced by multiple determinants, making it necessary to simultaneously consider the effect of several explanatory variables.

From a geometrical point of view, while simple regression aims to identify the line that best fits the cloud of points in the Cartesian plane, multiple regression extends this approach to the search for the **optimal (hyper) plane** in the multidimensional space containing the points corresponding to the sample observations.

The probabilistic model, which offers advantages over the limitations of the deterministic one, defines the dependent variable y as follows:

$$y_j = f(x_{j1}, x_{j2}, \dots, x_{jn}) + \varepsilon_j$$

for $j = 1, 2, \dots, k$, where $(x_1, x_2, \dots, x_n)$ are the explanatory variables and ε_j is the random error term.

The function $f(\cdot)$ is assumed to be linear in the parameters:

$$f(\cdot) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n$$

Incorporating the stochastic component, this becomes:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n + \varepsilon$$

(30)

It is worth noting that a simple regression model is merely a restricted version of the multiple regression framework, obtained by imposing:

$$\beta_2 = \beta_3 = \dots = \beta_n = 0$$

Thus, for each of the k sample observations, the probabilistic specification yields:

$$\begin{aligned}
 y_1 &= \beta_0 + \beta_1 x_{11} + \beta_2 x_{12} + \beta_3 x_{13} + \cdots + \beta_n x_{1n} + \varepsilon_1 \\
 y_2 &= \beta_0 + \beta_1 x_{21} + \beta_2 x_{22} + \beta_3 x_{23} + \cdots + \beta_n x_{2n} + \varepsilon_2 \\
 y_3 &= \beta_0 + \beta_1 x_{31} + \beta_2 x_{32} + \beta_3 x_{33} + \cdots + \beta_n x_{3n} + \varepsilon_3 \\
 &\quad \text{-----} \\
 y_k &= \beta_0 + \beta_1 x_{k1} + \beta_2 x_{k2} + \beta_3 x_{k3} + \cdots + \beta_n x_{kn} + \varepsilon_k
 \end{aligned}$$

The Multiple Regression Model (MRM) can be specified in a linear form where $f(\cdot)$ is the linear function represented as:

$$y_j = \beta_0 + \beta_1 x_{j1} + \beta_2 x_{j2} + \beta_3 x_{j3} + \cdots + \beta_n x_{jn} + e_j \quad j = 1, 2, \dots, k \quad (31)$$

or, using summation notation:

$$y_j = \beta_0 + \sum_{i=1}^n \beta_i x_{ji} + e_j \quad i = 1, \dots, n; \quad j = 1, 2, \dots, k \quad (32)$$

Multiple regression analysis is typically implemented through matrix notation,

$$\mathbf{Y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_k \end{bmatrix} \quad \mathbf{X} = \begin{bmatrix} 1 & x_{11} & x_{12} & \cdots & x_{1n} \\ 1 & x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & x_{k1} & x_{k2} & \cdots & x_{kn} \end{bmatrix} \quad \mathbf{b} = \begin{bmatrix} b_0 \\ b_1 \\ \vdots \\ b_n \end{bmatrix} \quad \mathbf{e} = \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_k \end{bmatrix} \quad (33)$$

which proves especially useful in simplifying the model's framework when a substantial number of variables is involved.

Just like in the simple regression framework, the multiple regression model (MRM) calls for a series of diagnostic checks, which can be grouped into two main phases:

1. Evaluating how well the regression hyperplane fits the observed sample data points;
2. Testing the significance of the estimated coefficients $\beta_0, \beta_1, \beta_2, \dots, \beta_n$

The diagnostic tests applied to the multiple regression model are largely the same as those used in the simple regression framework, though they are accompanied by additional measures – not strictly essential for the testing procedure itself – which are worth calculating given the increased number of regressors.

Key statistics include:

The coefficient of determination R^2

$$R^2 = \frac{\mathbf{b}^T \mathbf{X}^T \mathbf{y} - k \bar{y}^2}{\mathbf{y}^T \mathbf{y} - k \bar{y}^2}$$

(34)

Bold symbols represent matrices.

The adjusted coefficient of determination R_c^2

$$R_c^2 = R^2 - \frac{n(1 - R^2)}{k - n - 1}$$

(35)

The adjusted R^2 is employed to counteract the well-known tendency of multiple regression to overstate the goodness of fit as additional explanatory variables are included in the model.

The standard error of the estimate SE

This statistic measures the typical discrepancy between the actual observed values and the model's fitted values:

$$SE = \sqrt{\frac{\mathbf{y}^T \mathbf{y} - \mathbf{b}^T \mathbf{X}^T \mathbf{y}}{k - (n + 1)}}$$

(36)

Parameter significance tests, performed on the associated variables, follow the same logic as in the simple regression case:

$$t_{\beta_i} = \frac{\beta_i}{S_{\beta_i}} i = 1, 2, \dots, n$$

(37)

where S_{β_i} represents the standard error of the coefficient under examination. The resulting t-statistic is then compared against the critical value from the Student's t-distribution, based on the degrees of freedom and the selected significance level for testing H_0 .

- **The Fisher F-test** is used to evaluate the joint significance of all regression coefficients together, in contrast to the t-test, which examines the significance of each coefficient individually.
- **Variance Inflation Factors (VIF)**. By examining the diagonal entries of the inverse of the correlation matrix, one can detect the presence or absence of multicollinearity among the independent variables included in the model.

MULTIPLE REGRESSION APPLIED IN THE REAL ESTATE MARKET ANALYSIS

When the generic regression model is used in the real estate field, the function becomes:

$$P = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n + \varepsilon$$

(38)

where P is the explicit market price, β_0 is the constant, $\beta_1, \beta_2, \dots, \beta_n$ are the implicit prices for each variable considered, and ε is the stochastic and measuring error.

According to Simonotti (1988): *"The regression model makes it possible to establish a correlation between the market price of a real estate asset and the intrinsic and extrinsic features that most significantly influence it, as well as the reciprocal relationships among those features and, most importantly, the quantitative impact that each feature has on the market price."*¹⁰⁰

¹⁰⁰ M. Simonotti, (1988), L'analisi di regressione nelle valutazioni immobiliari, Bollettino degli Interessi Sardi. Studi di Economia e Diritto, n. 3, p. 369.

Regression is a statistical tool that is generally used for several main purposes, even in the real estate field, namely:

- describing the relationship between variables;
- isolating the marginal effect of a variable, i.e., estimating its influence while netting out the effects of all other covariates;
- generating predictions, i.e., estimating the expected value of the dependent variable conditional on a given set of predictors.

Functional form: linear and non-linear specifications

The regression model presented in (22) assumes a **linear relationship** between the market price P and the explanatory variables; each coefficient β_i represents a constant marginal contribution of the corresponding characteristic to price, independent of the level of the variable itself. While this specification offers computational simplicity and direct interpretability, it may not always adequately reflect the behavior of real estate markets, where the marginal effect of certain characteristics is not constant but varies across the range of observations.

A common refinement involves the application of **logarithmic transformations** to one or both sides of the equation. Three specifications are widely adopted in the literature:

- **Linear-log:** $P = \beta_0 + \beta_1 \cdot \ln(X) + \varepsilon$ - the effect of X on price is decreasing; a 1% increase in X produces a change of $\beta_1/100$ units in P
- **Log-linear:** $\ln(P) = \beta_0 + \beta_1 X + \varepsilon$ - price changes at a constant percentage rate as X varies; β_1 approximates the percentage change in P for a one-unit increase in X
- **Log-log:** $\ln(P) = \beta_0 + \beta_1 \cdot \ln(X) + \varepsilon$ - constant elasticity model; β_1 represents the percentage change in P for a 1% change in X , independently of the level of either variable

A key property of all three specifications is that, despite modelling a non-linear relationship between X and P in their original scales, they remain linear in the parameters and can therefore still be estimated through Ordinary Least Squares. The non-linearity is absorbed by the transformation of the variables, not by a change in the parameter structure.

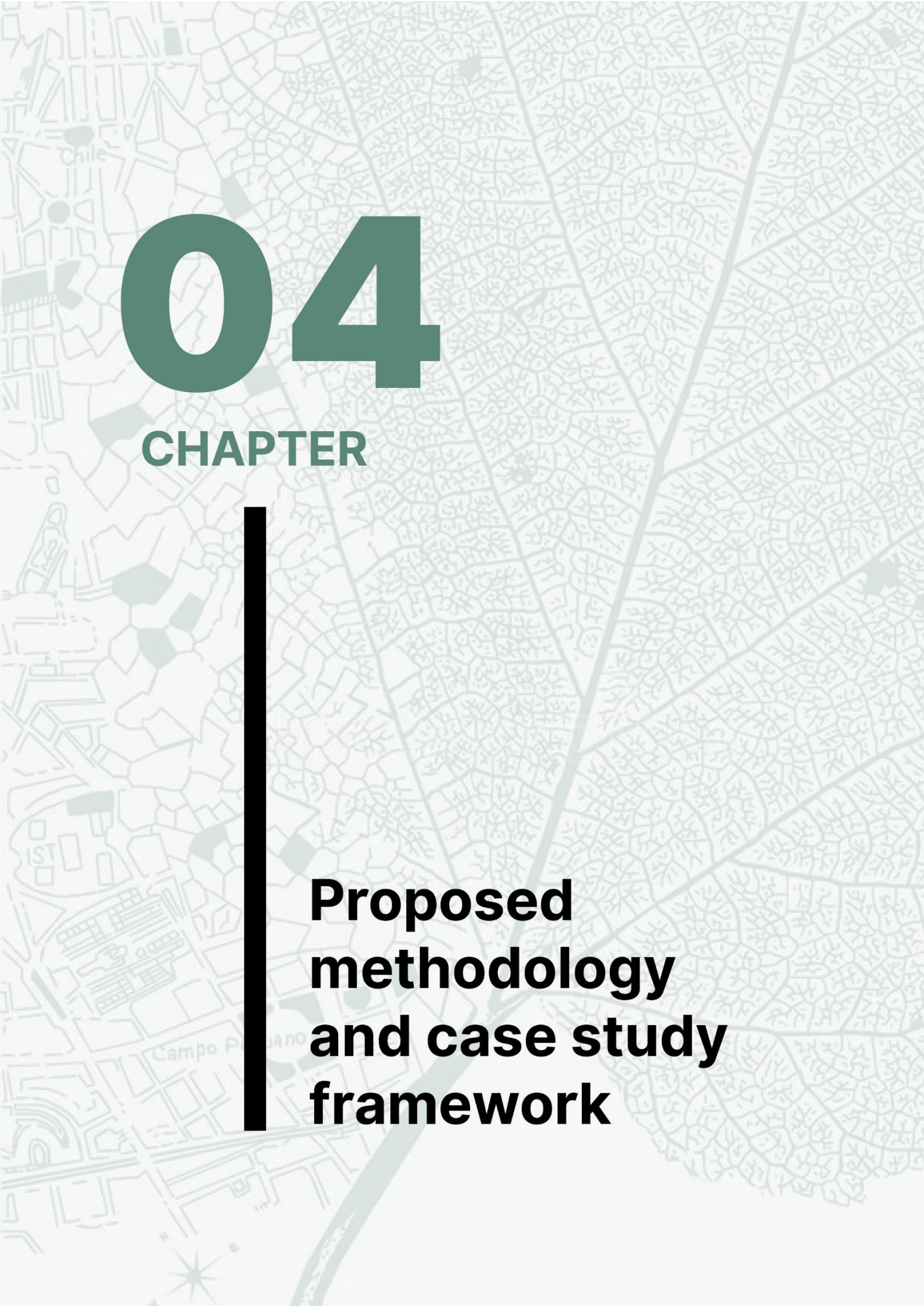
In real estate hedonic models, the log-linear and log-log specifications are particularly common, since property prices tend to respond proportionally rather than additively to changes in their determinants.

In the specific context of proximity to NBS, empirical evidence suggests that the marginal effect of distance on property values follows a decay pattern; strongest in immediate proximity to green infrastructure and progressively attenuating beyond a threshold distance. A linear-log specification of the distance variable therefore represents a methodologically appropriate refinement of the base linear model, and is considered as a development direction within the framework proposed in this thesis.

Before estimating the model, its suitability must be assessed. Despite its considerable strengths, regression analysis is not without drawbacks. Among the most common are the presence of *outliers* in the sample and *collinearity* among the explanatory variables. Further challenges include the difficulty of gathering enough observations within a single market segment, the potential subjectivity involved in converting qualitative attributes into numerical values, and the risk of errors arising from the removal of outliers.

Due to these inherent limitations, regression analysis should always be performed with a sound knowledge of the underlying phenomenon and a critical mindset, so that the estimated outcomes can be properly interpreted and validated.¹⁰¹

¹⁰¹ Serena Loro, *The Influence of Daylight in the Housing Market: A Case Study in Turin*, Master's thesis, Politecnico di Torino, 2023.



04

CHAPTER



Proposed methodology and case study framework

4.1. A multicriteria framework for NBS evaluation

The previous chapters have highlighted how the evaluation of NBS remains a complex and often contested terrain. Despite the growing recognition of their potential, the assessment process continues to face significant challenges, ranging from indicator fragmentation and contextual rigidity to difficulties in capturing the full spectrum of benefits and trade-offs. These limitations, as discussed, often undermine the practical usability of existing frameworks, making it difficult for practitioners and decision-makers to adopt NBS in real-world settings. Building on these critical observations, this chapter aims to consolidate the insights gained so far and propose a new preliminary framework.

The intention is not to replace established approaches (as the ones seen in CHAPTER 2), but rather to offer a more flexible and adaptable structure that can mitigate the evaluative shortcomings identified, while maintaining coherence with existing frameworks. The ultimate goal is to provide a practical and accessible decision-support tool that can support the application of NBS in diverse operational contexts by integrating selected economic valuation methods within a broader multicriteria model.

4.1.1 Methodological rationale

The idea underlying this framework stems from the considerations that emerged immediately after the analysis of the existing literature. As we have seen in the previous chapters, conventional methods and even the more advanced ones have over the years sought to refine the evaluation technique, aiming to encompass an increasing number of NBS dimensions. However, the difficulties that remain evident are those related to the monetization of non-economic benefits and the complexity and data-consuming nature of these approaches. These factors, even when methods are more precise, make them less appealing for practical and market-oriented evaluations, shifting interest towards grey methods.

Within the frameworks present in the literature, it is indeed possible to identify two recurring basic mechanisms for NBS evaluation:

- Reducing everything to the economic dimension;
- Evaluating separately the economic dimension from the environmental-social one, and then translating the results of the non-monetary dimension through coefficients that can provide monetary equivalents.

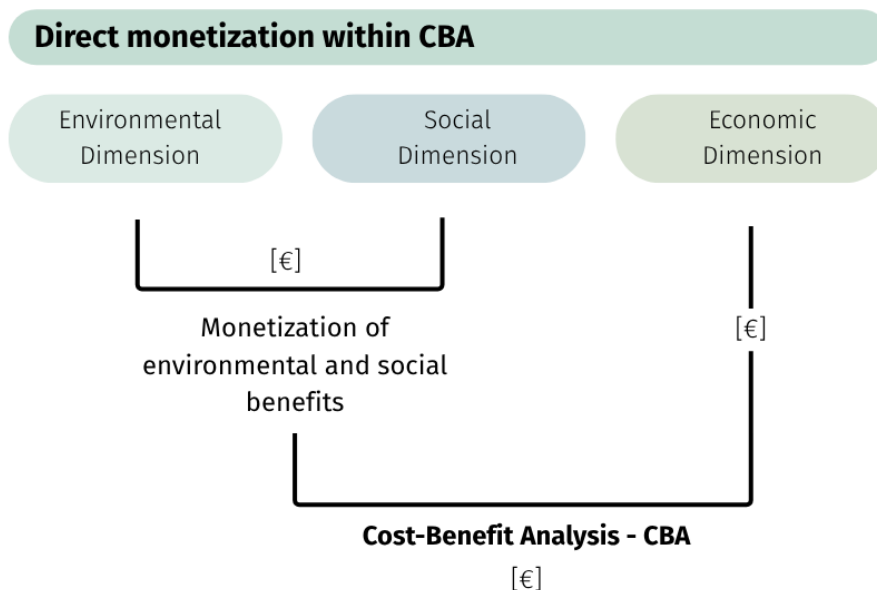


Figure 40 - Direct monetization approach within Cost-Benefit Analysis
Author's elaboration

In synthesis, with the exception of the MAGICA 2-step (see. CHAPTER 2) approach, where there is no actual conversion into monetary terms of the environmental-social dimension, but rather a comparison through ranking, the non-monetary dimension is invariably translated into monetary terms.

It is always sought to be commensurated, through proportions or trade-offs, to a unit of measurement that is not its own, ultimately favouring monetary estimation over the intrinsic value of the non-economic dimensions.

These different approaches reveal a common research gap: the difficulty of integrating the multidimensional nature of NBS without reducing environmental and social benefits to monetary or monetary-equivalent values.

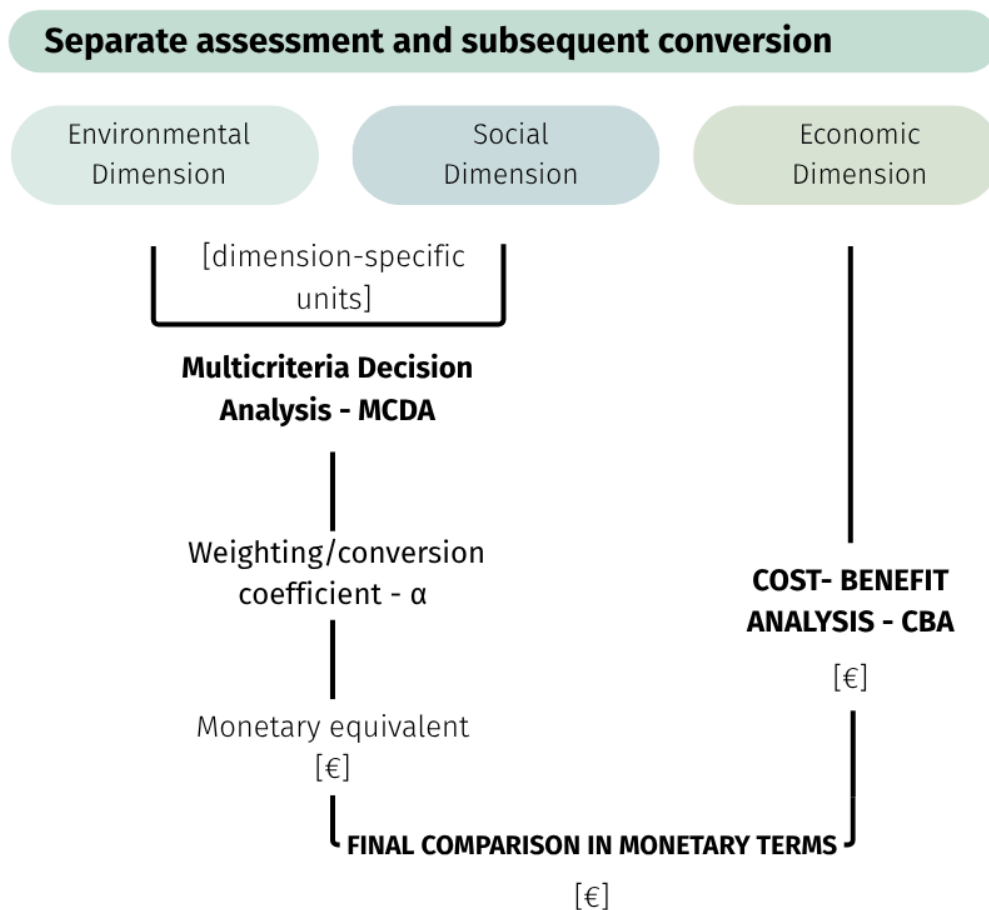


Figure 41 - Separate assessment of environmental, social and economic dimensions with subsequent monetary conversion.

Author's elaboration

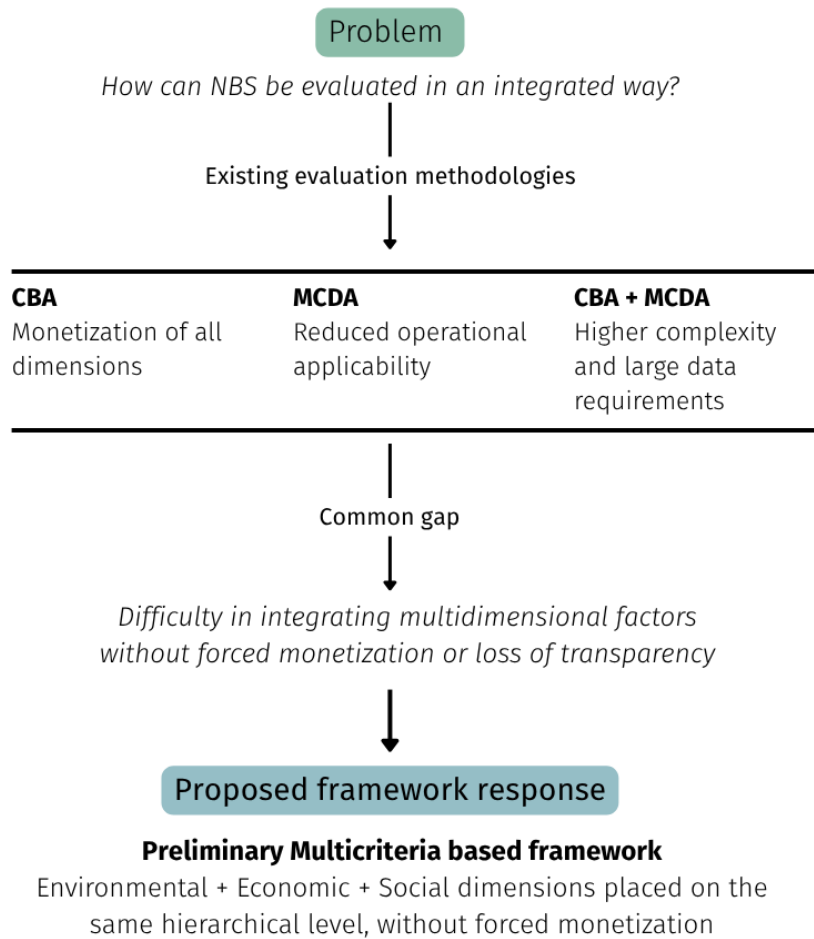


Figure 42 - Methodological gap in existing evaluation approaches and proposed response of the framework.

Author's elaboration

One of the few frameworks and guides that instead positions itself within a comparative dimension, placing the three typical NBS dimensions on the same level, is that of Chairat and Gheewala (2024) (see. Figure 30).

Starting from this perspective, the rationale of the present research is based on the hypothesis that, in order to promote the implementation of NBS and make them more easily applicable within urban policy and planning processes, it may be more effective to develop a **preliminary, flexible and easily adaptable decision-support framework** rather than immediately relying on highly detailed monetary evaluation methods. The proposed framework therefore does not aim to replace more advanced economic assessment tools, such as Cost-Benefit

Analysis, but rather to anticipate them through an instructive and preparatory phase. The objective is to organize the evaluation process at an earlier stage, where environmental, economic and social dimensions can be considered on the same hierarchical level and compared without being immediately reduced to monetary terms. In this way, each dimension can be assessed according to its own indicators, units of measurement and evaluation methods, while still being integrated into a common multicriteria structure.

This represents the core of the thesis: the construction of a preliminary evaluation framework capable of translating the multidimensional nature of NBS into operational criteria and sub-criteria, supporting decision-makers before the more detailed project and monetary assessment phase.

Within this structure, economic valuation is not excluded, but it is repositioned as one component of a broader decision-making process. More specific monetary tools, such as CBA, can therefore be introduced at a later stage, once the most suitable areas or intervention alternatives have already been identified through a balanced multicriteria assessment. In the specific case of this thesis, the framework is developed at a broader urban scale and is used to compare three areas of the city of Turin as potential alternatives for future NBS implementation. The analysis is therefore not focused on the assessment of an already implemented intervention, but on the construction of a preliminary analytical basis, with attention to the baseline scenario and to the different environmental, economic and social conditions characterizing each urban area.

At the same time, the proposed framework is conceived as flexible and scalable. Although the alternatives considered in this research are urban areas, the same structure could be adapted in future applications to compare different project alternatives or different types of NBS within the same site. In that case, the alternatives would no longer be the urban zones, but the intervention scenarios themselves, while indicators and sub-criteria could be adjusted according to the scale of analysis, the available data and the specific planning objectives.

4.1.2 Multicriteria as evaluation structure

The core idea that inspired this thesis is to introduce a dimension that precedes those already proposed in the literature. While existing studies largely focus on comparing different project options, a well-established application in the field, this work aims to broaden the scope, envisioning the framework as a larger-scale instrument for reading the territory and identifying priority areas for intervention.

At the same time, the ambition is to develop a model that is not limited to this broader application but remains flexible. By adjusting certain parameters, it should also be applicable to the preliminary evaluation of project-level alternatives or Nature-Based Solution (NBS) options.

The methodological approach deemed most suitable for this purpose is the multicriteria decision-making model. This choice is supported both by its well-documented presence in the literature and by its intrinsic structure, which is specifically designed to handle complex, multidimensional problems. For these reasons, it appeared to align naturally with the challenges posed by NBS assessment.

As discussed in CHAPTER 3, multicriteria methods are based on the decomposition of a problem into a hierarchical structure. This typically involves defining an overarching objective, followed by criteria, sub-criteria, indicators, and finally, a set of alternatives to be evaluated.

Among the different MCDA methods, the Analytic Hierarchy Process (AHP)¹⁰² was selected because it is particularly suitable for structuring multidimensional decision problems into hierarchical levels and for comparing heterogeneous criteria through pairwise comparisons.

¹⁰² Thomas L. Saaty, *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*, New York, McGraw-Hill, 1980.

It should also be noted that the assignment of weights in the AHP is based on relative judgments and therefore retains a subjective component. However, this subjectivity is made explicit through the construction of pairwise comparison matrices. The weighting process may be carried out by experts, policymakers, public administrations, or mixed panels involving citizens and institutional actors, depending on the purpose of the evaluation.

In this way, the framework can incorporate different perspectives while maintaining a structured and verifiable decision-making procedure.

On this basis, the following section defines the hierarchical structure adopted in the framework.

4.1.3 Hierarchy levels: objective. Criteria, sub-criteria, and alternatives

The selection of criteria is a crucial step in the development of the evaluation framework. Criteria must be relevant and selected case by case, in order to reflect the specific characteristics of the alternatives and of the phenomenon under analysis.

OBJECTIVE

As already mentioned, the aim of this thesis is to build a preliminary assessment framework for the evaluation of urban and territorial proposals. At the same time, this framework is strongly connected to the nature of NBS, which are based on the conservation, restoration and improvement of ecosystems. For this reason, the criteria selection is embedded in a broader sustainability perspective, and would be the pivotal point for the objective.

Objective

Evaluating the sustainability of Nature-Based Solutions and identifying optimal urban contexts for their implementation

CRITERIA

To maintain a coherent line of reasoning, both with the broader concept of sustainability and with the specific nature of NBS, the framework is structured according to the well-established *three-pillar model* of sustainability. This conceptual model, widely discussed in the literature, is commonly associated with the integration of environmental, social and economic dimensions, and is closely related to the “*Triple Bottom Line*” approach, popularized by Elkington (1997)¹⁰³ through the formulation “*People, Planet, Profit*”.

¹⁰³ Elkington, J. (1997). *Cannibals with Forks: The Triple Bottom Line of 21st Century Business*. Capstone, Oxford.

While earlier contributions, such as Meadows et al. (1972)¹⁰⁴ and the Brundtland Report (1987)¹⁰⁵, played a fundamental role in shaping the modern sustainability debate by emphasizing the interdependence and inseparability of environmental, social and economic systems, the three-pillar structure has become one of the most widely adopted ways to represent sustainable development. As discussed by Purvis, Mao and Robinson (2019),¹⁰⁶ sustainability is conventionally understood as the integrated pursuit of environmental protection, social equity and economic development.

This tripartite structure is also consistent with the United Nations' interpretation of sustainable development, which identifies economic growth, social inclusion and environmental protection as core and interdependent dimensions.¹⁰⁷ Adopting this framework therefore ensures conceptual alignment with mainstream sustainability discourse and provides a clear basis for organizing the evaluation criteria within the proposed multicriteria model.

CRITERIA

1. Environmental sustainability (C_1)
2. Economic sustainability (C_2)
3. Social sustainability (C_3)

¹⁰⁴ Meadows, D. H., Meadows, D. L., Randers, J., & Behrens, W. W. (1972). *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*. Universe Books, New York.

¹⁰⁵ WCED (1987). *Our Common Future*. Oxford University Press.

¹⁰⁶ Ben Purvis, Yong Mao, and Darren Robinson, "Three Pillars of Sustainability: In Search of Conceptual Origins," *Sustainability Science* 14, no. 3 (2019): 681–695, <https://doi.org/10.1007/s11625-018-0627-5>.

¹⁰⁷ United Nations (2015). *Transforming Our World: The 2030 Agenda for Sustainable Development*. UN, New York.

SUB-CRITERIA

For the definition of the sub-criteria, the framework developed by Chairat and Gheewala (2024) was taken as a methodological reference, as it proposes a quantitative assessment framework explicitly aligned with the criteria of the IUCN Global Standard for NBS.

Considering the lack of binding and operational frameworks for the assessment of NBS, already discussed in CHAPTER 1, it was considered appropriate to refer to existing and internationally recognized frameworks as much as possible. This choice is based on the idea that a **greater alignment between shared conceptual standards and operational assessment methods may support the comparability of evaluations and contribute to the further development of common methodological approaches.**

However, differently from the cited model, this thesis does not adopt the IUCN Global Standard as the main basis for the definition of the sub-criteria.

The IUCN Standard is primarily conceived as a benchmark to determine whether an intervention can be considered a Nature-Based Solution and whether it complies with a set of global principles. For the purposes of this research, the EU Handbook ²⁶ was considered more appropriate, since it provides an evaluation-oriented framework aimed at assessing the effectiveness and impacts of NBS interventions over time.

Rather than defining what qualifies as an NBS, the Handbook focuses on how to systematically measure its outcomes. For this reason, it was adopted as the main reference for the identification of the sub-criteria within the proposed AHP framework.

As discussed in Chapter 1, the *EU Handbook for Practitioners* ¹⁰⁸ structures the assessment of NBS around 12 societal challenge areas (see *Figure 4*).

¹⁰⁸ European Commission, *Evaluating the Impact of Nature-Based Solutions*. pp.116-171.

No.	Indicator	Units	Class	Applicability to NBS [†]		
				Type 1	Type 2	Type 3
RECOMMENDED						
2.9.1	Human comfort: Universal Thermal Climate Index	°C	O	●		●
2.9.2	Thermal Comfort Score	unitless	O	●		●
2.9.3	Human comfort: Physiological Equivalent Temperature	°C	O	●		●
2.9.4	Mean or peak daytime temperature – Predicted Mean Vote–Predicted Percentage Dissatisfied	unitless	O	●		●
2.10.1	Urban Heat Island (incidence)	°C	O	●		●

No.	Indicator	Units	Class	Applicability to NBS [†]		
				Type 1	Type 2	Type 3
RECOMMENDED						
23.1.1	Valuation of NBS: Value of NBS calculated using GI-Val	€	O	●	●	●
23.1.2	Economic value of urban nature	€	O	●	●	●
23.2	Mean land and/ or property value in proximity to green space	€	O	●		●
23.2.1	Change in mean house prices/ rental markets	€	O	●		●
	new business creation					
23.6	Recreational monetary value	€/year	O	●		●

No.	Indicator	Units	Class	Applicability to NBS [†]		
				Type 1	Type 2	Type 3
RECOMMENDED						
7.1	Green space accessibility	%	O	●		●

8.35.2	Sustainable transportation modes allowed	Number	S	●		
8.36	Links between urban centres and NBS	Number	S	●		
8.37	Walkability	Number	O	●	●	●

Figure 43 - Selection of EU Handbook indicators used for the definition of the proposed AHP sub-criteria. Author's elaboration based on European Commission, *Evaluating the Impact of Nature-Based Solutions: A Handbook for Practitioners*, 2021

Each challenge area is associated with recommended and additional indicators, including their units of measurement, indicator classes, assessment methods and applicability to different types of NBS (see *Figure 7*).

Starting from this structure, the sub-criteria of the proposed framework were selected by comparing the indicators provided by the Handbook with the specific urban dimension addressed by this research.

The resulting correspondence between the EU framework and the sub-criteria adopted in this thesis is summarized below:

EU – societal challenge	EU - indicators	Framework - subcriteria
Climate resilience	2.9.1 Human comfort: Universal Thermal Climate Index - [°C]	Universal Thermal Climate Index (UTCI) - [°C]
Climate resilience	2.10.1 Urban Heat Island (incidence) [°C]	Urban Heat Island (incidence) - UHI [°C]

New Economic Opportunities and Green Jobs	23.2.1 Change in mean house prices/ rental markets [€]	Change in mean house prices/ rental markets [€]
New Economic Opportunities and Green Jobs	23.6 Recreational monetary value [€/year]	Adapted - Willingness to Pay [€/year]
Green space management	7.1 Green space accessibility [%]	Adapted - Green space accessibility [%]
Green space management	8.37 Walkability [number]	Walkability [m/m ²]

The indicators provided by the EU Handbook were not adopted as a fixed and exhaustive list, but rather as a methodological reference for the selection of sub-criteria consistent with the urban scale of the proposed framework.

Some indicators were therefore operationally adapted in order to make them measurable within the available data structure and suitable for integration into the AHP model.

- **Universal Thermal Climate Index - UTCI (SC₁):** a biometeorological index that captures the "perceived" rather than actual temperature felt by the human body in outdoor environments, measuring heat or cold stress. It considers a combination of four variables: air temperature, relative humidity, wind speed, and mean radiant temperature. The index is measured in degrees Celsius and, based on the result, is divided into 10 categories.
- **Urban Heat Island incidence - UHI (SC₂):** the mathematical difference between the urban temperature recorded in a given area and a reference rural temperature. In the framework, for practical purposes, the reference value is considered to be the average urban temperature of the city of Turin.

- **Change in mean house prices/rental markets (SC₃):** in the context of ex-ante evaluation, this indicator represents the potential effect of the qualities brought by NBS projects on the real estate market. The indicator is calculated through hedonic regression based on the study of Turin's real estate market.
- **Willingness to pay (SC₄):** estimates citizens' willingness to pay for the implementation and maintenance of NBS. It reflects the perceived value of non-market benefits and is administered through a questionnaire.
- **Green space accessibility (SC₅):** a metric used to measure how easily residents can physically reach and use natural areas, such as parks, forests, and public gardens. The indicator is designed to calculate the percentage of buildings (and therefore of the population) within 300 meters of urban parks or usable urban green spaces.
- **Green space walkability (SC₆):** a metric that measures the ease and quality of pedestrian movement in urban spaces. In the context of the framework, this is a simplification given by the sum of variables calculated using GIS tools, namely pedestrian network density, intersection density, and accessibility to services, normalized and weighted according to an arithmetic mean.

In order to complete the hierarchical structure of the model, two operational sub-criteria were selected for each macro-criterion. This choice was made to ensure a balanced organization of the framework, avoiding the over-representation of one dimension over the others. Each sub-criterion is primarily associated with one higher-level criterion, while still maintaining potential relationships with the other dimensions of sustainability. This reflects the multidimensional nature of NBS, whose impacts often extend beyond a single evaluation category.

The selection of the sub-criteria was also influenced by the intended scale of the assessment. Although the specific alternatives had not yet been defined at the moment of sub-criteria selection, the objective of developing a preliminary urban-scale framework had already been established.

For this reason, the model was not conceived to compare different design solutions or specific NBS typologies, but rather to support the comparison of different urban areas according to their suitability for future NBS implementation. This led to the selection of indicators capable of capturing broader urban conditions.

If the framework were applied to a different object of evaluation, such as alternative project proposals or specific NBS interventions, different indicators could reasonably be selected.

This aspect highlights one of the main features of the proposed framework: its adaptability.

By modifying the scale of analysis, the evaluation perspective and the set of alternatives, the model can remain theoretically valid while being adjusted to different decision-making contexts.

In this sense, the framework can also be applied to smaller-scale studies, provided that a coherent set of indicators is selected, preferably in continuity with the EU Handbook, and that the alternatives are defined according to the specific objective of the assessment.

SUB-CRITERIA

1. Universal Thermal Climate Index - UTCI (SC1)
2. Urban Heat Island incidence - UHI (SC2)
3. Change in mean house prices/rental markets (SC3)
4. Willingness to pay (SC4)
5. Green space accessibility (SC5)
6. Green space walkability (SC6)

ALTERNATIVES

The criteria for selecting the alternatives will be outlined in the subsequent stages. Rather than being a straightforward choice, the selection will be grounded in a preliminary assessment of the urban context. A detailed description of the decision-making process is provided in the following sections.

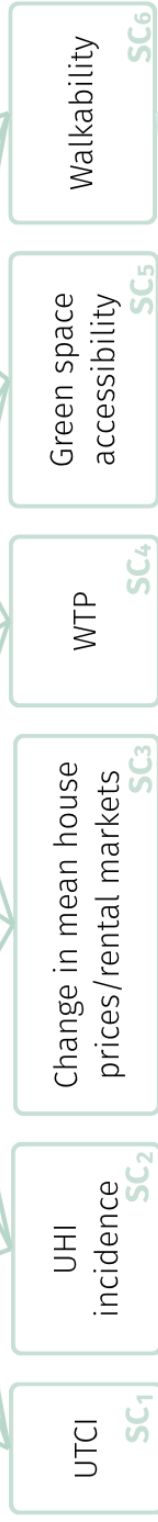
OBJECTIVE
Level - 0

Evaluating the sustainability of Nature-Based Solutions and identifying optimal urban contexts for their implementation **O**

CRITERIA
Level - 1



SUB-CRITERIA
Level - 2



ALTERNATIVES
Level - 3



4.2. Case study presentation

As outlined earlier, the definition of alternatives does not come first; it comes last. The starting point of this chapter is precisely the opposite: rather than selecting intervention zones across Turin in advance, the idea here is that the choice should emerge from the territory itself.

This may seem like a minor methodological nuance, but it has real consequences for how the results should be read and, more practically, for **how the framework could be applied elsewhere**.

Much of the literature reviewed in this thesis insists on the importance of baseline conditions. This is worth taking seriously. Knowing where a city stands before any intervention is not just good practice; it changes what the indicators actually measure. A performance score means something very different depending on what the starting point was.

The same logic applies to additionality, which becomes a much more interesting question once territorial analysis is on the table. Areas with more green cover or lower surface temperatures do not automatically benefit less from new NBS. Real estate dynamics and patterns of use can tell a more nuanced story: in some cases, moderate baseline conditions may actually amplify the marginal effect of green infrastructure, including on property values. None of this is visible without first mapping the city.

This is why the evaluation is preceded by a **spatial diagnostic phase**.

4.2.1 Urban context – Turin

The case study focuses on Turin, a city located in northwestern Italy.

From an environmental standpoint, Turin falls within the Po Valley, a predominantly flat area, yet bounded to the north by the Alps and to the south by the Apennines. The city is also crossed by two rivers, the Po and the Dora Riparia, which contribute to its distinctive environmental setting. However, this specific geographical configuration already introduces the first critical issues: poor natural ventilation, frequent temperature inversions, and increasingly hot summers.

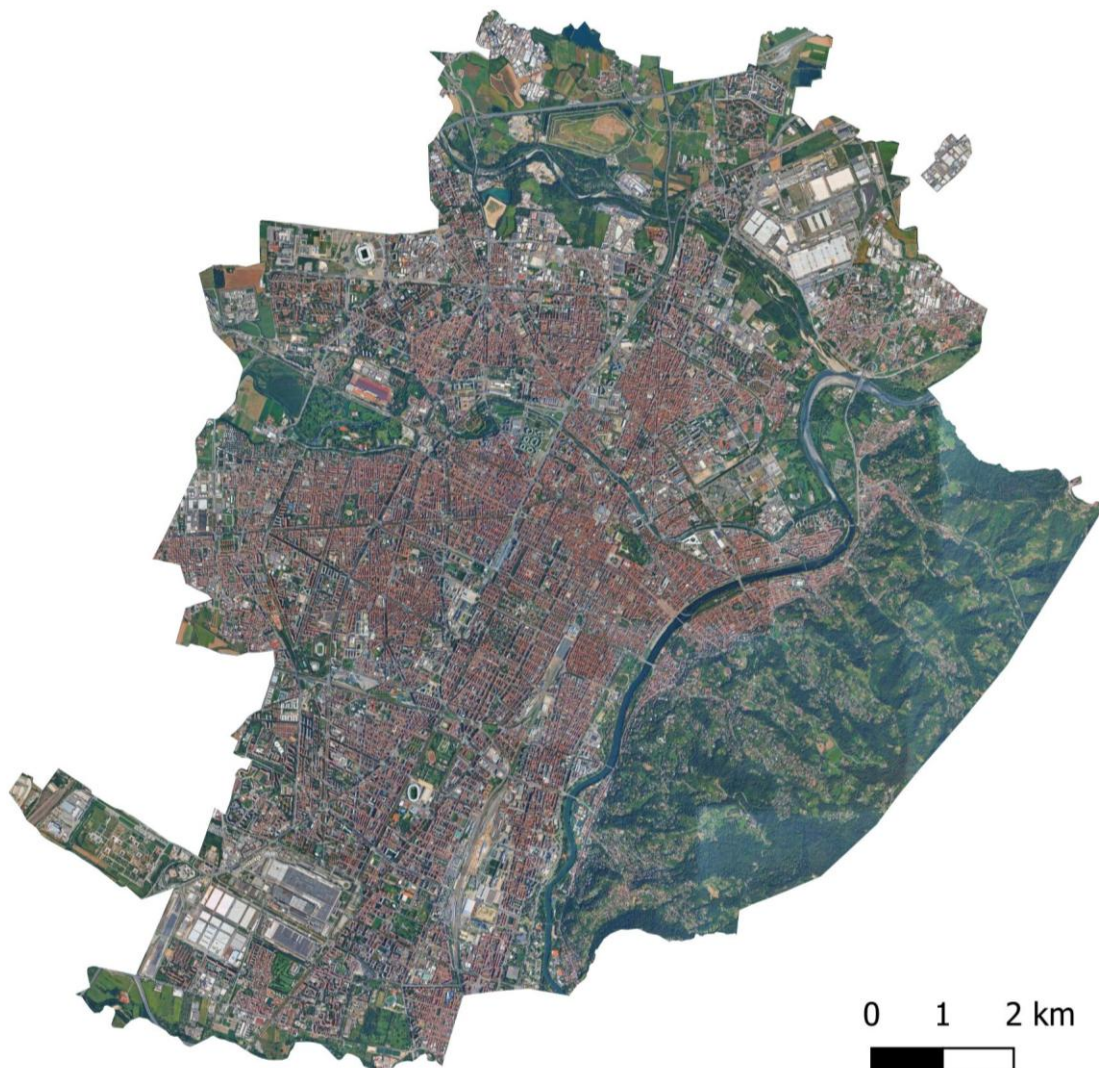


Figure 44 - Spatial delimitation and orthophoto representation of the municipal area of Turin.
Source: author's own elaboration using GIS

In terms of urban morphology, the city's layout is largely regular, reflecting the orthogonal grid inherited from its Roman and Baroque historic centre.

This dense structure results in low soil permeability and, consequently, a high degree of surface sealing. The industrial expansion that occurred during the twentieth century, further sharpened urban differentiation. Toward the southern areas, in fact, the urban fabric becomes more homogeneous, less green, and characterized by large-scale industrial buildings. Building density is not uniformly distributed across the city. Certain districts, especially those on the hill, are comparatively more sparse, due primarily to topographical constraints.



Figure 45 -Spatial structure of Turin municipality: road network, green areas and hydrographic system.
Source: author's own elaboration using GIS and GeoPortale data.

Although Turin does possess extensive green areas, such as *Parco del Valentino*, *Parco della Pellerina*, and several smaller urban parks, their spatial distribution remains markedly uneven. It is precisely because of these combined features that the Urban Heat Island effect is particularly pronounced in Turin, making it one of the most frequently cited Italian cases in the literature on the subject.

4.2.2 Real-estate sub-segmentation

Turin's urban territory has long been organized, for cadastral purposes, into 40 *Microzone*, officially approved by the city council in June 1999.¹⁰⁹ These units are distinct from the OMI zones (*Osservatorio del Mercato Immobiliare*), the real estate market areas defined by the Italian Revenue Agency, which numbered 41 until 2023 and were subsequently expanded to 47 in 2024.¹¹⁰

The two systems coexist but respond to different logics: the cadastral *Microzone* reflect a primarily administrative and fiscal reading of the territory, while *OMI* zones track market segmentation as observed by national property monitoring.

A 2017 study by Barreca, Curto and Rolando¹⁰⁹ - predating the most recent OMI reorganization - pushed this spatial granularity further. Working within the boundaries of the existing 40 *Microzone* without altering them, the authors proposed a finer sub-segmentation based on a historical and urban-morphological reading of the city, producing 93 units defined as *Porzioni Territoriali Storiche* (PTS). (see. Figure 49)

These units are subdivided according to the internal historical, morphological and real estate heterogeneity of each *Microzone*, with the aim of identifying more homogeneous urban portions. The rationale was straightforward: the

¹⁰⁹ Alice Barreca, Rocco Curto, and Diana Rolando, "Localizzazione e valori immobiliari: uno studio per la sub-segmentazione territoriale delle Microzone di Torino," *Territorio Italia* (2017): 49–71, Agenzia delle Entrate, accessed June 25, 2026

¹¹⁰ Città di Torino, "Osservatorio Immobiliare della Città," Comune di Torino, last modified July 23, 2025, accessed June 25, 2026, <https://www.comune.torino.it/schede-informative/osservatorio-immobiliare-della-citta>.

Microzone, useful as administrative containers, are too coarse to capture the genuine plurality of urban landscapes that characterises a city like Turin. A single micro-zone can encompass neighbourhoods with very different spatial identities, building fabrics and, critically, price dynamics.

The study tested this hypothesis by applying a hedonic pricing model twice - first using *Microzone* as the locational variable, then replacing them with *PTS*. Both specifications produced statistically significant results with high coefficients of determination, but the finer sub-segmentation proved more explanatory: average prices attributed to individual PTS were found to distribute

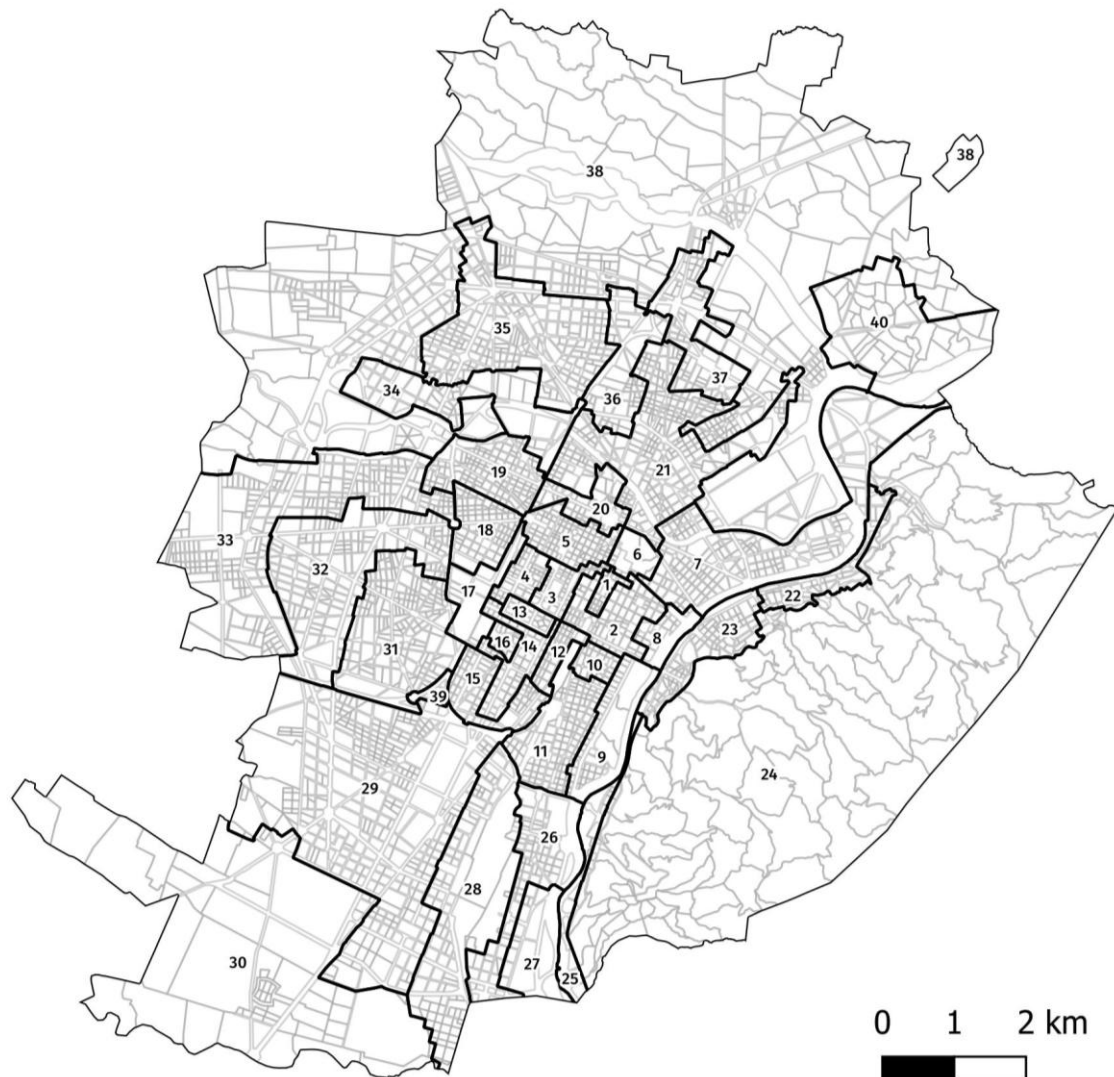
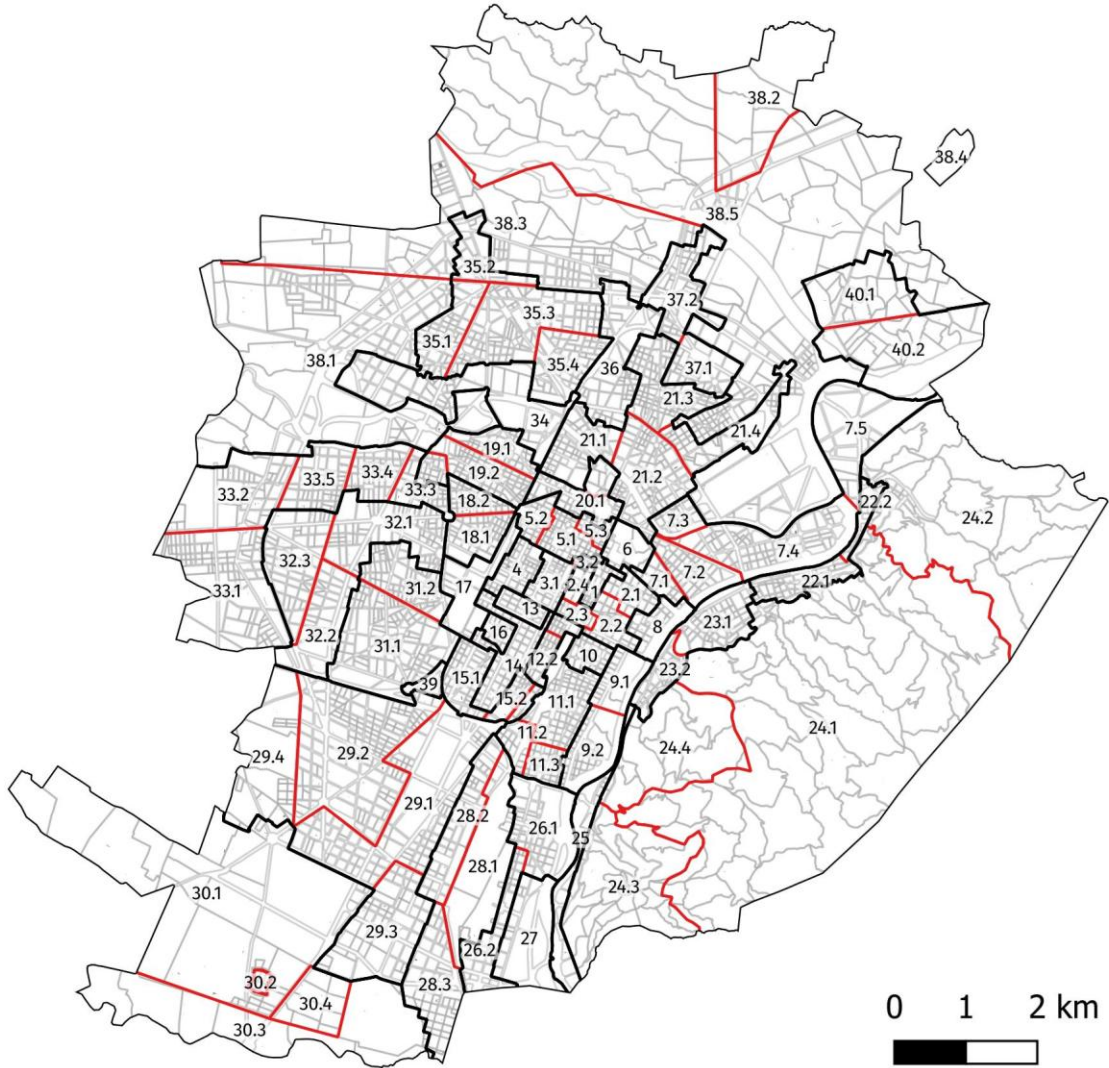


Figure 46 - Cadastral microzones of Turin municipality.
Source: author's own elaboration using GIS and GeoPortale data.

Appendix A reports the correspondences between the numbers and the different micro-zones, namely the initial 40 units, and their subsequent subdivisions, which ultimately result in 93 urban portions.



Source: author's elaboration using GIS, based on Barreca, Curto and Rolando (2017) study of PTS (p.55, fig.1) and GeoPortale data.

multicriteria framework choices. The underlying idea is to maintain a comprehensive perspective while keeping the framework practically manageable.

This requires ensuring coherence across both property market trends and spatial patterns, so that different urban areas, each characterized by its own market behavior and environmental profile, can be effectively compared.

Legend:

- Turin Microzones
- Turin Sub-Segmentation [93]

Property Values (€/m²)

- Data Not Available
- 1 - 1551 €
- 1551 - 2101 €
- 2101 - 2734 €
- 2734 - 3100 €
- 3101 - 5000 €

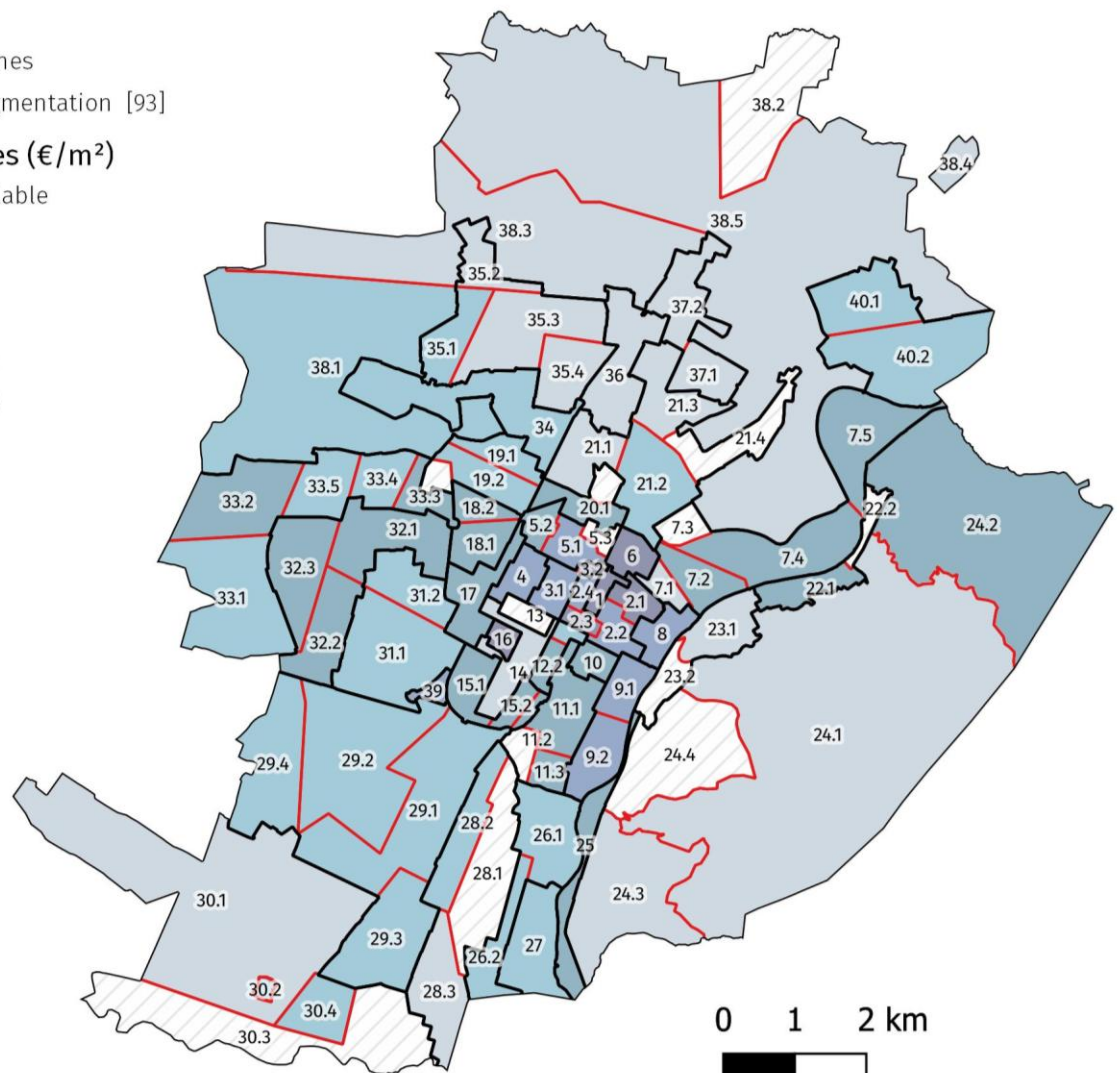


Figure 48 - Spatial distribution of property values across Turin's cadastral microzones and historical territorial sub-segmentations.

Source: author's elaboration using GIS, based on Barreca, Curto and Rolando (2017) study of PTS (p.60, fig.3) and GeoPortale data.

This decision was further motivated by technical requirements, aimed at maintaining coherence with the measurement instruments used to compute the indicators, as will be explained in greater detail later on.

Even a preliminary reading of the map is enough to confirm a few things. (See Figure 50)

A centre-to-periphery gradient in property values exists and is fairly consistent across the city, with the highest prices concentrated in the historical centre and the eastern hillside areas, tapering off towards the outer rings. That much is not surprising.

What is more interesting is what happens within individual Micro-zone. The internal heterogeneity is considerable - particularly in the north-western sectors (Micro-zones 33 and 38) and in the southern ones (29 and 39), where adjacent PTS can fall into quite different price brackets despite sharing the same administrative boundary. This is precisely the kind of variation that a Microzone-level analysis would have averaged out, and it provides a concrete, map-readable justification for working at the finer PTS scale.

Areas shown in white lacked sufficient transaction data to produce reliable estimates and are therefore excluded from the analysis.

4.3. Preliminary territorial diagnosis

To extend the territorial analysis beyond property values, the same *Microzone* boundaries were used to frame an assessment of the city's environmental and social characteristics. This phase draws on open-source datasets available through the *GeoPortale di Torino*,¹¹¹ processed and mapped using GIS software; the same workflow applied consistently across all cartographic outputs in this thesis.

According to the dataset metadata, these data were derived from the processing of Landsat 8-9 satellite imagery acquired during the summer of 2019, with reference to the June–September period. This timeframe was selected as it is particularly representative of the conditions associated with urban heat island phenomena.

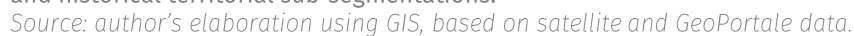
4.3.1 Land Surface Temperature and Urban Heat Island mapping

Land Surface Temperature (LST) measures the thermal state of the Earth's surface as recorded by satellite sensors, reflecting how different materials absorb and release heat. Unlike air temperature, LST refers specifically to the physical surfaces themselves: vegetation, soil, water, and urban materials such as asphalt and concrete. It is derived from thermal infrared data and expressed in degrees Celsius.

The distinction from air temperature matters. A rooftop and a park can sit under the same atmospheric conditions and read very differently in LST terms. In urban environments, dense built surfaces absorb and retain heat, producing higher LST values, while vegetated areas remain cooler through shading and evapotranspiration.

¹¹¹ Regione Piemonte, *Geoportale Piemonte – Catalogo dei dati geografici*, accessed June 26, 2026, <https://www.geoportale.piemonte.it/geonetwork/srv/ita/catalog.search#/home>.

As shown in *Figure 51*, the Land Surface Temperature layer provides a clear representation of the spatial distribution of surface temperatures across the city of Turin.



Lower temperature values, corresponding to cooler surfaces, are represented in blue, while the progressive intensification of red indicates increasing land surface temperatures.

At first glance, two main aspects can be observed. The first is the evident relationship between LST values and the main vegetated or natural features of the urban fabric. Areas located close to rivers and watercourses generally show lower surface temperatures, even when they are embedded within densely built-up contexts. This can be partly explained by the cooling effect associated with the presence of water and vegetation. Similarly, the eastern micro-zones, corresponding to the hilly part of the city, show significantly lower temperatures, due to their specific topography, extensive tree cover and lower building density.

A second relevant observation concerns the areas where the highest LST values are concentrated. The most critical peaks are mainly located in correspondence with large peripheral industrial areas, either still in use or partially abandoned, such as the *Stellantis* former *Fiat* area and the former *ThyssenKrupp* site. High values are also visible in the northern peripheral areas of *Barriera di Milano*, particularly *PTS 38.1*, and in the southern sector around *Mirafiori Sud*, especially *PTS 30.1* and *30.2*. This aspect is particularly interesting because it suggests that the historical city centre, although characterized by medium-high LST values, does not reach the most extreme temperatures. This may be related to the presence of internal courtyards, arcades, narrow streets and historical paving materials, which can partially mitigate surface overheating compared to large paved or industrial surfaces.

Finally, the map also confirms the usefulness of the adopted sub-segmentation. The differences between micro-zones are not only relevant from the point of view of the urban fabric and real estate structure, but also in terms of thermal behavior. In several cases, significant internal variations can be observed within the same broader micro-zone, with temperature differences reaching approximately 5–8 °C.

This is particularly evident in micro-zones 29, 30, 33 and 38, where the spatial heterogeneity of the built environment is clearly reflected in the distribution of LST values.

4.3.2 Vegetation cover analysis (NDVI)

The Normalized Difference Vegetation Index (NDVI) is a remote sensing indicator that measures the presence and condition of vegetation by analysing how surfaces reflect light.

It is calculated as:

$$\text{NDVI} = (\text{NIR} - \text{RED}) / (\text{NIR} + \text{RED})$$

where *NIR* refers to near-infrared radiation and *RED* to visible red light.

The logic behind the formula is straightforward: vegetation absorbs red light for photosynthesis and strongly reflects near-infrared radiation due to its internal leaf structure.

This contrast is what the index captures. Dense, healthy vegetation produces values approaching +1; built-up areas and bare soil return values close to 0; water surfaces generate negative values.

In urban analysis, NDVI serves as a direct proxy for green cover distribution. Read alongside LST, it helps explain why surface temperatures vary across the city: where NDVI is high, LST tends to be lower, and vice versa.

The two indices are in this sense complementary, and mapping them together over the same territorial units gives a more complete picture of the thermal and ecological conditions of the urban fabric.

As anticipated, Figure 52 shows an almost specular relationship between the NDVI map and the LST distribution. Areas characterized by low or negative NDVI values, represented in red tones, largely correspond to the hottest zones identified in the Land Surface Temperature map.

This spatial coherence is particularly evident in the dense urban core, in *Mirafiori Sud*, and in the western industrial areas, which display a very similar pattern in both maps.

This relationship is also clearly visible when looking at the main green areas within the compact city. Large urban parks, such as *Parco del Valentino* and *Giardini Reali*, are immediately recognizable in the NDVI map because they appear as green patches strongly contrasting with the surrounding red tones of

Legend:

□ Turin Microzones

□ Turin Sub-Segmentation [93]

Max_NDVI

- -0,1002
- -0,0029
- 0,0945
- 0,1918
- 0,2892
- 0,3865
- 0,4839
- 0,5812
- 0,6785
- 0,7759
- 0,8732

Satellite

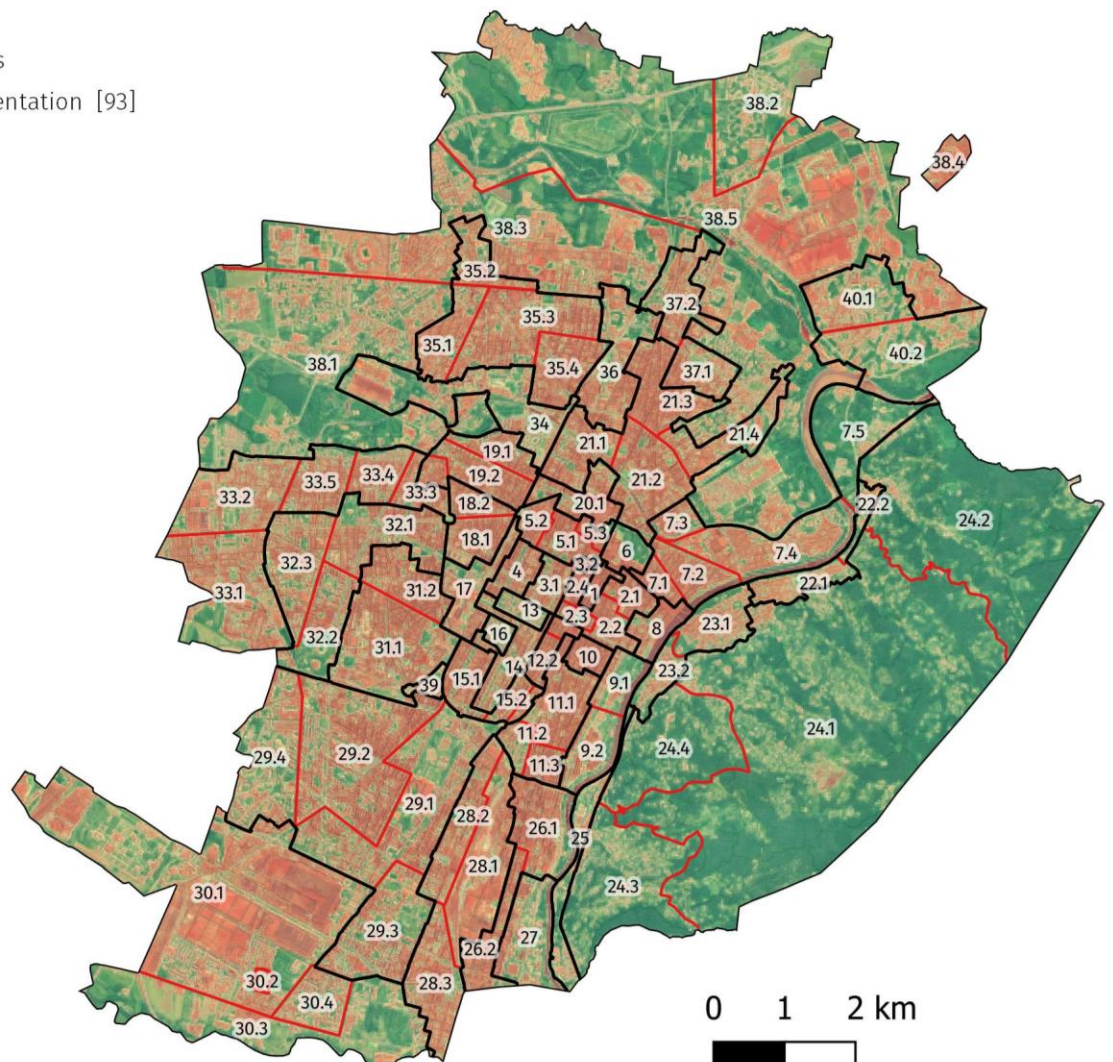


Figure 50 - Spatial distribution of the Normalized Difference Vegetation Index (NDVI) across Turin's cadastral microzones and historical territorial sub-segmentations.

Source: author's elaboration using GIS, based on satellite and GeoPortale data.

the dense built fabric. This contrast makes the cooling and ecological role of urban vegetation particularly evident, even within highly urbanized contexts.

It is also important to observe that, moving away from the central and most densely built-up areas, NDVI values progressively increase, reaching values around 0.6–0.8. This is especially visible in the eastern hilly sector and along the northern edge of the city, particularly in *PTS* 38.2 and 38.4, where vegetation cover is more significant and the urban fabric becomes less compact.

A particularly relevant observation for the subsequent analytical choices concerns the south-western quadrant of Turin, which emerges as one of the most critical areas. Neighbourhoods such as *Mirafiori Sud*, especially sub-segmentations 30.1 and 30.2, combine very low NDVI values with extremely high LST values. The two indicators therefore converge in highlighting a condition of marked environmental vulnerability. This area is characterized by limited vegetation cover, high surface temperatures and a historically industrial urban structure, making it particularly relevant for the identification of priority areas for potential NBS interventions.

4.3.3 Vulnerability analysis

The vulnerability index combines layers already introduced in the preceding sections (LST and NDVI, derived from summer Landsat acquisitions to capture peak heat island conditions) with demographic data from the *ISTAT 2011* census, specifically the share of population under ten and over 65 years of age, disaggregated at enumeration area level. These are the two groups most physiologically exposed to heat stress. All four layers were normalized on a 0 to 100 scale, with 100 marking the most adverse conditions, and combined through a weighted formula that assigns double weight to the thermal component, while the two demographic layers each contribute a quarter of the final score. The

resulting index is classified into five vulnerability classes, ranging from Low (below 50) to Very High (above 80).

The index therefore weights environmental conditions heavily, but the demographic component introduces a layer of complexity that pure thermal analysis cannot capture on its own. The medium-high patches visible on the map tend to cluster around the areas already flagged by the LST and NDVI analysis as thermally stressed, confirming a degree of spatial overlap between physical exposure and population vulnerability.

Legend:

- Turin Microzones
- Turin Sub-Segmentation [93]

Vulnerability

- Low
- Medium
- Medium-High
- High
- Really High

Satellite

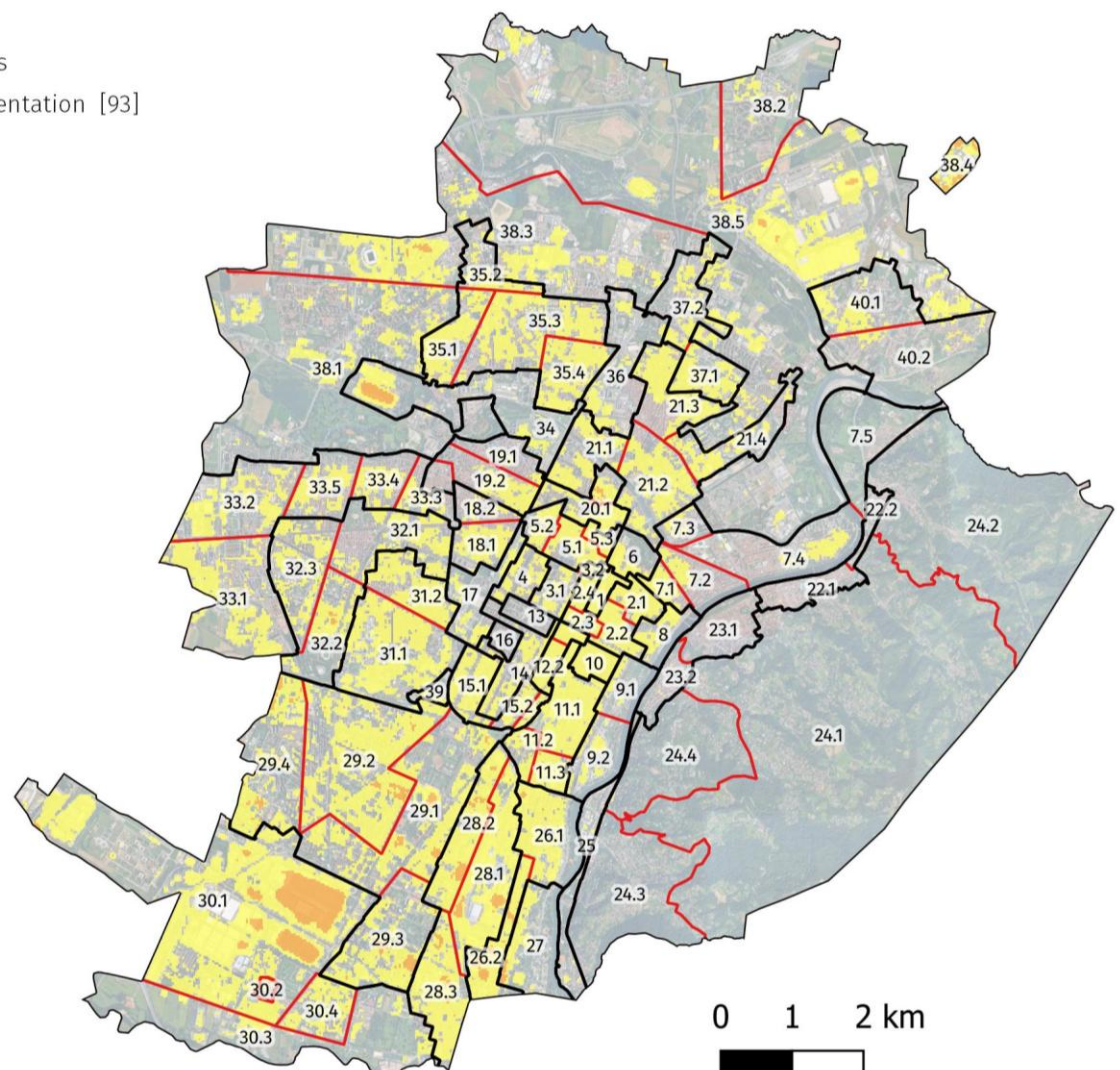


Figure 51 - GIS-based overlay between urban vulnerability, cadastral microzones and historical territorial sub-segmentations in Turin.

Source: author's elaboration using GIS, based on geospatial and GeoPortale data.

The south-western sector shows a broad and fairly continuous distribution of media vulnerability, again consistent with what the previous maps suggested about that quadrant.

One pattern that emerges more clearly here than in the earlier analyses is the corridor running along the railway axis toward *Porta Nuova* - the north-south vertical passing through Micro-zones 28, 26, 11 and 10. This strip shows a notably uniform vulnerability profile, likely reflecting a combination of dense built fabric, limited green cover and a resident population that includes a significant share of elderly households. More broadly, the central urban tissue tends toward media vulnerability wherever it sits at a distance from parks and the river, with no single dominant hotspot but a persistent baseline of moderate exposure distributed across much of the consolidated city.

4.3.4 Real estate values across the city

At this stage, following the preliminary territorial analysis, it was considered relevant to compare the environmental patterns identified with the real estate market dimension. For this reason, a series of maps was produced by overlaying the environmental layers previously described with the economic *PTS* sub-segmentation of the city.

In Figure 54, the **Land Surface Temperature layer is overlaid with the average real estate market values** of the 93 *PTS* sub-segments. Property values are represented through a grey gradient, where lighter shades correspond to lower average prices per square metre, while darker shades indicate higher market values.

One of the most relevant observations concerns the spatial correspondence between high LST values and low real estate values. This pattern is particularly evident in the southern sector of the city, especially in *Mirafiori Sud*. Micro-zones 30.1 and 30.2 represent one of the clearest examples: they show some of the

highest surface temperatures in Turin, while also belonging to the lowest property value ranges. This suggests the presence of areas where environmental stress and weaker market conditions overlap.

However, this relationship is not uniform across the city. Central areas also show medium-high LST values and lower vegetation density, but they are associated with much higher property prices per square meter.

Legend:

-  Turin Microzones
-  Turin Sub-Segmentation [93]

Property Values (€/m²) copy

-  Data Not Available
-  1 - 1551 €
-  1551 - 2101 €
-  2101 - 2734 €
-  2734 - 3100 €
-  3101 - 5000 €

Land Surface Temperature [°C]

-  22
-  24
-  25
-  27
-  28
-  30
-  31
-  33
-  34
-  36
-  37
-  39
-  40

Satellite

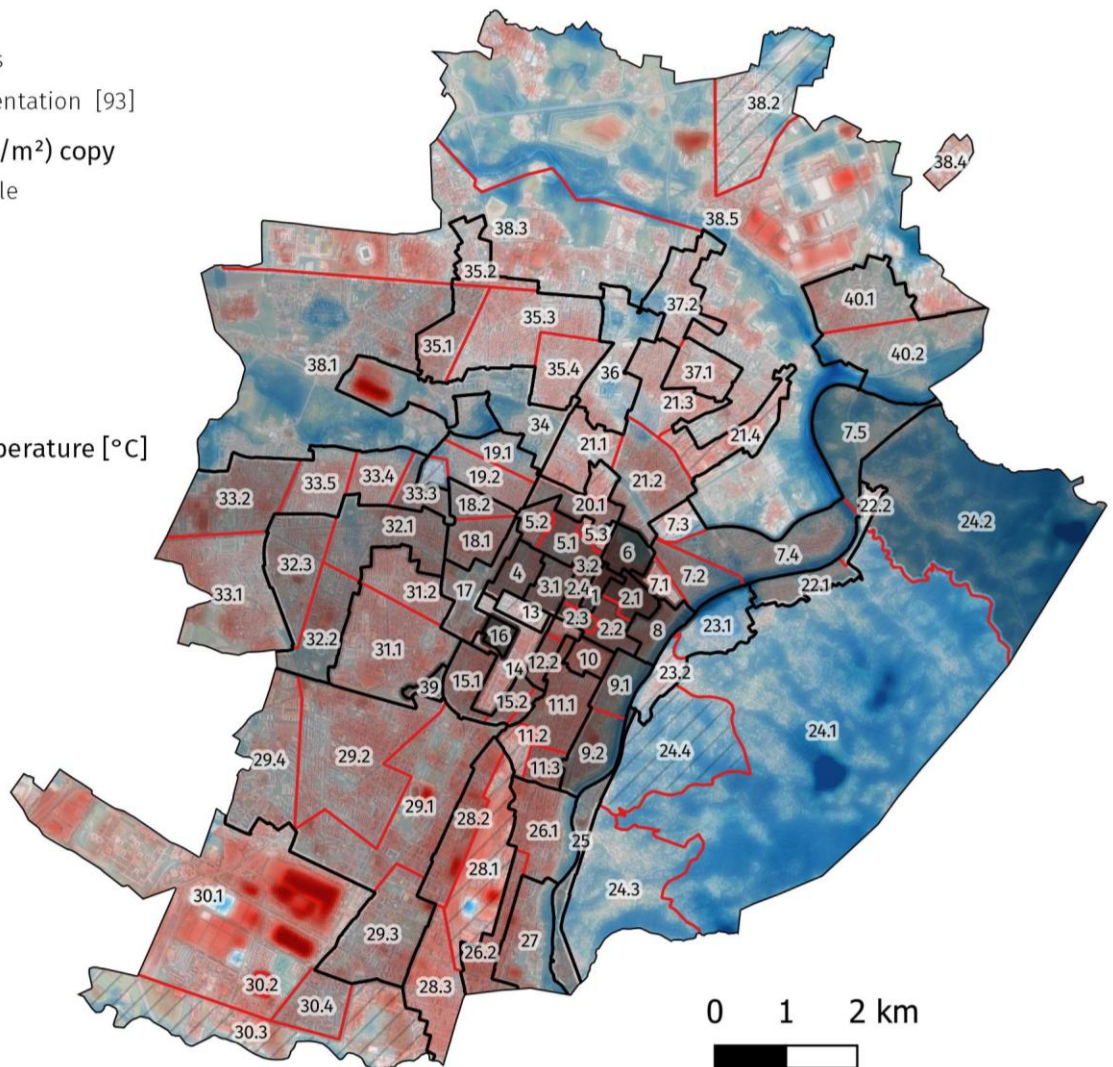


Figure 52 - GIS-based overlay between property value classes and Land Surface Temperature (LST) across Turin's cadastral microzones and historical territorial sub-segmentations.

Source: Author's elaboration using GIS, based on Barreca, Curto and Rolando (2017) study of PTS (p.60, fig.3) and GeoPortale data.

This contrast highlights an important point: surface temperature and environmental quality alone cannot explain the formation of real estate values.

The maps clearly show that central areas maintain the highest market values despite less favorable environmental conditions. In other words, the “*functional city*” - defined by accessibility, services, centrality and urban prestige - still appears to be valued more than the “*healthy city*”.

Between these two opposite conditions, the intermediate urban belt shows a more nuanced pattern.

Areas located outside the historic core but not yet belonging to the most peripheral sectors generally display medium property values combined with medium to high LST levels.

These zones as *PTS 31.1 San Paolo* do not show the same strong market centrality of the city centre, but neither do they present the same low-value condition observed in the southern periphery.

Their position is therefore particularly relevant from an evaluative perspective: environmental improvements in these areas may have a more visible effect on urban attractiveness and liveability, precisely because market values are not already strongly driven by centrality. In this sense, intermediate areas can be interpreted as transition zones, where the relationship between environmental quality and real estate value may be more sensitive and potentially more responsive to future NBS implementation.

Market prices are therefore influenced by a wider set of factors, including location, accessibility, historical and architectural quality, service provision, symbolic value and demand dynamics.

With regard to **vulnerability**, its spatial distribution appears more heterogeneous when compared with real estate market values.

A perfect correlation cannot be identified; however, the map suggests that areas with lower market attractiveness often tend to coincide with more critical environmental and demographic conditions. This aspect is particularly relevant in relation to the concept of *additionality*.

In fact, in these contexts, even relatively small-scale NBS could generate a proportionally significant benefit, both in terms of environmental improvement and potential urban regeneration effects.

Legend:

- Turin Microzones
- Turin Sub-Segmentation [93]

Property Values (€/m²) copy

- Data Not Available
- 1 - 1551 €
- 1551 - 2101 €
- 2101 - 2734 €
- 2734 - 3100 €
- 3101 - 5000 €

Vulnerability

- Low
- Medium
- Medium-High
- High
- Very High

Satellite

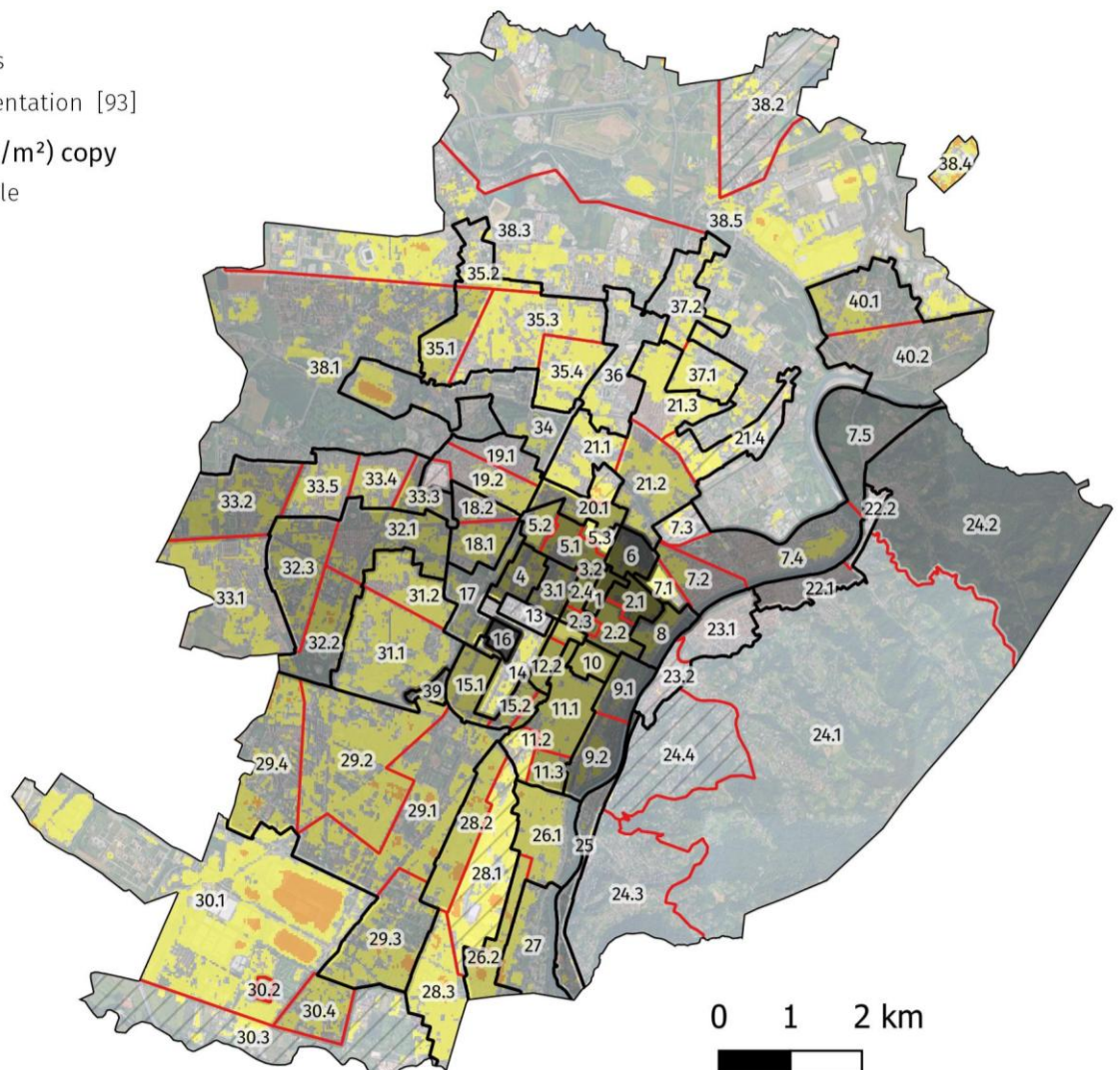


Figure 53 - Spatial relationship between property value classes and urban vulnerability in Turin, represented across cadastral microzones and historical territorial sub-segmentations.

Source: author's elaboration using GIS, based on Barreca, Curto and Rolando (2017) study of PTS (p.60, fig.3) and GeoPortale data.

Finally, a third map was produced by overlaying the **real estate market sub-segmentation with the land use layer** provided by the *Copernicus open-source* platform, considering only green and open spaces. The aim of this representation was to understand, even at a preliminary visual level, whether the presence of green areas showed any spatial correspondence with higher property values (see Figure 56).

The relationship appears only partially evident. In some cases, small green areas seem to be associated with a slight increase in market values: within the same broader micro- zone, the *PTS* sub-segments located closer to green spaces often belong to a slightly higher price range. This can be observed, for example, in micro-zone 7, corresponding to the *Vanchiglia* area, where *PTS* 7.4 and 7.5 show higher property values and are located close to *Parco della Colletta*.

At the same time, the relationship becomes much clearer in areas such as *Collina*, *Michelotti* and *Crimea*, corresponding to microzones 22, 23 and 24. In these cases, the presence of larger and more structured green areas, together with a high-quality residential context, overlaps more systematically with higher property value ranges. This represents one of the most direct spatial confirmations of the relationship between green amenities and real estate value.

However, the map also shows that the relationship between green space and property value is not linear or automatic. A possible explanation is the existence of a threshold effect: the real estate market may react only when green areas reach a certain size, quality, accessibility or symbolic value. Fragmented, residual or less recognizable green spaces seem to have a weaker influence on prices.

For instance, *Parco del Valentino* appears to contribute more clearly to the attractiveness of nearby properties, whereas other large green areas, such as *Parco della Pellerina* or *Piazza d'Armi*, although relevant from a thermal-regulation perspective, do not seem to produce the same visible effect on surrounding real estate values.

Legend:

- Turin Microzones
- Turin Sub-Segmentation [93]

Land Cover/Land Use 2021

- 13400: Land without current use
- 14110: Green urban areas (Public access)
- 14120: Green urban areas (Private access)
- 14130: Green urban areas (Unknown access conditions)
- 14200: Sports and leisure facilities
- 21000: Arable land (annual crops)
- 22000: Permanent crops (vineyards, fruit trees, olive groves)
- 23000: Pastures
- 31000: Forests
- 32000: Herbaceous vegetation associations (natural grassland, moors...)
- 33000: Open spaces with little or no vegetation (beaches, dunes, bare rocks, glaciers)
- 50000: Water

Property Values €/m²) copy

- Data Not Available
- 1 - 1551 €
- 1551 - 2101 €
- 2101 - 2734 €
- 2734 - 3100 €
- 3101 - 5000 €

Satellite

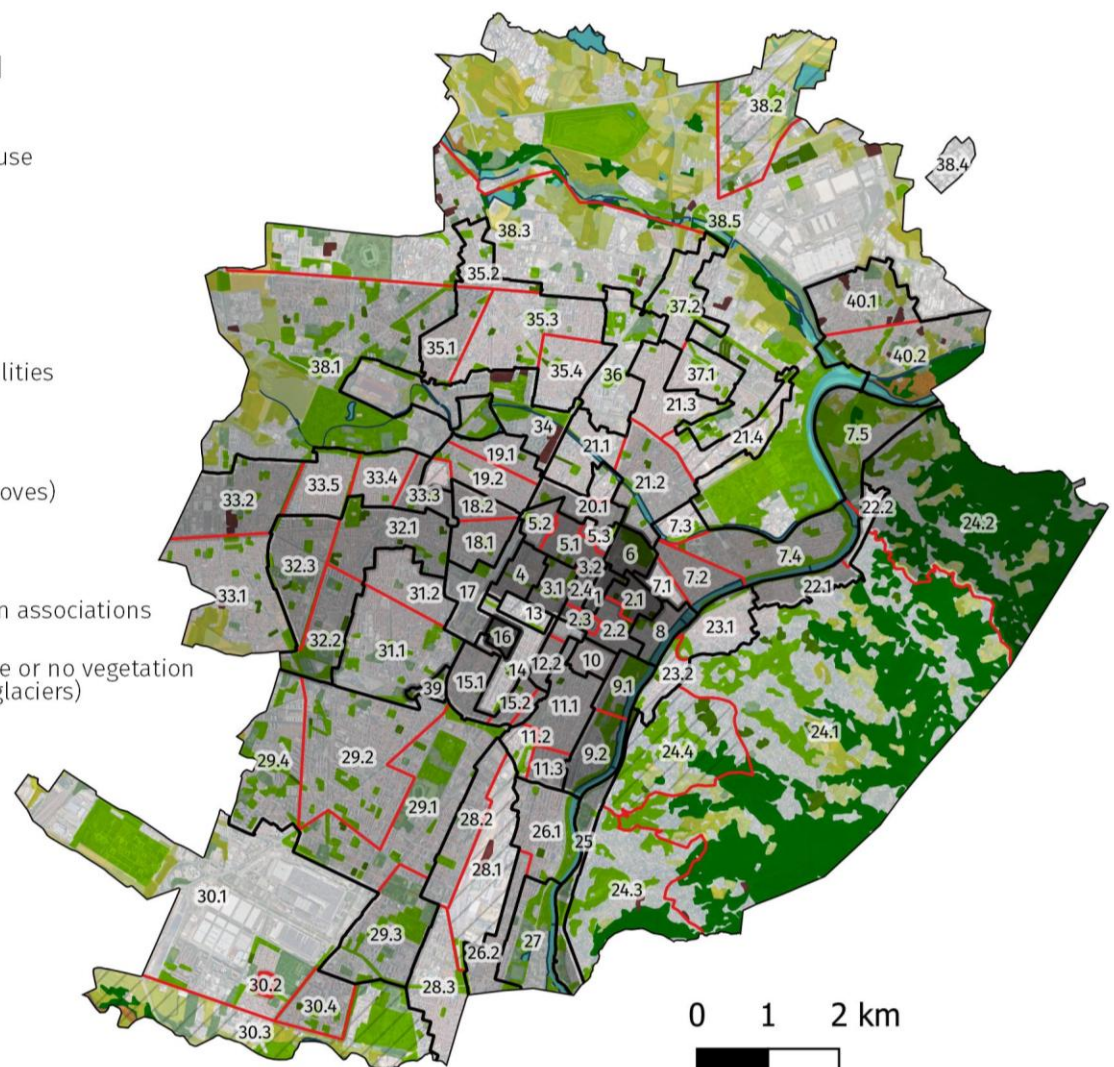


Figure 54 -GIS-based overlay between land cover/land use classes and property value classes across Turin's cadastral microzones and historical territorial sub-segmentations.

Source: author's elaboration using GIS, based on land cover/land use geospatial data from Copernicus, based on Barreca, Curto and Rolando (2017) study of PTS (p.60, fig.3) and GeoPortale data.

This confirms that green space alone is not sufficient to explain property value formation. Its influence depends on several factors, including location, accessibility, perceived quality, urban context and the socio-economic profile of the surrounding area. The locational factor therefore remains one of the most influential drivers of real estate prices, while the presence of green areas may act as an additional value component only under specific spatial and qualitative conditions.

4.3.5 Spatial mismatches and areas of intervention potential

Given the complexity of the topic and the heterogeneous nature of the analysis, the selection of the alternatives was approached strategically. The underlying idea was to make the choice of the case-study areas both meaningful and non-obvious. For this reason, the alternatives were not selected simply among the most critical areas, but rather among urban contexts sharing a comparable level of vulnerability, generally within a medium to medium-high range. This makes them comparable from the point of view of exposure to thermal risk, urban heat island conditions and demographic sensitivity.

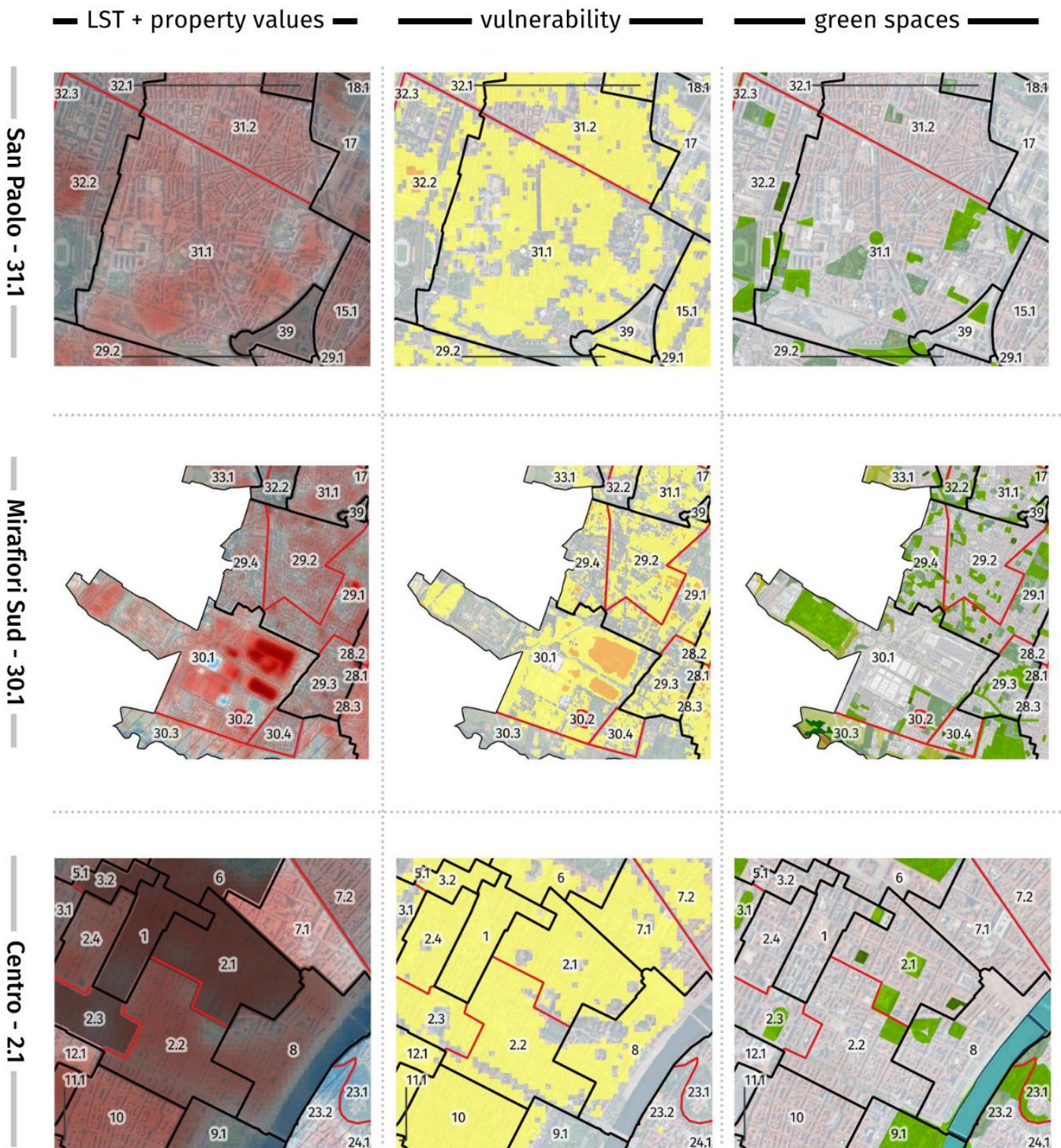
In this sense, vulnerability can be considered the common baseline condition of the selection process, while two dimensions were intentionally allowed to vary: real estate market value and green space provision. This approach made it possible to identify three different urban contexts, each characterized by a specific combination of environmental, economic and spatial conditions.

The first selected area is **Borgo San Paolo – PTS 31.1**. This area shows a medium level of vulnerability, intermediate real estate values, ranging approximately between **2,101 and 2,734 €/m²**, and a limited and fragmented provision of urban green spaces. LST values are moderate, although still relatively high when compared with the cooler parts of the city. For these reasons, *Borgo San Paolo* can be interpreted as an intermediate case: neither the most critical nor the

most advantaged, but potentially interesting for evaluating how NBS could operate in a consolidated and relatively balanced urban fabric.

The second area is **Mirafiori Sud (Unione Sovietica-Orbassano) – PTS 30.1**. Here, vulnerability is classified as medium, although the area is directly adjacent to PTS 30.2, where vulnerability reaches higher levels. Real estate values fall within the lowest price range, approximately between **1 and 1,551 €/m²**, while the presence of public green space is extremely limited, also due to the historical and industrial development of this part of the city. At the same time, LST values are among the highest in Turin, indicating strong exposure to urban heat island conditions. This represents the case in which the environmental deficit is most evident and where the marginal effect of NBS could potentially be more significant, both in terms of environmental improvement and possible market response. For this reason, *Mirafiori Sud* may be interpreted as a potential high-additionality context.

The third selected area is **Centro (Po-Vittorio Emanuele) – PTS 2.1**. This area also presents a medium level of vulnerability, but it is associated with high real estate values, ranging approximately between **2,734 and 5,000 €/m²**. Unlike the previous cases, this area benefits from proximity to consolidated green and blue infrastructures, such as the *Po River* and *Parco del Valentino*, which may provide environmental benefits even when not directly accessible from every point of the micro-zone. LST values are generally within an intermediate range. This case is particularly relevant because it allows the analysis to explore whether additional NBS could still generate a measurable real estate premium in an already attractive and central urban context, or whether other market drivers - such as location, services, accessibility and prestige - remain predominant.



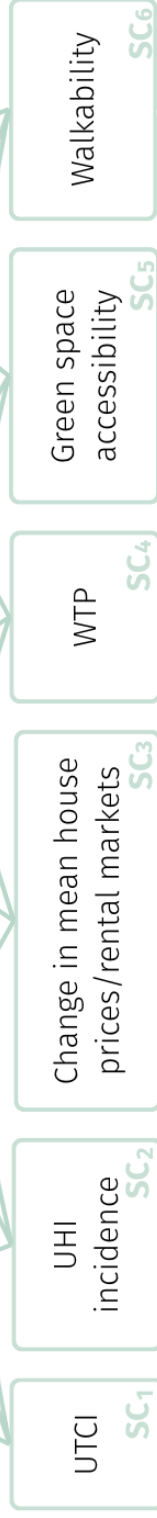
OBJECTIVE
Level - 0

Evaluating the sustainability of Nature-Based Solutions and identifying optimal urban contexts for their implementation **O**

CRITERIA
Level - 1



SUB-CRITERIA
Level - 2



ALTERNATIVES
Level - 3



4.4. Analytical and computational tools

To complete the definition of the study model, it was considered useful to describe the tools that could be employed for the calculation of the proposed indicators. This section therefore has a mainly theoretical and methodological purpose, as it aims to clarify how each indicator could be operationally measured within a future application of the framework. In the present thesis, these tools are not directly applied, with the exception of *GIS*, which was used for the preliminary territorial analysis and for the production of the cartographic elaborations.

GIS-based spatial analysis – QGIS

The term *GIS* – *Geographic Information System* – refers to an information system, including software, hardware and data, designed to acquire, store, analyse and manage geospatial data. It allows descriptive information to be integrated with its precise location on the Earth's surface.

In the specific case of this thesis, the open-source and free *software QGIS* was used to implement the spatial analysis described above.

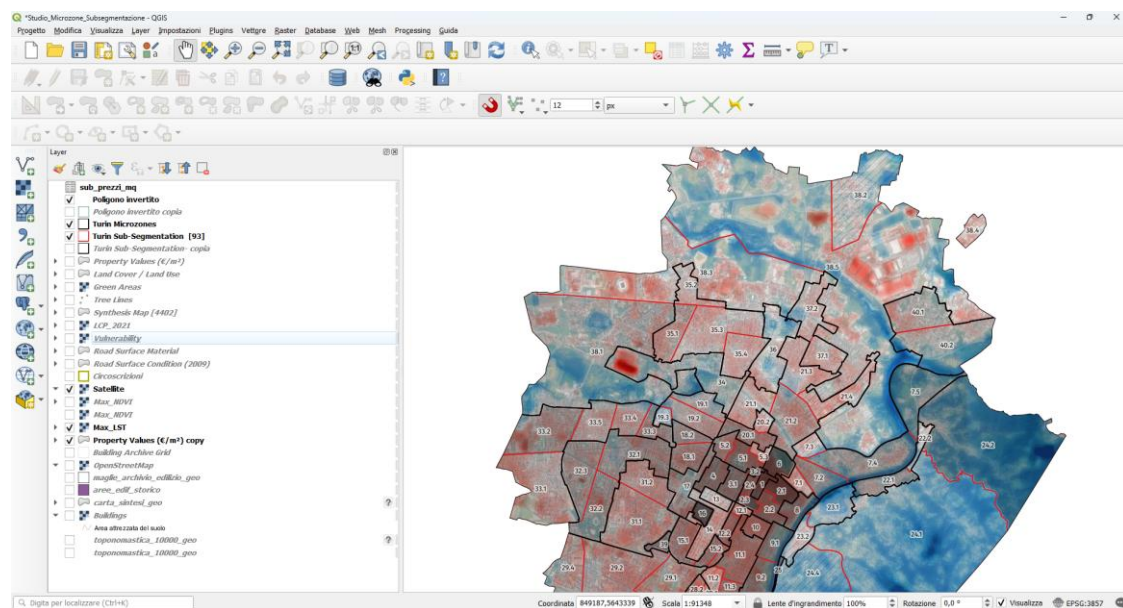


Figure 55 - QGIS working environment used for the spatial overlay between property values, Land Surface Temperature and Turin's territorial sub-segmentations.

Source: QGIS interface

The datasets were imported from the *Geoportale Piemonte* and subsequently organized, filtered and analysed within the GIS environment.

In particular, the attribute tables were used in a similar way to a spreadsheet, allowing the data to be selected and filtered according to the relevant micro-zones and *PTS* sub-segments. The different spatial information was then managed through separate layers and overlaid in order to compare environmental indicators, real estate market values and urban land-use characteristics. QGIS will also be employed for the calculation of the social indicators related to *walkability* and *green space accessibility*, as further explained in the following sections.

Microclimatic simulation – ENVI-MET

ENVI-met is a three-dimensional microscale simulation software designed to model complex urban environments according to the fundamental principles of fluid dynamics, thermodynamics and atmospheric physics, including wind flow, temperature distribution and turbulence processes.

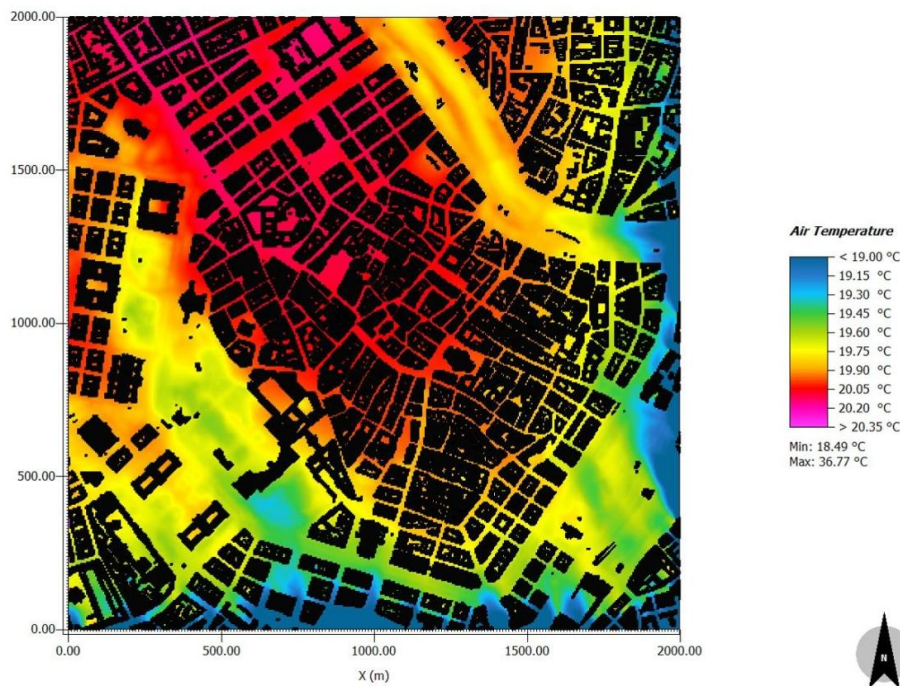


Figure 56 - Example of ENVI-met output showing the spatial distribution of air temperature within an urban simulation

Source: *One Click LCA*, ENVI-met from *One Click LCA*, accessed 28 June 2026.

Its innovative aspect lies in its integrated approach: rather than analysing individual components separately, the software simulates the interactions between buildings, ground surfaces, vegetation and the surrounding urban atmosphere. The software is widely recognized in the literature on green infrastructure and NBS. As highlighted by Wang et al. (2022), “*the ENVI-met model is currently the most holistic three-dimensional microclimate model to present high-resolution interactions among surfaces, plants and the atmosphere*”.¹¹²

In their study, the software is used as a microclimatic assessment tool to support the evaluation of walkability within the *15-minute city framework*, taking into account the risks associated with heat stress. ENVI-met is therefore employed to simulate urban microclimatic conditions and to provide environmental data that can inform the assessment of pedestrian comfort and accessibility.

Even more important is its role in comparing different design options. In the study by Herath et al. (2018), ENVI-met is used as a microclimatic simulation tool to test how effective various green infrastructure scenarios are at reducing the Urban Heat Island effect. By comparing the current situation with alternative greening strategies, the software offers tangible, quantitative evidence of how much urban vegetation and NBS can help cool the city.¹¹³ For these reasons, ENVI-met was considered a suitable tool for the simulation of environmental impacts, as it allows a more detailed analysis of the baseline scenario and provides an indication of possible post-intervention conditions, particularly in relation to the calculation of UTCI and UHI effects.

¹¹² Yu Wang et al., “Assessment of Walkability and Walkable Routes of a 15-min City for Heat Adaptation: Development of a Dynamic Attenuation Model of Heat Stress,” *Frontiers in Public Health* 10 (2022): 1011391, p.12, doi: 10.3389/fpubh.2022.1011391.

¹¹³ H. M. P. I. K. Herath, R. U. Halwatura, and G. Y. Jayasinghe, “Evaluation of Green Infrastructure Effects on Tropical Sri Lankan Urban Context as an Urban Heat Island Adaptation Strategy,” *Urban Forestry & Urban Greening* 29 (2018), pp. 212–222, doi: 10.1016/j.ufug.2017.11.013.

Multicriteria decision support – SuperDecision

SuperDecisions is a decision-support software designed to implement the Analytic Hierarchy Process (AHP) and its more general formulation, the Analytic Network Process (ANP). The tool allows the user to structure a decision problem in terms of goals, criteria, sub-criteria and alternatives, to perform pairwise comparisons, and to derive a final ranking of the available options.¹¹⁴

In the context of this research, *SuperDecisions* is proposed as an operational tool for the final evaluation phase – that is, as a means of systematically assessing and ranking the alternatives once the broader analytical framework has been defined.

Tools integration within the framework workflow

Having examined the software and tools employed for the definition of indicators and for the implementation of the AHP multicriteria method, it is now possible to update the operational framework with all the features required for the simulation. On the economic side, the assessment relies on regression analysis and the *Contingent Valuation Method* (CVM).

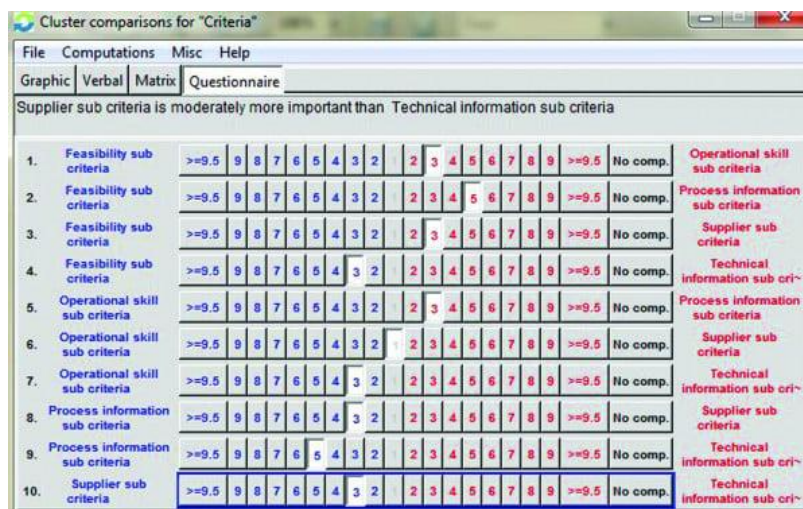
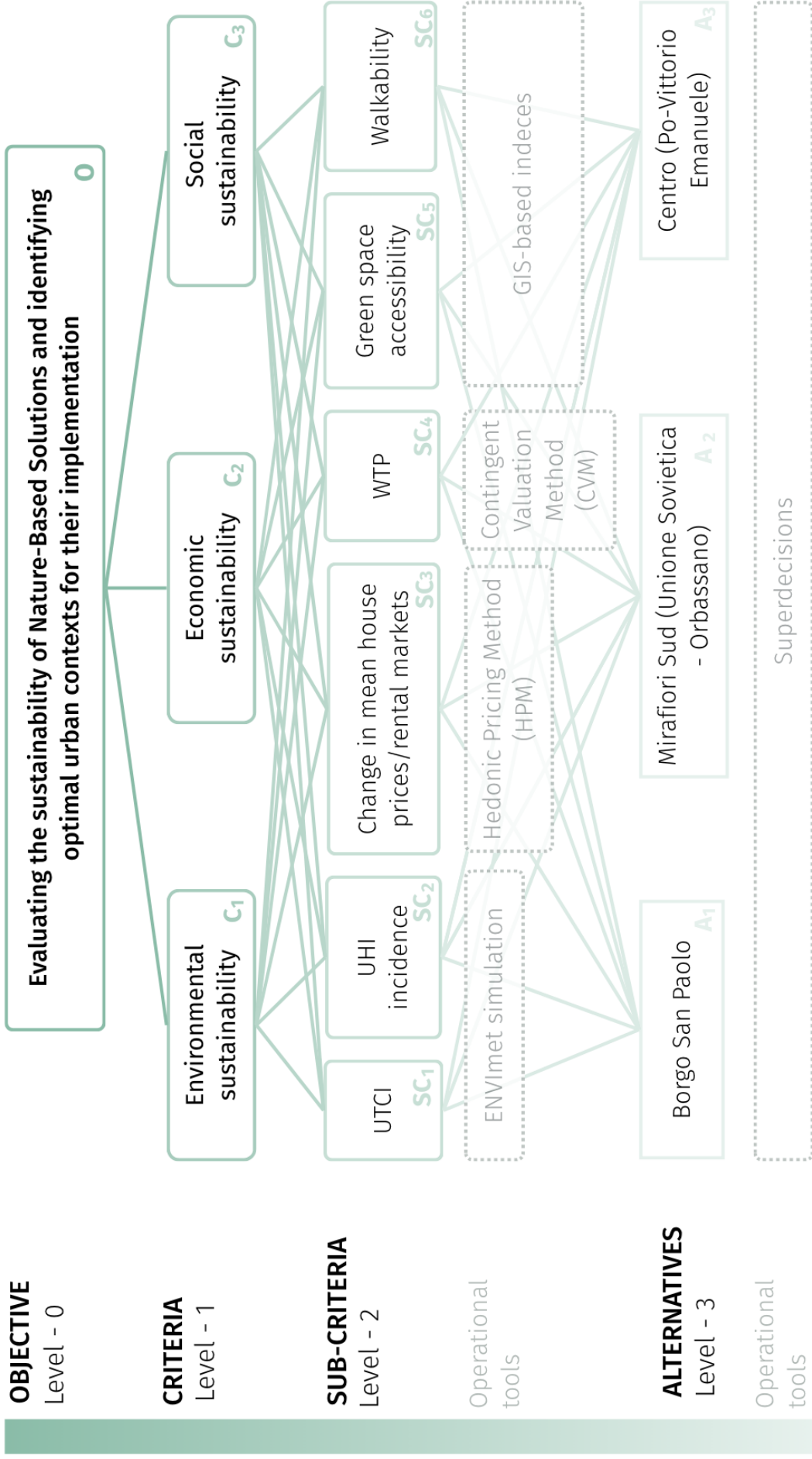


Figure 57 - Pairwise comparison interface in SuperDecisions software for the weighting of criteria within an AHP/ANP model.

Source: <https://www.superdecisions.com/>

¹¹⁴ <https://www.superdecisions.com/>



4.5. Operationalization of sub-criteria

In this section, the calculation logic underlying each sub-criterion is presented, showing how they have been designed to be quantified either through the selected software tools or by means of economic and statistical methods.

Since the proposed framework is conceived as a preliminary and methodological model, the indicators described below should not be interpreted as already validated outputs, but rather as **operational components of a theoretical structure** intended to support future applications.

Their full empirical validation would require a complete application to real data, expert-based weighting, consistency testing and sensitivity analysis.

The aim of this section is therefore to clarify how each sub-criterion could be measured, normalized and integrated within the AHP structure, while acknowledging that the framework remains open to refinement according to data availability, local conditions and the specific objectives of future NBS assessments.

4.5.1 Environmental dimension

As previously discussed, the decision to work at the scale of real estate sub-segmentations, rather than at the broader scale of cadastral micro-zones, responds not only to the need for a higher level of analytical detail, but also to a functional requirement of the proposed methodology.

This aspect becomes particularly relevant in the environmental dimension of the framework, where the use of ENVI-met was considered for the microclimatic assessment of the selected urban areas.

As a microscale simulation model, ENVI-met is not intended to simulate an entire city or very large urban districts, but rather to analyze smaller and more detailed portions of the urban fabric, such as neighbourhood sections, street canyons, squares or representative urban blocks. Its spatial application is therefore necessarily limited by the size and resolution of the 3D model, as well as by the computational complexity of the simulation. For instance, detailed models may cover areas of approximately 750 × 750 metres, depending on the selected grid resolution and level of geometric detail.

For this reason, the use of sub-segmentations appears coherent with the operational scale required by ENVI-met, allowing the environmental indicators to be assessed on spatial units that are sufficiently detailed, comparable and technically manageable.

Universal Thermal Climate Index (UTCI) – SC₁

UTCI measures outdoor thermal comfort not as a raw temperature reading but as a physiological equivalent - the air temperature that would produce the same thermal response in a reference human body under standardized conditions. This makes it more suitable than LST or air temperature alone for comparing urban alternatives according to heat stress criteria.

Model construction

Building the ENVImet model requires four inputs:

- Urban geometry - reconstructed from GIS data, DWG files and technical cartography, defining a study area of equal size for each alternative to ensure spatial comparability.
- Surface materials - assigned using orthophotos and the ENVImet materials database.
- Vegetation - street trees, green roofs and green walls, mapped through GIS layers and Google Maps imagery.
- Climate conditions - local weather station data processed into an .epw file, which provides ENVImet with the initial atmospheric conditions for the dynamic simulation.

From simulation to UTCI

The raw simulation outputs - air temperature, relative humidity, wind speed, mean radiant temperature, surface temperature and solar radiation, all at pedestrian height (1.5 m) - are fed into *BioMet*, ENVImet's post-processing thermal comfort module. BioMet combines these variables into spatially distributed UTCI values. The same module can also compute PET and SET.

The output is a map classified into ten thermal stress categories:

UTCI range (°C)	Thermal stress category
> +46	Extreme heat stress
+38 to +46	Very strong heat stress
+32 to +38	Strong heat stress
+26 to +32	Moderate heat stress
+9 to +26	No thermal stress
0 to +9	Slight cold stress
-13 to 0	Moderate cold stress
-27 to -13	Strong cold stress
-40 to -27	Very strong cold stress
< -40	Extreme cold stress

Operationalisation in the AHP

The indicator can be applied in two ways depending on the analytical scenario:

Baseline only

→ SC_1 = % of study area under strong or very strong heat stress ($UTCI \geq +32^\circ C$) during peak hours

Example: if 60% of Mirafiori Sud falls above $+32^\circ C$ and 35% of Centro Po-Vittorio does, the two alternatives receive different scores in the pairwise comparison matrix accordingly.

Post-intervention

→ $SC_1 = \Delta\%$ reduction in area under severe stress ($UTCI \geq +32^\circ C$) between baseline and NBS scenario

Example: a reduction from 60% to 38% corresponds to a -22 percentage point improvement, directly comparable across alternatives.

In both cases the indicator produces a single quantitative value per alternative.

It is worth noting that when applied to the baseline scenario alone, this indicator does not measure the performance of a NBS intervention, it measures the **thermal criticality of the starting condition**.

In this configuration, the AHP is not selecting the alternative that benefits most from NBS, but the urban context where the need for intervention is greatest. This is a legitimate and internally consistent use of the framework, provided the distinction is made explicit in the interpretation of results.

Urban Heat Island incidence - SC_2

While UTCI captures the physiological experience of heat stress at the individual level, the second environmental indicator focuses on the spatial distribution of urban overheating. It is not intended to measure perceived thermal comfort, but rather the degree to which each study area is affected by surface overheating in relation to the city as a whole.

Definition and reference condition

In its canonical formulation, the Urban Heat Island effect is defined as the temperature differential between an urban area and its surrounding rural environment:

$$UHI = T_{\text{urban}} - T_{\text{rural}}$$

This captures the core phenomenon - urban areas tend to be warmer than their rural surroundings due to sealed surfaces, dense built fabric, anthropogenic

heat and reduced vegetation cover. At the city scale, the rural fringe serves as the undisturbed thermal baseline.

At the intra-urban scale adopted in this thesis, however, the rural reference loses its comparative utility. Since the same rural value would be subtracted from all three alternatives, the relative ranking between them would remain unchanged regardless. The indicator is therefore adapted to the sub-urban scale and expressed as an intra-urban surface thermal anomaly:

$$\text{Intra-urban LST anomaly (UHI)} = \text{LST}_{\text{study area}} - \text{LST}_{\text{city average}}$$

The citywide mean LST is adopted as the common reference condition. Each alternative is measured against this baseline, and the resulting differential indicates how much warmer or cooler that specific area is compared to the average thermal condition of the city. The conceptual structure of the original UHI index is preserved, while the reference is rescaled to fit a comparative intra-urban framework.

Model construction

The modelling workflow follows the same logic described for UTCI. No additional post-processing module is required - the surface temperature parameter is extracted directly from the ENVI-met simulation outputs at the selected simulation hour and day. This also ensures methodological continuity with the preliminary GIS analysis, where LST was already used as the primary thermal indicator at the city scale.

Operationalisation in the AHP

In order to translate the result in the AHP framework the indicators will be quantified as it follows.

Baseline scenario

→ $SC_2 = \text{Mean intra-urban LST anomaly (UHI)} = LST_{\text{study area}} - LST_{\text{city average}}$, at the established simulation hour

Example: if Mirafiori Sud shows a mean differential of +4.2°C and Borgo San Paolo +2.8°C, Mirafiori presents a more critical thermal condition.

If the objective shifts to identifying priority areas for NBS deployment, however, the same values can be read as indicators of intervention urgency - areas with greater thermal anomaly have more to gain from mitigation measures. The interpretation therefore depends on the analytical framing, and this should be made explicit when entering the values into the pairwise comparison matrix.

Post-intervention scenario

→ $SC_2 = \Delta_{UHI} = LST_{\text{anomaly baseline}} - LST_{\text{anomaly NBS scenario}}$

In this case the indicator becomes a benefit criterion - higher reductions correspond to greater thermal improvement.

Example: a decrease from +4.2°C to +2.9°C corresponds to a -1.3°C improvement, directly comparable across alternatives.

When applied to the baseline alone, this indicator measures the thermal criticality of the starting condition rather than the performance of any specific intervention. Higher intra-urban LST anomaly values signal greater environmental stress and can support the identification of areas where NBS implementation may be most urgent or potentially most impactful.

4.5.2 Economic dimension

The economic dimension is estimated through the application of statistical and economic valuation methods suitable for pre-design contexts, where no intervention has yet taken place and market responses to future NBS cannot be directly observed.

The two indicators incorporated into the AHP model were selected to capture complementary and conceptually distinct dimensions of economic value. Hedonic regression is primarily intended to identify the value already capitalized in property prices as a result of existing environmental amenities - vegetation, parks, green infrastructure - providing a market-based reading of how the real estate sector currently prices proximity to nature in each study area.

Willingness to Pay, by contrast, measures residents' stated readiness to financially support the implementation of future interventions, capturing a dimension of value that market prices alone cannot reveal.

The risk of double counting is addressed through the conceptual separation of what each method actually values. Hedonic regression concerns existing environmental characteristics and their observed effects on real estate market values. The contingent valuation instrument, on the other hand, concerns a hypothetical future good and the willingness of residents to contribute to its provision. The two indicators also rely on fundamentally different valuation approaches - revealed preferences and stated preferences respectively - and are therefore treated as separate economic dimensions within the AHP framework rather than being aggregated as independent monetary estimates of the same intervention.

Economic indicator	Valuation method	Object of measurement
Impact on property values	Hedonic regression; revealed preference	Ex-post capitalized value of existing NBS and environmental amenities reflected in market property prices
Willingness to Pay	Contingent Valuation Method; stated preference	Ex-ante willingness of residents to contribute to the implementation and maintenance of proposed NBS that do not yet exist

Change in real estate values - hedonic regression model - SC₃

At this stage, it should be specified that the following reasoning and the resulting regression formula are developed at a theoretical and methodological level. The model has not yet been empirically estimated or validated within this thesis; rather, it is proposed as a possible operational structure for future applications of the framework, once a sufficiently robust real estate dataset is available.

The reasoning behind this indicator is straightforward. The question is not simply whether proximity to green space affects property prices, but whether it does so differently across the three study areas - and by how much. If it does, the hedonic regression would provide a market-based signal of how sensitive each zone is to environmental amenities, which in turn could inform the AHP comparison.

A naive formulation such as:

$$Price = f(\text{Distance to green})$$

would be insufficient. Property prices are strongly driven by locational dynamics, as confirmed by Barreca, Curto and Rolando (2017) in their study of Turin's sub-segmentation. Location must therefore be controlled for before the effect of green proximity can be isolated.

Dependent variable

The unit of observation is the individual property listing. The dependent variable is the unit price expressed in €/m²:

$$y = P_{sqm,i}$$

Given that price distributions tend to be right-skewed, the model uses the natural logarithm of the unit price:

$$\ln(P_{sqm,i})$$

This allows coefficients to be read directly as approximate percentage changes.

Spatial control variables - dummy encoding

The three study areas enter the model as dummy variables, controlling for baseline price differences between zones. Centro (Po-Vittorio Emanuele) is retained as the reference category, coded 0 on both dummies:

Area	San Paolo dummy	Mirafiori Sud dummy
Centro	0	0
San Paolo	1	0
Mirafiori Sud	0	1

Distance to green

The core environmental variable is:

$D_{Green,i}$ - distance from the property to the nearest green space or NBS (metres)

Interaction terms

The model does not assume that the effect of green proximity is uniform across zones. In a high-value central area, prices may already be so strongly driven by locational prestige that green proximity adds relatively little at the margin. In a lower-value peripheral zone like Mirafiori Sud, the same amenity could have a proportionally larger effect. Interaction terms are therefore introduced to allow the distance coefficient to vary by zone:

- $SanPaolo_i \times D_{Green,i}$
- $Mirafiori_i \times D_{Green,i}$

Full model specification

$$\ln(P_{sqm,i}) = \beta_0 + \beta_1 D_{Green,i} + \beta_2 SanPaolo_i + \beta_3 Mirafiori_i + \beta_4 (SanPaolo_i \times D_{Green,i}) + \beta_5 (Mirafiori_i \times D_{Green,i}) + \gamma X_i + \epsilon_i$$

(39)

where:

- $\ln(P_{sqm,i})$ - natural logarithm of the unit price (€/m²) of property i ; the log transformation is applied to address the right-skewed distribution typical of real estate prices and to allow coefficients to be read as approximate percentage changes.
- β_0 - *intercept*; the expected log-price for a property in *Centro* (the reference zone) when distance from green equals zero and all other variables are held constant (*ceteris paribus*).

- $\beta_1 D_{\text{Green},i}$ - effect of distance from the nearest green space or potential NBS on log-price, estimated for the reference zone (Centro); a negative value indicates that prices decrease as distance from green increases.
- $\beta_2 \text{SanPaolo}_i$ - dummy variable equal to 1 if the property is located in Borgo San Paolo, 0 otherwise; captures the average baseline price differential between San Paolo and Centro, holding all other variables constant.
- $\beta_3 \text{Mirafiori}_i$ - dummy variable equal to 1 if the property is located in Mirafiori Sud, 0 otherwise; captures the average baseline price differential between Mirafiori Sud and Centro, holding all other variables constant.
- $\beta_4 (\text{SanPaolo}_i \times D_{\text{Green},i})$ - interaction term between the San Paolo dummy and distance from green; captures whether the effect of green proximity on prices in San Paolo differs from that observed in Centro. **The total distance effect in San Paolo is $\beta_1 + \beta_4$.**
- $\beta_5 (\text{Mirafiori}_i \times D_{\text{Green},i})$ - interaction term between the Mirafiori dummy and distance from green; captures whether the effect of green proximity on prices in Mirafiori Sud differs from that observed in Centro. **The total distance effect in Mirafiori Sud is $\beta_1 + \beta_5$.**
- γX_i - vector of property-level control variables (floor area, floor level, building age, presence of lift, balconies); included to isolate the effect of green proximity from other characteristics that independently affect price.
- ε_i - error term; captures unexplained variation in prices not accounted for by the model.

Example dataset structure

ID	Area	€/m ²	ln(€/m ²)	DGreen	San Paolo	Mirafiori	SP × DGreen	MF × DGreen
1	Centro	3,800	8.24	150m	0	0	0	0
2	San Paolo	2,700	7.90	420m	1	0	420	0
3	Mirafiori Sud	1,900	7.55	250m	0	1	0	250
4	Centro	4,100	8.32	600m	0	0	0	0
5	San Paolo	2,500	7.82	180m	1	0	180	0

Interpreting the coefficients

Each β coefficient has a specific meaning within the model:

- β_0 - intercept; expected log-price for a property in Centro when all other variables equal zero.
- β_1 - effect of distance from green in Centro (the reference zone); a negative value means that as distance increases, price falls.
- β_2, β_3 - average price differential of San Paolo and Mirafiori Sud relative to Centro, holding distance and property characteristics constant. Negative values confirm lower baseline prices in the peripheral zones.
- β_4 - captures whether the distance effect in San Paolo differs from Centro. The total distance effect in San Paolo is not β_4 alone, but:
 - β_1 = effect of distance in Centro (reference zone)
 - β_4 = difference in the distance effect in San Paolo relative to Centro

- $\beta_1 + \beta_4$ = total distance effect in San Paolo
- β_5 - same logic for Mirafiori Sud:
 - β_1 = effect of distance in Centro (reference zone)
 - β_5 = difference in the distance effect in Mirafiori Sud relative to Centro
 - $\beta_1 + \beta_5$ = total distance effect in Mirafiori Sud

The zone-specific models can be written out explicitly:

Centro ($\text{SanPaolo}_i = 0$, $\text{Mirafiori}_i = 0$):

$$\ln(P_{\text{sqm},i}) = \beta_0 + \beta_1 D_{\text{Green},i} + \gamma X_i + \varepsilon_i \quad (40)$$

San Paolo ($\text{SanPaolo}_i = 1$, $\text{Mirafiori}_i = 0$):

$$\ln(P_{\text{sqm},i}) = (\beta_0 + \beta_2) + (\beta_1 + \beta_4) D_{\text{Green},i} + \gamma X_i + \varepsilon_i \quad (41)$$

Mirafiori Sud ($\text{SanPaolo}_i = 0$, $\text{Mirafiori}_i = 1$):

$$\ln(P_{\text{sqm},i}) = (\beta_0 + \beta_3) + (\beta_1 + \beta_5) D_{\text{Green},i} + \gamma X_i + \varepsilon_i \quad (42)$$

Reading the coefficients

Since the dependent variable is in log form, coefficients are read as approximate percentage changes. For continuous variables, it is often more intuitive to express the effect per 100 metres rather than per metre:

Example: if $\beta_1 = -0.0004$, then per 100 metres of additional distance from green space in Centro: $-0.0004 \times 100 = -0.04$, meaning approximately -4% in price, if statistically significant.

For dummy variables, the more precise transformation is:

$$(e^{\beta} - 1) \times 100$$

Example: if $\beta_2 = -0.25$, San Paolo properties are on average $(e^{-0.25} - 1) \times 100 \approx -22\%$ cheaper than Centro, all else equal.

Operationalisation in the AHP

The interaction coefficients provide the key input for the AHP matrix. The zone-specific distance effects are:

Zone	Distance effect
Centro	β_1
San Paolo	$\beta_1 + \beta_4$
Mirafiori Sud	$\beta_1 + \beta_5$

These values indicate how sensitive the real estate market in each area is to green proximity. A more negative coefficient means that distance from green weighs more heavily on prices - and therefore that the introduction of NBS would likely generate a larger property value premium in that zone. Where a fully quantitative AHP input is preferred, the coefficients enter the pairwise comparison matrix directly. Where a qualitative reading is more appropriate, the magnitude of each coefficient can be translated into a verbal judgement - distinguishing for instance between weak, moderate and strong market sensitivity to green amenities.

Willingness to Pay - contingent valuation design - SC₄

The second sub-criterion selected to operationalize the economic sustainability criterion is Willingness to Pay (WTP). As discussed in CHAPTER 2, WTP can be estimated through stated preference techniques, which derive economic values from individuals' responses to hypothetical scenarios involving non-market goods or services.¹¹⁵

Within the stated preference framework, two main approaches can be distinguished: Contingent Valuation and Choice Modelling.

Contingent Valuation directly asks respondents to state whether, and how much, they would be willing to pay for a clearly defined project or environmental improvement. It therefore addresses the question "How much is this project worth to respondents?" and provides an estimate of the overall WTP associated with the proposed intervention. Choice Modelling, by contrast, presents respondents with alternative project scenarios characterized by different combinations of attributes and cost levels. By analyzing the choices made among these alternatives, it addresses the question "Which project characteristics generate value?" and allows the marginal WTP associated with each individual attribute to be estimated.

For the development of the operational model, the Contingent Valuation Method (CVM) was selected because of its comparatively simple, direct, and transparent structure. This choice was intended to ensure a high degree of applicability and flexibility, while maintaining consistency with the broader evaluation framework proposed in this research.

The questionnaire reported in *Appendix B* constitutes the operational instrument developed to estimate residents' stated Willingness to Pay for the implementation and maintenance of NBS in their neighborhood. It is structured

¹¹⁵ Ian J. Bateman et al., *Economic Valuation with Stated Preference Techniques: A Manual*, Cheltenham: Edward Elgar, 2002.

according to the Contingent Valuation Method, a well-established approach in environmental economics for the valuation of non-market public goods (Mitchell & Carson, 1989).¹¹⁶

The questionnaire design also draws on the recommendations of the NOAA Panel (Arrow et al., 1993),¹¹⁷ which represent a widely recognized methodological benchmark for the development of reliable Contingent Valuation surveys. Attention is therefore given to the clear definition of the environmental good, the description of the hypothetical intervention scenario, the identification of a credible payment vehicle, the elicitation of respondents' maximum WTP, and the distinction between genuine zero values and protest responses.

The survey is structured as follows.

First, the **purpose** of the survey is clearly stated in the introductory section. This provides respondents with the necessary context, explains the objectives of the study, and assures them that their responses will be treated confidentially.

Section 1 - Residential and socio-demographic information collects information on respondents' socio-demographic, spatial, and behavioral characteristics.

Participants are classified according to their area of residence or frequent use, age group, and relationship with the selected urban area, for example as residents, students, workers, or frequent visitors. These variables would allow future applications of the questionnaire to identify systematic differences in Willingness to Pay across neighborhoods and demographic or user groups.

In addition to these conventional background questions, Question 4, "*How often do you use urban green spaces, such as parks, gardens, or tree-lined streets?*"

¹¹⁶ Robert Cameron Mitchell and Richard T. Carson, *Using Surveys to Value Public Goods: The Contingent Valuation Method*, Washington, DC: Resources for the Future, 1989.

¹¹⁷ Kenneth Arrow, Robert Solow, Paul R. Portney, Edward E. Leamer, Roy Radner, and Howard Schuman, "Report of the NOAA Panel on Contingent Valuation," *Federal Register* 58, no. 10 (1993): 4601–4614.

is included to measure respondents' frequency of interaction with urban green infrastructure.¹¹⁸

This variable may help explain variations in WTP, as individuals who use and directly experience urban green spaces more frequently may perceive their benefits differently and consequently express a different willingness to contribute to their improvement or expansion.¹¹⁹

Section 2 - Perceptions of urban heat and NBS benefits is designed to establish the cognitive context required for an informed and credible expression of Willingness to Pay. Before respondents are asked to assign a monetary value to the proposed intervention, they should adequately understand both the environmental problem being addressed and the potential benefits generated by NBS.

The questions included in this section therefore investigate respondents' perceptions of urban heat, the perceived shortage of green spaces and trees, and the expected contribution of NBS to improving the quality of their neighborhood.

Question 7 *"Have you ever heard of NBS , namely urban solutions based on natural processes, such as green roofs, pocket parks, depaving, or rain gardens?"* is strategically included to assess respondents' prior familiarity with NBS. During the data analysis, this variable could be used to examine whether different levels of knowledge and awareness are associated with variations in stated WTP.

This question also provides an initial interpretative element for the analysis of zero-WTP responses.

¹¹⁸ Tyrväinen, Liisa, and Helena Väänänen, "The Economic Value of Urban Forest Amenities: An Application of the Contingent Valuation Method," **Landscape and Urban Planning** 43, no. 1–3 (1998): 105–118, [https://doi.org/10.1016/S0169-2046\(98\)00103-0](https://doi.org/10.1016/S0169-2046(98)00103-0)

¹¹⁹ Bark, Rosalind H., J. M. Colloff, S. G. Hatton MacDonald, and G. M. Pollino, "Incorporating Ecosystem Services into Cost–Benefit Analysis: Are We Counting What Counts?," *Environmental and Resource Economics* 48, no. 2 (2011): 177–194, <https://doi.org/10.1007/s10640-010-9396-1>.

It may help distinguish respondents who reject the proposed contribution despite being familiar with the good and its potential benefits from those whose response may be influenced by limited knowledge or an incomplete understanding of the proposed intervention.

However, the formal distinction between **true-zero responses** and **protest-zero responses** is established through the follow-up question investigating the reasons underlying the respondent's answer, as discussed in the following sections.

Section 3 – NBS scenario description consists of a short paragraph presenting respondents with the situation they are asked to evaluate and potentially support through an annual contribution.

In this case, the scenario describes the possible implementation of NBS by the City of Turin in the respondent's neighborhood, including street trees, pocket parks, the depaving of impermeable surfaces, rain gardens, and green roofs on public buildings.

In accordance with the guidelines provided by the NOAA Panel, the scenario must be credible, specific in its description of the environmental good to be evaluated, and neutral with respect to respondents' preferences. It is therefore important that the wording does not lead respondents towards either a positive or a negative answer. The paragraph clearly identifies the proposed interventions, their expected benefits, and the payment vehicle, defined as an annual contribution allocated exclusively to their implementation and maintenance within the neighborhood. An annual municipal contribution was preferred to a one-off payment because NBS involve recurring maintenance costs over time.

Section 4 – Willingness to pay assessment contains the actual questions used to assess the amount that respondents would be willing to pay. Questions 9 and 10 adopt a *dichotomous-choice format* with a *follow-up question*.

Respondents are first asked whether they would be willing to pay an annual contribution for the implementation and maintenance of the proposed interventions. Those who answer positively are then asked to indicate the maximum amount they would be willing to pay.

More specifically, the questionnaire combines an initial **dichotomous-choice** question with a **payment-card follow-up**. Question 9 distinguishes between respondents who are willing to contribute, those who are not willing to contribute, and those who require further information.

Question 10 then presents a series of predefined annual contribution levels from €0, €5, €10, €20, up to €50 and even more, from which respondents can select their maximum WTP.

These amounts are intended to represent reasonable contribution levels for European local public environmental goods and should be calibrated on the basis of values reported in the literature and, in a future application, through pilot testing.¹²⁰

The final category, corresponding to contributions higher than €50 per year, includes an open field in which respondents can specify the exact amount. This makes it possible to avoid the upper censoring of respondents whose WTP exceeds the highest predefined value.

This two-stage structure simplifies the valuation task and is closer to an actual decision-making process than a fully open-ended question. The payment-card follow-up also reduces the cognitive burden associated with directly assigning a monetary value to a non-market environmental good. However, the proposed ranges must be carefully calibrated to limit possible anchoring and range biases.

120 Amiran, D. H., and D. A. Hagen, "The Value of Urban Trees: A Hedonic Property Price Model in Portland, Oregon," *Landscape and Urban Planning* 94, no. 2 (2010): 77–83, <https://doi.org/10.1016/j.landurbplan.2009.07.019>.

Question 11, which investigates the main reason underlying each respondent's answer, is essential for distinguishing true-zero responses from the previously mentioned protest-zero responses. Protest-zero responses correspond to a stated WTP of €0 that does not reflect an absence of perceived value, but rather objections external to the valuation of the proposed environmental good.

These may include a lack of trust in the management and allocation of the collected funds, opposition to the proposed payment mechanism, or the belief that the municipality should be solely responsible for financing the interventions.

By contrast, responses associated with an actual inability to afford an additional contribution represent budget-constrained true-zero responses, while the absence of perceived benefits may also constitute a genuine zero valuation.

During the data analysis, protest-zero responses should therefore be identified and treated separately from valid zero values. Their uncritical inclusion in the calculation of mean WTP could generate a systematic downward bias, as they do not represent the respondents' actual valuation of the proposed NBS. The treatment of these observations should be clearly reported and, where possible, supported by sensitivity analyses comparing estimates obtained with and without protest-zero responses.

Section 5 – Preferences for NBS interventions is not intended to estimate WTP in monetary terms. Instead, it collects qualitative information on respondents' preferences regarding the types of NBS interventions considered most suitable for each neighborhood.

The mean WTP values estimated for each neighborhood will subsequently be normalized and converted into an ordinal classification, such as high, medium, or low. These scores will be used to assess the performance of the alternatives under the WTP sub-criterion within the AHP model.

More specifically, the normalized values may be used either to populate the alternative-performance matrix or to inform the pairwise comparison of alternatives with respect to the WTP sub-criterion.

Where they are translated into pairwise judgements, an explicit conversion rule should be defined to ensure consistency with the Saaty scale.

This procedure is consistent with approaches integrating values derived from Contingent Valuation into broader MCDA frameworks, as documented by Nijkamp et al. (1990)¹²¹.

¹²¹ Nijkamp, Peter, Piet Rietveld, and Henri Voogd, *Multicriteria Analysis for Physical Planning*. Amsterdam: Elsevier Science Publishers, 1990.

4.5.3 Social dimension

For the social dimensions as well, indicators have been selected with the aim of being as spatially based as possible. The calculation of these factors is straightforward yet effective, as both rely on techniques derived from GIS-based territorial analysis.

Green space accessibility - GSA index - SC₅

The GSA index measures the share of buildings within each study area that have access to at least one green space within a walkable distance.

Rather than mapping the total amount of green cover, it captures how well distributed that green cover is in relation to where people actually live.

Definition

The indicator is defined as:

$$\text{GSA} = (\text{Buildings within 300m buffer of green space} / \text{Total buildings in sub-segmentation}) \times 100$$

(43)

The 300m threshold is used as a proxy for walkable accessibility - the distance within which a resident can reasonably reach a green space on foot. Green spaces considered include public parks, urban gardens, pocket parks.

Model construction

The GIS workflow requires three input layers:

- *PTS/Microzone boundaries* - define the spatial extent of each study area and constrain the counting procedure.
- *Building footprints* - each building polygon is converted to its centroid, providing a single georeferenced point per building from which distances are calculated.

- *Green space geometries* - the boundaries of all urban green areas are used to generate georeferenced 300m buffers. Each buffer represents the catchment area within which any building centroid is considered accessible to that green space.

The procedure then runs as follows. For each green space geometry, a 300m buffer is generated in the GIS environment. Building centroids are spatially filtered by their position - first to select those falling within any of the buffers, then to retain only those also falling within the sub-segmentation boundary. The count of centroids meeting both conditions is divided by the total number of centroids within the study area, and the result is expressed as a percentage.

Methodological note

The buffer calculation considers all urban green spaces available across the city, not only those located within the sub-segmentation boundary. Green areas sitting at or near the edge of a study area would otherwise be excluded, artificially penalizing zones whose nearest green space happens to lie just across an administrative boundary. Including cross-boundary green spaces ensures the accessibility measure reflects actual spatial conditions rather than administrative constraints.

Operationalisation in the AHP

Baseline scenario

→ SC_5 = % of buildings within 300m of a green space

Example: if 78% of buildings in Centro Po-Vittorio fall within 300m of a green space and only 43% in Mirafiori Sud, the former scores better on this criterion.

Post-intervention scenario

→ SC_5 = $\Delta\%$ increase in buildings within 300m of a green space after NBS introduction

Example: a new pocket park in Mirafiori Sud brings coverage from 43% to 61%, corresponding to an +18 percentage point improvement, directly comparable across alternatives.

Higher GSA values indicate better green space distribution and represent a benefit criterion in the AHP matrix.

Walkability - pedestrian density index SC_6

The Walkability Index is constructed (simplification) as the unweighted average of three normalized sub-indicators, each capturing a distinct dimension of pedestrian accessibility:

$$\text{Walkability Index} = (ND + ID + AS) / 3$$

(44)

where all three components are normalized to a 0–1 scale before aggregation.

Model construction

The GIS workflow requires the following input layers, in addition to those already used for the GSA index:

- *Pedestrian street network (lines)* - the walkable road and path network within and around the study area.
- *Pedestrian intersections (nodes/points)* - the intersection points extracted from the pedestrian network.
- *Basic services (points)* - including bus stops, pharmacies, schools and supermarkets.

Each sub-indicator is calculated as follows:

Pedestrian Network Density (ND)

ND = Total length of pedestrian network (km) / Area of sub-segmentation (km²)

The street network layer is clipped to the sub-segmentation boundary, the length of all internal segments is summed and divided by the total area of the study zone.

Intersection Density (ID)

ID = Number of pedestrian intersections / Area of sub-segmentation (km²)

Intersection nodes are extracted from the pedestrian network layer. Only nodes falling within the sub-segmentation boundary are counted, and the total is divided by the area of the zone. A higher intersection density indicates a more permeable and connected street grid, generally more conducive to walking.

Accessibility to Services (AS)

AS = Buildings within buffer of basic services / Total buildings in sub-segmentation × 100

The procedure follows the same logic as the GSA index. A buffer is generated around each service point rather than around green spaces, and building centroids falling within any of the buffers are counted and expressed as a share of total buildings in the study area. Basic services considered are bus stops, pharmacies, schools and supermarkets.

Normalization

Since the three sub-indicators have different units - km/km², intersections/km² and percentage respectively - they are brought to a common 0–1 scale before aggregation using min-max normalization:

$$x_{\text{normalised}} = (x - x_{\text{min}}) / (x_{\text{max}} - x_{\text{min}})$$

where x_{min} and x_{max} are calculated across the three alternatives, so that the best-performing zone scores 1 and the worst scores 0 on each sub-indicator.

Final index calculation

Once normalized, the three components are averaged:

$$\text{Walkability Index} = (\text{ND norm} + \text{ID norm} + \text{AS norm}) / 3$$

The result is a single score between 0 and 1 per alternative, directly comparable within the AHP pairwise comparison matrix.

Operationalisation in the AHP

Baseline scenario

$$\rightarrow \text{SC}_6 = \text{Walkability Index score (0–1)}$$

Example: if Centro Po-Vittorio scores 0.74 and Mirafiori Sud scores 0.38, the former presents significantly better pedestrian accessibility conditions.

Post-intervention scenario

$\rightarrow \text{SC}_6 = \Delta \text{Walkability Index}$ between baseline and NBS scenario, where new green infrastructure also introduces tree-lined paths or improves connectivity.

Higher Walkability Index values indicate better pedestrian accessibility and represent a benefit criterion in the AHP matrix.

4.6. AHP matrix structure

This section defines the operational steps required to complete the AHP-based assessment and to identify the most suitable alternative. After the definition of the evaluation indicators, the procedure moves to the construction of pairwise comparisons and the derivation of weights.

However, the present thesis is conceived as a methodological framework and does not aim to produce a final ranking of the alternatives. Therefore, this section is intended to clarify how the selected indicators could be used in a subsequent full application of the model, in order to support the comparative evaluation of the alternatives.

Within this framework, the relative importance of criteria and sub criteria is defined through pairwise comparisons, while the performance of the alternatives can be derived from measurable, estimated or simulated indicators. In this way, the evaluation does not rely exclusively on arbitrary judgements when quantitative or semi-quantitative information is available.

More specifically, indicators may be obtained through different methodological tools, such as GIS-based spatial analysis, ENVI-met simulations, hedonic pricing models or contingent valuation surveys.

4.6.1 Pairwise comparison and weighting logic

Once all the elements to be evaluated have been defined, the pairwise comparison phase can be developed through the construction of the comparison matrices.

In the proposed AHP structure, the hierarchy is composed of 3 first-level criteria, 6 second-level subcriteria and 3 alternatives.

Therefore, the pairwise comparison process requires a total of **10 matrices**.

- **1 matrix (3 × 3)** is constructed to compare the three first-level criteria with respect to the overall objective:

$$M1 = C_1 \text{ vs } C_2 \text{ vs } C_3$$

- **3 matrices (6x6)** are constructed to compare the second-level sub criteria with respect to each first-level criterion. In this case, the six sub criteria are compared under each criterion:

$$M2 = SC_1 \text{ vs } SC_2 \text{ vs } SC_3 \text{ vs } SC_4 \text{ vs } SC_5 \text{ vs } SC_6 \text{ with respect to } C_1$$

$$M3 = SC_1 \text{ vs } SC_2 \text{ vs } SC_3 \text{ vs } SC_4 \text{ vs } SC_5 \text{ vs } SC_6 \text{ with respect to } C_2$$

$$M4 = SC_1 \text{ vs } SC_2 \text{ vs } SC_3 \text{ vs } SC_4 \text{ vs } SC_5 \text{ vs } SC_6 \text{ with respect to } C_3$$

- **6 matrices (3 × 3)** are constructed to compare the three alternatives with respect to each sub criterion:

$$M5 = A_1 \text{ vs } A_2 \text{ vs } A_3 \text{ with respect to } SC_1$$

$$M6 = A_1 \text{ vs } A_2 \text{ vs } A_3 \text{ with respect to } SC_2$$

$$M7 = A_1 \text{ vs } A_2 \text{ vs } A_3 \text{ with respect to } SC_3$$

$$M8 = A_1 \text{ vs } A_2 \text{ vs } A_3 \text{ with respect to } SC_4$$

$$M9 = A_1 \text{ vs } A_2 \text{ vs } A_3 \text{ with respect to } SC_5$$

$$M10 = A_1 \text{ vs } A_2 \text{ vs } A_3 \text{ with respect to } SC_6$$

This procedure produces the ten comparison matrices listed above, from which the local priorities or weights of criteria, sub criteria and alternatives can be derived and subsequently aggregated into the final ranking.

MATRIX	MATRIX NAME	SIZE
M1	Objective	3X3
M2	Environmental sustainability	6X6
M3	Economic sustainability	6X6
M4	Social sustainability	6X6
M5	UTCI	3X3
M6	UHI	3X3
M7	Change in real estate values	3X3
M8	WTP	3X3
M9	GSA	3X3
M10	GSW	3X3

The pairwise comparisons are carried out using Saaty's Fundamental Scale.

Example:

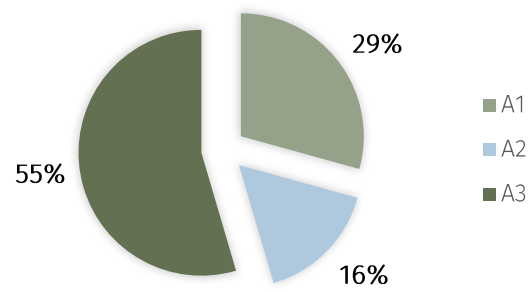
Costrution of green space accessibility

Zones	GSA Index	Rank
A ₁ – Borgo San Paolo	65%	2
A ₂ – Mirafiori Sud (Unione Sovietica – Orbassano)	45%	3
A ₃ – Centro (Po–Vittorio Emanuele)	80%	1

Matrix 9 – Green space accessibility

CR= 0.0001

	A ₁	A ₂	A ₃	Weights	Rank
A ₁	1	2	1/2	0.297	2
A ₂	1/2	1	1/3	0.163	3
A ₃	2	3	1	0.540	1



4.6.2 Software simulation and result interpretation

Once the comparison matrices have been completed, we can move on to using the Super Decisions software. By importing the methodological structure—that is, the network with its hierarchical levels (*clusters*) and all the relevant elements for each level (*nodes*)—we can then enter the *judgments*, filling in the pairwise comparison matrices one by one.¹²²

The software will calculate the *Consistency Index* – *CI* for each matrix, which must not exceed 0.10. More importantly, it will also compute the overall final score for each element in the model.

	Weights			Weights			Weights	
C ₁	x	1	SC ₁	x	3	A ₁	x	2
C ₂	x	3	SC ₂	x	2	A ₂	x	3
C ₃	x	2	SC ₃	x	6	A ₃	x	1
			SC ₄	x	1			
			SC ₅	x	4			
			SC ₆	x	5			

This score represents the element's relative importance—that is, how much it contributes to achieving the overall objective.

These values are obtained by multiplying the eigenvector of each matrix by the weight of the corresponding element at the higher level to which they are being compared. This yields the comprehensive weights of all elements with respect to a given criterion. These values are then summed to obtain the total weight, which takes into account every element from the upper level.

The general formula for the final global weight of a sub-criterion SC_k is:

¹²² Gazzera, “Valutazione della sostenibilità economica dei progetti: un’applicazione congiunta dell’approccio Life Cycle.”

$$W_{SC_k} = \sum_{j=1}^m W_{C_j} \times W_{SC_k|C_j} \quad (45)$$

where:

W_{SC_k} = final global weight of sub-criterion SC_k ;

W_{C_j} = weight of main criterion C_j ;

$W_{SC_k|C_j}$ = local weight of sub-criterion SC_k with respect to criterion C_j ;

m = total number of main criteria.

In our case, with three main criteria:

- $C_1 = \textit{Environmental}$
- $C_2 = \textit{Economic}$
- $C_3 = \textit{Social}$

the formula becomes:

$$W_{SC_k} = (W_{Env} \times W_{SC_k|Env}) + (W_{Eco} \times W_{SC_k|Eco}) + (W_{Soc} \times W_{SC_k|Soc}) \quad (46)$$

For example, the overall weight of the Urban Thermal Climate Index (UTCI) is calculated as:

$$W_{UTCI} = (W_{Env} \times W_{UTCI|Env}) + (W_{Eco} \times W_{UTCI|Eco}) + (W_{Soc} \times W_{UTCI|Soc}) \quad (47)$$

For example, to calculate the overall weight of San Paolo (A1), we need to multiply the partial weights it obtained in each sub-criterion matrix (SC1 through SC6) by the overall weight of each of those sub-criteria, and then sum all the resulting products.¹²³

¹²³ Gazzera, "Valutazione della sostenibilità economica dei progetti: un'applicazione congiunta dell'approccio Life Cycle."

4.7. Methodological limitations and future developments

The methodological framework described in this thesis does not claim to be a finished application. Its purpose is to provide an integrated, modular, transparent and adaptable structure for evaluating real urban contexts - one that, if applied across multiple settings, could contribute meaningfully to the diffusion of NBS in urban ecosystems.

The framework is methodological, not an empirical validation. It is an operational structure with an illustrative application grounded in a real context. It is consistent with the thesis objective of producing a preliminary decision-support framework, and it would be genuinely interesting to see it tested in full in the future - ideally across different urban contexts - to understand how it performs operationally.

That said, the framework does require a reasonable amount of data to function properly, even if less so than some of the other methods reviewed in earlier chapters. And the quality of the output depends directly on the quality and availability of the inputs. Several of the approximations made in the Turin application rely on data that are already four or five years old. Up-to-date and homogeneous GIS layers, sufficiently large and georeferenced property datasets, and regularly updated thematic maps can make a real difference. Given the pace at which urban climates and real estate markets are changing, access to current data would be a significant asset for any future application of this framework.

Some of the limitations are intrinsic to the tools used to measure and quantify the indicators.

ENVImet is a powerful microclimate modelling platform, but it requires time, data, careful calibration, and works on relatively small portions of the city. Hedonic regression produces robust results but needs large datasets - and as the spatial scale decreases, assembling those datasets becomes increasingly

difficult. WTP does not rely on observed behaviour but on stated preferences, which are subject to well-known biases: hypothetical bias, protest zeros, strategic responses.

The most structurally significant limitation, however, is the subjectivity of the weights assigned to criteria. Judgements can be rationalized - and AHP provides a formal structure for doing so - but they remain judgements. Even when the indicators themselves are quantitative, the weights can shift the final result, and they inevitably reflect the perspective of whoever assigns them. A local government might prioritize heat reduction; a real estate investor might weight property value more heavily; residents might care most about green space accessibility and walkability.

A future application could usefully test multiple weighting scenarios to explore the sensitivity of the results to these choices.

One interesting possibility would be to *hybridise the AHP* by replacing the Saaty-scale pairwise comparisons for the alternatives with a direct normalization of the empirical indicator values - treating them as the local priority vector. For instance:

Construction of green space accessibility weights

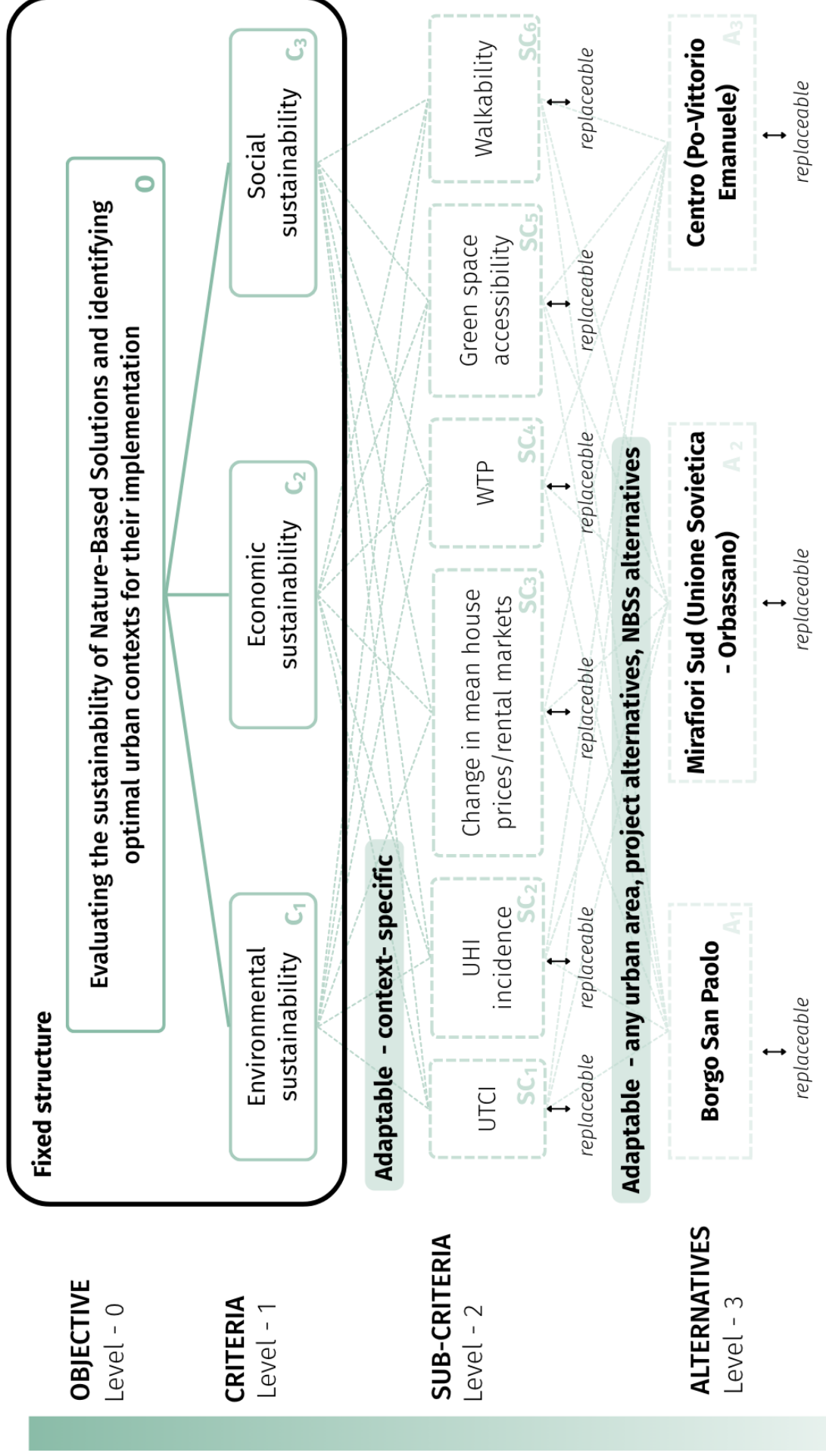
	GSA Index	Calculation	Normalized score	Rank
A ₁ – Borgo San Paolo	65%	65/190	0.342	2
A ₂ – Mirafiori Sud (Unione Sovietica – Orbassano)	45%	45/190	0.237	3
A ₃ – Centro (Po–Vittorio Emanuele)	80%	80/190	0.421	1

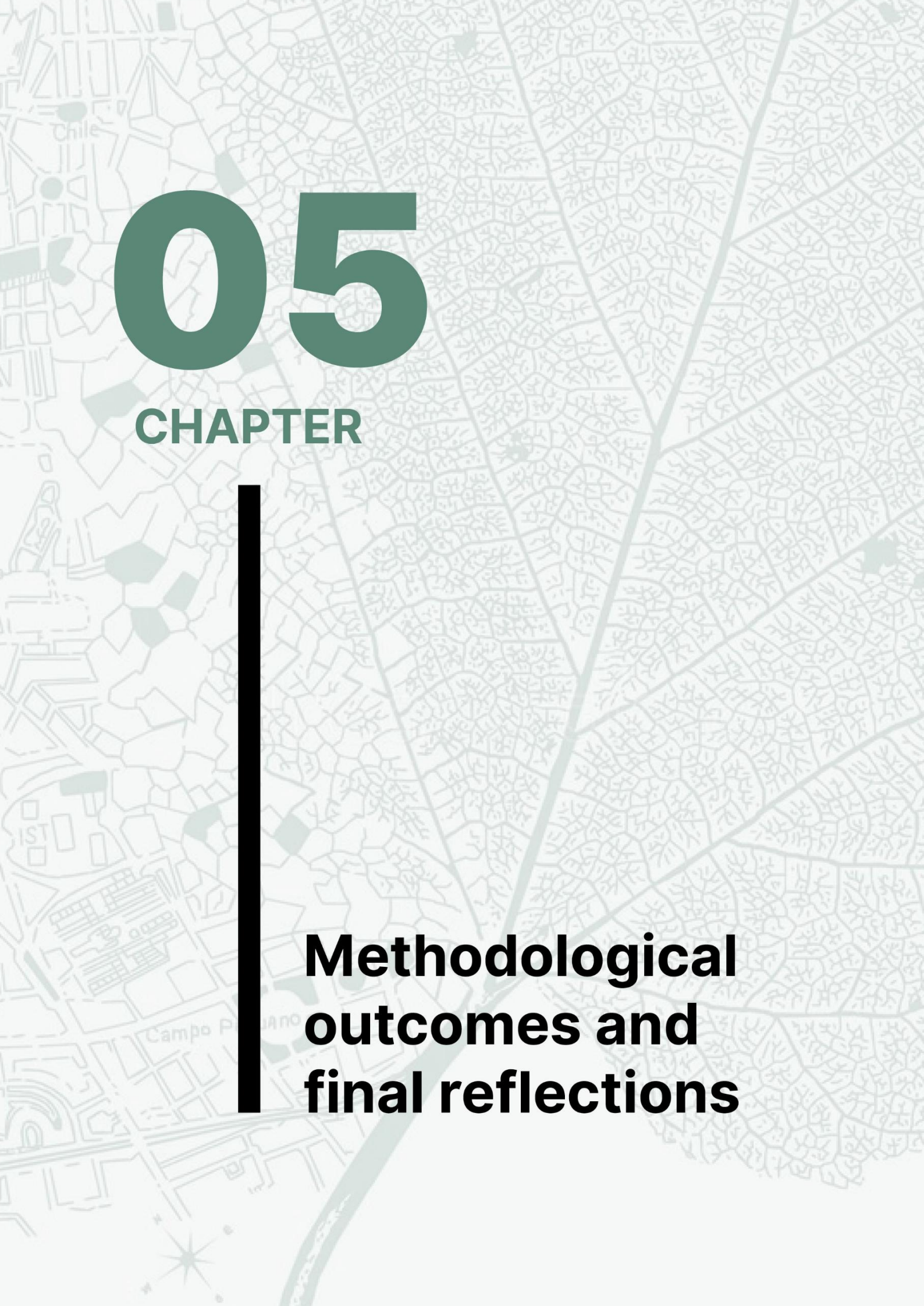
This approach is particularly suitable when alternatives can be measured through objective or GIS-based indicators. It avoids converting quantitative data

into subjective judgements and integrates the indicator directly into the AHP structure. No Consistency Ratio is calculated in this case, since no pairwise comparison matrix is constructed for the alternatives. Rather than a loss, this should be read as a methodological gain: by grounding alternative scores in empirical values rather than subjective pairwise judgements, the approach reduces the aleatory component that is structurally embedded in classical AHP. The framework becomes less dependent on who is applying it and more anchored to what the data actually show.

Finally, the framework has been designed and calibrated for Turin, but it is intended to be transferable. The structure at Level 0 and Level 1 - the overarching objective and the three sustainability criteria - is conceived as fixed. This is not an arbitrary choice: it reflects the theoretical foundations of the framework itself, rooted in the Total Economic Value and the three pillars of sustainability. These levels provide the conceptual backbone that should remain consistent across applications, ensuring comparability and methodological coherence.

What can and should change are the components below. The sub-criteria at Level 2 are context-dependent and replaceable - different urban settings may call for different environmental, economic or social indicators, selected on the basis of data availability, local priorities and the specific characteristics of the territory under analysis. Similarly, the alternatives at Level 3 are not limited to spatial areas: they could represent different NBS typologies or project options competing for implementation in the same context - green roofs versus urban forests versus pocket parks, for instance - making the framework applicable not only to site selection but also to NBS design choices. The underlying logic is replicable; the application is context-dependent.



The background of the page is a light gray map of a city, showing streets and buildings. A large, stylized leaf is overlaid on the map, with its veins running diagonally from the top right towards the bottom left. The leaf is a light green color. The word 'Chile' is visible in the top left corner of the map. The number '05' is prominently displayed in a large, dark green font in the upper left quadrant.

05

CHAPTER

A thick, solid black vertical line is positioned to the left of the chapter title, extending from the level of the word 'CHAPTER' down to the level of the chapter title.

Methodological outcomes and final reflections

5.1. Summary of main findings

This thesis has developed a detailed analysis of the current landscape of NBS evaluation: from their definition and theoretical foundations, to their positioning within European and global frameworks, and to the main methodological debates emerging from the academic literature. More specifically, **the research has led to the development of a preliminary and integrated framework for assessing urban areas according to their suitability for future NBS implementation.**

The value of the proposed framework lies in its attempt to bring together the main dimensions that NBS share with the broader concept of sustainability: environmental, social and economic performance. In doing so, it avoids a reductive evaluation approach based exclusively on monetary valuation or, conversely, on purely environmental assessment. The selection of criteria and sub-criteria is not arbitrary, but draws on existing evaluation frameworks and methodological gaps identified in the literature, with the aim of narrowing the distance between descriptive assessment systems and operational decision-making practice.

At the methodological level, the thesis has aimed to define a structured and weighted model through the integration of tools belonging to different disciplinary traditions, each capable of producing valid and replicable outputs. The combination of analytical and computational tools - GIS, ENVI-met, statistical modelling, contingent valuation and AHP - within a coherent methodological structure results in a framework that is ordered, transparent, operational and potentially transferable.

5.2. Recommendation for future research

As already discussed, the most important recommendation for future research is the operational application of the framework, either through a complete simulation of the Turin case as outlined in this thesis or through its application to a different urban context. This would make it possible to assess the operational feasibility of the method and to verify whether it can function as a valid tool for preliminary urban analysis. It would also clarify whether the data requirements are sustainable in practice, whether the indicators interact coherently at the operational level, and whether the market dynamics hypothesized during the research are supported by empirical evidence.

In the longer term, it would also be relevant to test the same framework not only for comparing spatial alternatives within a city, but also for choosing between different project design options or alternative NBS typologies competing for implementation within the same area.

Finally, as noted in the previous chapter, a promising direction for future methodological development would be to reduce the subjectivity inherent in multicriteria methods by moving towards more data-driven approaches. For instance, normalized empirical indicator values could be used directly as priority scores for the alternatives, rather than being converted into Saaty-scale pairwise judgements. This would allow the framework to preserve the transparency of the AHP structure while strengthening the objectivity of the alternative scoring phase.

5.3. Final reflections on the role of holistic evaluation in sustainable planning

As this study has shown, NBS cannot be adequately evaluated through purely economic or purely environmental lenses. Their assessment is inherently complex, multidimensional and multifactorial, requiring different types of information and value dimensions to be brought into dialogue. Sustainable planning is therefore particularly demanding, as it must account simultaneously for urban climate, economic value, accessibility, spatial justice and human well-being. Choosing with all these variables in mind is not simply a matter of identifying the best alternative; rather, it means making trade-offs, priorities and potential synergies visible.

The framework proposed in this thesis was not conceived to eliminate the complexity that characterizes the multidimensional nature of NBS. That complexity remains, and should remain, as it reflects the real functioning of urban systems. The aim was instead to provide this complexity with a more direct, transparent and integrated evaluation logic: one capable of making the assessment process more understandable, comparable and operationally useful for those involved in planning and decision-making.

Ultimately, the value of holistic evaluation lies in its capacity to transform NBS from isolated environmental interventions into strategic planning tools, capable of supporting climate adaptation, social well-being and long-term urban sustainability.

Glossary

AHP – Analytic Hierarchy Process

A multicriteria decision-making method used to structure complex decision problems into a hierarchy of objective, criteria, sub-criteria and alternatives. It supports the comparison and prioritization of alternatives through pairwise comparison matrices.

AS – Accessibility to Services

A component of the walkability index measuring the accessibility of buildings or residents to basic urban services, such as public transport stops, schools, pharmacies, supermarkets, public facilities and green spaces.

BCR – Benefit-Cost Ratio

An economic indicator used in Cost-Benefit Analysis, calculated as the ratio between total benefits and total costs. A value greater than 1 indicates that benefits exceed costs.

CBA – Cost-Benefit Analysis

An economic evaluation method used to compare the costs and benefits of a project or intervention, usually by translating impacts into monetary terms.

CBR – Cost-Benefit Ratio

An alternative formulation of the benefit-cost relationship used in economic appraisal. It expresses the relationship between project benefits and costs.

CE – Choice Experiment

A stated preference method in which respondents choose between alternative scenarios described by different attributes. It is used to estimate preferences and willingness to pay for specific changes.

CI – Consistency Index

An index used in the AHP to measure the degree of inconsistency in a pairwise

comparison matrix. It is calculated from the maximum eigenvalue of the matrix.

CM – Choice Modelling

A family of stated preference methods used to analyse how individuals make choices among alternatives characterized by different attributes.

CR – Consistency Ratio

An AHP consistency measure obtained by comparing the Consistency Index with the Random Index. It is used to verify whether the judgements expressed in a pairwise comparison matrix are sufficiently consistent.

CV – Contingent Valuation

A stated preference valuation technique based on hypothetical scenarios, used to estimate the economic value that individuals assign to non-market goods or services.

CVM – Contingent Valuation Method

A survey-based stated preference method used to estimate individuals' willingness to pay for environmental improvements, public goods or non-market benefits.

ENVI-met – Environmental Meteorology Model

A three-dimensional microclimatic simulation software used to model interactions between buildings, vegetation, surfaces and the urban atmosphere. In this framework, it is identified as a reference tool for future operational assessment of thermal and microclimatic indicators.

ES – Ecosystem Services

The benefits that ecosystems provide to human well-being, including regulating, cultural, supporting and provisioning services.

ESS – Ecosystem Services

An alternative abbreviation for Ecosystem Services, used to refer to the functions and benefits generated by ecosystems.

GI – Green Infrastructure

A strategically planned network of natural and semi-natural areas designed to provide environmental, social and economic benefits.

GIS – Geographic Information System

A digital system used to collect, manage, analyse and visualize spatial and geographic data. In this thesis, GIS supports territorial diagnosis, spatial overlays and the calculation of accessibility and walkability indicators.

GSA – Green Space Accessibility

An indicator measuring the accessibility of buildings or residents to public green spaces, usually expressed as the percentage of buildings or population located within a defined walking distance from green areas.

HPM – Hedonic Pricing Method

A revealed preference valuation method used to estimate the value of environmental or urban characteristics by observing their influence on market prices, especially property values.

ID – Intersection Density

A component of the walkability index measuring the number of street or pedestrian network intersections per unit of area. It is used as a proxy for urban permeability and network connectivity.

IRR – Internal Rate of Return

An investment appraisal indicator representing the discount rate at which the Net Present Value of a project becomes zero.

LCA – Life Cycle Assessment

A method used to assess the environmental impacts associated with the different stages of a product, project or intervention throughout its life cycle.

LCC – Life Cycle Costing

An economic assessment method that considers costs over the entire life cycle

of a project, including implementation, operation, maintenance and end-of-life phases.

LST – Land Surface Temperature

The temperature of the Earth's surface measured through remote sensing data. In urban studies, it is commonly used to analyse heat patterns and identify areas affected by surface overheating.

MCA – Multi-Criteria Analysis

A decision-support approach used to evaluate alternatives according to multiple criteria, especially when both quantitative and qualitative dimensions are involved.

MCDA – Multi-Criteria Decision Analysis

A family of methods supporting decision-making processes involving multiple, often conflicting, criteria. It allows heterogeneous environmental, economic and social dimensions to be considered within a common evaluation structure.

MCDM – Multi-Criteria Decision-Making

A general term referring to decision-making approaches that compare alternatives according to multiple criteria. AHP is one of the most widely used MCDM methods.

MRA – Multiple Regression Analysis

A statistical method used to examine the relationship between one dependent variable and several independent variables. In this thesis, it is connected to the estimation of real estate value variation.

ND – Pedestrian Network Density

A component of the walkability index measuring the total length of the pedestrian or walkable network per unit of area.

NBS / NbS – Nature-Based Solutions

Solutions inspired and supported by nature, designed to address

environmental, social and economic challenges while providing multiple benefits for human well-being and biodiversity.

NDVI – Normalized Difference Vegetation Index

A remote sensing index used to measure the presence, density and condition of vegetation. Higher values generally indicate greater vegetation cover or healthier vegetation.

NPV – Net Present Value

An economic indicator calculated as the difference between the present value of benefits and the present value of costs over time. A positive NPV indicates that a project generates net economic benefits.

OLS – Ordinary Least Squares

A regression estimation method that identifies the line or hyperplane of best fit by minimizing the sum of squared residuals between observed and predicted values.

OMI – Osservatorio del Mercato Immobiliare

The Italian real estate market observatory managed by the Agenzia delle Entrate. It provides property market data and territorial real estate zones.

PB / PBP – Payback Period

An investment appraisal indicator expressing the time required for an investment to recover its initial cost through the benefits or cash flows it generates.

PF / PFM – Production Function Method

An economic valuation method that estimates the value of ecosystem services by analysing their contribution to the production of market goods or services.

PTS – Porzioni Territoriali Storiche

Historical territorial portions used as a finer real estate and urban sub-segmentation of Turin's cadastral microzones.

QGIS – Quantum Geographic Information System

An open-source GIS software used to manage, analyse and visualize spatial data. In this thesis, QGIS is used for the preliminary territorial diagnosis and cartographic elaborations.

RI – Random Index

A reference value used in the AHP to calculate the Consistency Ratio. It depends on the order of the pairwise comparison matrix.

RP – Revealed Preference Methods

Economic valuation methods based on observed behaviours in real or related markets, such as property purchases or travel choices.

SE – Standard Error

A statistical measure indicating the typical deviation between observed values and model predictions, or the uncertainty associated with an estimated parameter.

S-LCA – Social Life Cycle Assessment

A method used to assess the social impacts associated with the life cycle of a product, project or intervention.

SP – Stated Preference Methods

Economic valuation methods based on hypothetical scenarios and respondents' declared preferences. Contingent Valuation and Choice Experiments belong to this category.

SuDS – Sustainable Urban Drainage Systems

Drainage systems designed to manage stormwater in a sustainable way, often using natural or semi-natural processes.

TEV – Total Economic Value

A valuation framework used to classify the total value of an environmental good or ecosystem service, including both use and non-use values.

TSS – Total Sum of Squares

A statistical measure representing the total variability of the dependent variable around its mean in a regression model.

UHI – Urban Heat Island

The phenomenon whereby urban areas experience higher temperatures than surrounding rural or less built-up areas, mainly due to impervious surfaces, dense urban fabric, reduced vegetation and anthropogenic heat.

UTCI – Universal Thermal Climate Index

A biometeorological index used to assess outdoor thermal comfort and heat or cold stress as perceived by the human body.

VIF – Variance Inflation Factor

A diagnostic statistic used in regression analysis to detect multicollinearity among independent variables.

WTA – Willingness to Accept

The minimum amount of compensation an individual is willing to accept for the loss or deterioration of a good or service.

WTC – Willingness to Contribute

The willingness of individuals or communities to contribute, financially or otherwise, to the implementation, management or maintenance of an intervention.

WTP – Willingness to Pay

The maximum amount an individual is willing to pay to obtain, preserve or improve a good or service. In this thesis, WTP is used as an economic sub-criterion to capture the perceived value of NBS benefits.

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Appendix - A

Microzone OICT Torino – porzioni territoriali storiche			
N°	Microzona	Codice porzione	Porzione territoriale storica
01	Roma	-	
02	Carlo Emanuele II	2.1	Po - Carlo Emanuele II
		2.2	Bodoni
		2.3	Carlo Felice
		2.4	Arsenale
03	Solferino	3.1	Solferino - Re Umberto
		3.2	Pietro Micca
04	Vinzaglio	-	
05	Garibaldi	5.1	Garibaldi - Savoia - Palestro
		5.2	Statuto
		5.3	Orfane - XX Settembre
06	Castello	-	
07	Vanchiglia	7.1	Po - San Maurizio
		7.2	Borgo Vanchiglia
		7.3	Vanchiglietta
		7.4	Regio Parco
		7.5	Borgata Rosa - Parco del Meisino
08	Rocca	-	
09	Valentino	9.1	Vittorio Emanuele II - Valperga Caluso
		9.2	Valperga Caluso - Bramante
10	San Salvario	-	
11	Dante	11.1	Marconi - Dante
		11.2	Arquata
		11.3	Dante - Bramante
12	San Secondo	12.1	Vittorio Emanuele - Stati Uniti
		12.2	Stati Uniti - Sommelier
13	Stati Uniti	-	
14	Galileo Ferraris	-	
15	De Gasperi	15.1	Cassini - Spina Centrale
		15.2	Turati - Re Umberto
		15.3	Chisone
16	Duca d'Aosta	-	

17	Spina 2	-
18	Duchessa Jolanda	18.1 Cit Turin
		18.2 Cibrario - Piffetti
19	San Donato	19.1 Regina Margherita - Umbria
		19.2 Cibrario - Regina Margherita
		19.3 Borgata Campidoglio
20	Porta Palazzo	20.1 Repubblica
		20.2 Borgo Dora
21	Palermo	21.1 Cigna
		21.2 Aurora
		21.3 Borgata Monterosa
		21.4 Borgata Regio Parco - Sofia
22	Michelotti	22.1 Barriera di Casale
		22.2 Madonna del Pilone
23	Crimea	23.1 Borgo Po
		23.2 Fiume
24	Collina	24.1 Val Salice - Val San Martino - Reagle
		24.2 Mongreno - Superga
		24.3 Cavoletto - Fioccardo
		24.4 San Vito
25	Zara	-
26	Carducci	26.1 Carducci - Giacomini
		26.2 Bengasi - Passo Buole
27	Unità d'Italia	-
28	Lingotto	28.1 Lingotto Fiere - Fiat Avio
		28.2 Sebastopoli - Galimberti
		28.3 Traiano - Onorato Vigliani
29	Santa Rita-Mirafiori	29.1 Traiano
		29.2 Orbassano - Santa Rita
		29.3 Zona olimpica
		29.4 Guido Reni
30	Mirafiori Sud	30.1 Unione Sovietica - Orbassano
		30.2 Città Giardino
		30.3 Drosso - Parco Colonnetti
		30.4 Borgata Mirafiori
31	San Paolo	31.1 Borgo San Paolo
		31.2 Cenisia
32	Pozzo Strada	32.1 Rivoli

		32.2	Monte Cucco - Bardonecchia
		32.3	Ruffini
33	Aeronautica/Parella	33.1	Borgata Parella
		33.2	Marche
		33.3	Risorgimento
		33.4	Chiorni
		33.5	Campanella
34	Spina 3	-	
35	Madonna di Campagna	35.1	Lucento
		35.2	Stampalia
		35.3	Borgata Madonna di Campagna
		35.4	Borgata Vittoria
36	Spina 4	-	
37	Rebaudengo	37.1	Respighi
		37.2	Derna - Rebaudengo
38	Corona Nord Ovest	38.1	Vallette
		38.2	Falchera
		38.3	Lanzo
		38.4	Taranto
		38.5	Stura
39	Spina 1	-	
40	Barca Bertolla	40.1	Barca
		40.2	Bertolla

Appendix - B

Questionnaire for Estimating Willingness to Pay (WTP)

Nature-Based Solutions for Addressing Urban Heat Islands in Turin

Purpose of the survey

This questionnaire has been designed to estimate residents' stated Willingness to Pay (WTP) for the implementation and maintenance of Nature-Based Solutions (NBS) within their neighbourhoods. The survey aims to investigate how citizens perceive the benefits associated with urban greening interventions, particularly in relation to the mitigation of Urban Heat Island (UHI) effects, the improvement of environmental quality, and the enhancement of urban liveability. All responses are anonymous and will be used exclusively for research purposes.

Section 1 - Residential and socio-demographic information

1. Which area do you live in or spend most of your time in?

- San Paolo (Borgo San Paolo)
- Centro (Via Po – Via Vittorio Emanuele II)
- Mirafiori Sud (Corso Unione Sovietica – Corso Orbassano)
- Other (specify): _____

2. Age group:

- Under 25
- 25–40
- 41–60
- Over 60

3. How would you describe your relationship with this urban area?

- Resident
- Student or worker in the area
- Frequent visitor (at least once a week)

4. How often do you use urban green spaces, such as parks, gardens, or tree-lined streets?

- Never

- Rarely (less than once a month)
- Once or twice a week
- Several times a week
- Every day

Section 2 – Perceptions of urban heat and NBS benefits

5. During the summer, to what extent do you perceive urban heat as a problem in your area?

- Not at all
- Slightly
- Moderately
- Very much
- Extremely

6. Do you think there is a lack of green spaces and trees in your area?

- Not at all
- Slightly
- Moderately
- Very much
- Extremely

7. Have you ever heard of NBS , namely urban solutions based on natural processes, such as green roofs, pocket parks, depaving, or rain gardens?

- Yes, I am familiar with them and understand how they work
- I have heard of them, but I do not know the details
- No, I had never heard of them

8. To what extent do you think that interventions such as street trees, pocket parks, depaving, or green roofs could improve the urban quality of your neighborhood?

- Not at all
- Slightly
- Moderately
- Very much
- Extremely

Section 3 – NBS scenario description

The City of Turin is considering the implementation of Nature-Based Solutions in your neighbourhood. The proposed interventions include street trees, pocket parks, the depaving of impermeable surfaces, rain gardens, and green roofs on public buildings.

These interventions would aim to reduce the urban heat island effect, improve pedestrian access to green spaces, and enhance the environmental quality of public spaces. Their implementation would require an annual contribution from residents, allocated exclusively to the construction and maintenance of the interventions within the neighbourhood.

Section 4 – Willingness to pay assessment

9. Would you be willing to pay an annual contribution allocated exclusively to the implementation and maintenance of these interventions in your neighbourhood?
 - Yes
 - No
 - I am not sure / I would need more information
10. [If you answered “Yes” to Question 9] What is the maximum annual contribution you would be willing to pay?
 - €0 (I would not pay anything, but I selected “Yes” for another reason)
 - €5 per year
 - €10 per year
 - €20 per year
 - €50 per year
 - More than €50 per year - please specify: €_____
11. What is the main reason for your answer?
 - I consider it important to reduce urban heat in my neighborhood
 - I would like to have more accessible green spaces near my home or workplace
 - The interventions would improve the overall quality of public space
 - I cannot afford an additional contribution due to budget constraints
 - I believe that these interventions should be funded by the City of Turin

- I do not trust that the funds would be properly managed and used for their stated purpose
- I do not perceive any direct benefits from the proposed interventions

Section 5 – Preferences for NBS Interventions

12. Which Nature-Based Solution would be most beneficial for your neighbourhood? (Select up to two options)

- Street trees and urban tree planting
- Pocket parks and small neighbourhood green spaces
- Green roofs on public buildings
- Depaving of impervious surfaces
- Rain gardens and sustainable drainage systems
- Green corridors and tree-lined pedestrian connections

13. Which benefit provided by NBS do you consider most important?

- Urban heat mitigation and thermal comfort
- Improved access to green spaces
- Enhancement of public space aesthetics
- Increased urban biodiversity
- Improved air quality
- Psychological well-being and urban liveability