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Bridging the Theory–Practice Gap: A Design Methodology for Green Infrastructure Implementation in Mid-Adriatic Coastal Cities

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Abstract

Green Infrastructure (GI) is crucial for urban climate adaptation, providing ecosystem services like mitigating the urban heat island effect and enhancing stormwater management, alongside benefits for public health and biodiversity. Effective GI implementation remains challenging, particularly in dense, rapidly urbanized mid-Adriatic coastal cities, classified as climate hotspots like other Mediterranean contexts. This paper presents a replicable applied trans-scalar methodology for detailed GI design scenarios, developed through the EU-funded LIFE+ A_GreeNet project to bridge the theory–practice gap and enable pilot implementations in multiple Italian mid-Adriatic coastal municipalities. The research details a comprehensive, multi-disciplinary, five-phase process applied to the Sant’Antonio district of San Benedetto del Tronto—a dense, trafficked urban area projected to face “extremely strong heat stress” by 2050. Design interventions included spatial optimization, strategic species replacement, the creation of vegetated bioretention basins, and systematic pavement de-sealing. The application of the model demonstrated significant improvements: a substantial increase in permeable surface area (+194%), a measurable reduction in the UTCI index (average ENVI-MET simulated reduction of 1.17 °C by 2030), and a series of benefits resulting from increased green space and enhanced meteorological water management. This research offers local authorities a tangible model to accelerate climate-adaptive solutions, showing how precise GI design creates resilient, comfortable, and human-centered urban spaces.

Keywords: green infrastructure; climate adaptation; urban micro-regeneration; mid-Adriatic coast

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1. Introduction

A substantial corpus of scientific research unequivocally highlights the efficacy of Green Infrastructure (GI) implementation as an instrument that can effectively regenerate outdoor urban spaces, recognizing their capacity to deliver a wide array of ecosystem services [1,2]. According to the European Union’s definition, Green Infrastructure constitutes “a strategically planned network of natural and semi-natural areas with other environmental features, designed and managed to deliver a wide range of ecosystem services, while also enhancing biodiversity” [3]. The potential implementation of GI offers an effective approach for addressing a complex set of contemporary challenges, particularly

those related to the effects of climate change on outdoor urban space [4]. Interventions based on GI not only enhance environmental quality by improving water and air purity [5,6] but also serve as a proven strategy for effective stormwater management [7] and mitigation of risks associated with rising urban temperatures, which are particularly exacerbated in urban contexts due to the urban heat island effect [8]. Ultimately, these benefits directly translate into a tangible improvement in the health and quality of life for urban inhabitants, both through the creation of climate-proof and more comfortable environments and indirectly by fostering mental and physical well-being [9], strengthening community bonds [10], and encouraging less sedentary lifestyles and greater utilization of urban spaces [11–13]. This research posits that outdoor urban spaces are primary elements for understanding and addressing the localized impacts of climate change. The scientific literature underscores that the risks associated with climate change are particularly pronounced in outdoor urban environments [14,15]. Their configuration—including the presence or absence of vegetation, the type of materials used, their relationship to surrounding built structures, the density of the built-up environment, and proximity to waterways—significantly influences how climate events manifest. Outdoor spaces can either amplify adverse climate effects, such as rising temperatures, or even sustain damage that impedes their functionality or safety [16]. The issue of limited space availability in urban environments calls for urgent reflection aimed at rethinking these outdoor areas to enhance cities' climate adaptiveness [17,18]. While the benefits of GI and the pressing need to rethink outdoor space are widely discussed, advocating for a rebalancing in favor of citizens (and thus for green areas), there remains an evident difficulty in identifying suitable spaces for intervention, especially in densely built or historically protected urban areas [2,19–21], and also due to the fact that green solutions often require more space than traditional “gray” systems [17].

Despite the widely acknowledged theoretical benefits and the urgent need for climate adaptation, the actual implementation of GI, particularly those involving Nature-Based Solutions (NBSs)—actions inspired and supported by nature that build resilience alongside other benefits—on urban outdoor surfaces, remains a limited practice in the Mediterranean context, with few implemented examples [22,23]. This represents a significant gap between theoretical understanding and practical application, which is particularly striking given the strong traditional connection between cities in this region and urban green spaces, which historically play a decisive social role and form part of a distinct cultural identity [24]. While the theoretical benefits of NBS are well-established, practical and effective implementation in Mediterranean urban settings faces significant limitations. It has been observed that the dissemination of certain solutions is more evident in Northern European climates, whereas the southern part of the continent is characterized by pronounced climatic variability [23]. This variability presents substantial challenges for the selection of suitable plant species capable of thriving in a potentially “tropicalized” future climate, further complicating design choices [25]. Indeed, a considerable proportion of the NBSs exemplified in realized projects, manuals, and dedicated abacuses are designed for climatic zones other than the Mediterranean urban settings, which experience a unique variability of hydrological and thermal regimes.

Beyond spatial limitations, particularly in dense urban areas, the effective implementation of GI faces various other challenges that frequently influence all design aspects across different project scales. Pervasive barriers include limited financial resources, institutional constraints, insufficient awareness among local administrators, varying public perception and citizen awareness, and the absence of robust economic evaluation frameworks for informed decision making [26–29]. Moreover, acquiring very specific site-based knowledge [30] and fostering the necessary interdisciplinary and transdisciplinary collaborations across ecology, urban design, architecture, urban policy, environmental

engineering, and multi-scalar governance are frequently cited difficulties [31]. Concerns regarding the long-term operation and maintenance phases also frequently arise, potentially affecting social acceptance [32]. Although some authors highlight that the implementation of GI is cost-effective [33], others highlight that the difficulty in verifying the true cost-benefits of its applications in urban contexts persists [34], in particular, by suggesting the need for comprehensive life-cycle assessments to ensure sustainable implementation and management [35].

The Adriatic geographical area, including its bordering Mediterranean regions, has recently been characterized as a high-temperature hotspot facing exacerbated climate change impacts, exhibiting a high degree of vulnerability to global warming [36–38], with observed trends including shifting precipitation patterns and coastal areas becoming drier, especially in summer [39]. The Intergovernmental Panel on Climate Change (IPCC) consistently classifies the Mediterranean region among the most vulnerable territories globally, underscoring its heightened susceptibility to climate-related events [40]. The region currently faces an average surface temperature 1.5 °C higher than pre-industrial levels, leading to increased recurring climate events, particularly temperature-related ones, with more prevalent droughts and sea surface temperatures rising by 0.29 °C to 0.44 °C per decade since 1980. Projections estimate a sea level rise of 0.15 to 0.33 m by 2050 [39]. These trends indicate widening climate-related disparities in Europe, with the South experiencing concentrated adverse events, including increased risks to human mortality, ecosystem changes, water scarcity, and flood impacts [41]. Furthermore, the combination of climate change and pollution exacerbates human health risks, leading to more intense heatwaves, respiratory/cardiovascular issues, food shortages, disease transmission [42], and various high-temperature-related complications, evidenced by an association between heat waves and increased hospital admissions in the region [43]. Urban areas in the Adriatic coastal regions have witnessed rapid, often unplanned, growth of dense built-up areas with limited green space. The presence of impermeable soil in urban areas, in conjunction with other factors characteristic of urban environments such as traffic, air conditioning, and air pollutants, further exacerbates the risks associated with climate change, raising local temperatures and creating discomfort for residents [44]. Furthermore, there has been an increase in the number and intensity of extreme hydro-meteorological events that affect urban areas, producing greater flow rates and runoff volumes in critical urban areas [45]. Consequently, there is a compelling need to initiate specific research, encompassing both theoretical and applied aspects, to address this regional specificity and develop novel, customized solutions tailored to Mediterranean cities. It is crucial to emphasize that research endeavors should be meticulously designed to identify solutions for urban outdoor spaces, which have historically been extensively utilized in Mediterranean regions and are currently facing significant challenges due to climate change [46]. Numerous existing proposals detailing various catalogs of NBSs for urban spaces [47,48] are, by necessity, highly generalized and often struggle to address the specific executive and site-specific issues pertinent to particular urban contexts. This results in a clear lack of detailed experimental approaches concerning GI implementation, especially within the unique context of Mediterranean coastal cities. There is, therefore, an urgent need to consistently structure a shared background based on knowledge from real case studies and technological design guidelines capable of bridging this existing gap between theory and practice [7].

The objective of this research is to identify and present a replicable applied methodology for determining detailed design scenarios based on the implementation of GI within specific urban areas, with a focus on selected coastal cities of the Middle Adriatic. Specifically, this research details a pathway implemented across several cities within the mid-Adriatic region, all part of a collaborative network within the ongoing LIFE+ A_GreeNet

Project [49]. Co-funded by the European Union through the LIFE+ program, the project aims to enhance the climate resilience of cities along the Italian Middle Adriatic coast through diverse green interventions, including soil restoration, forest and green area planting, and flexible green solutions. The partner municipalities, ranging from smaller towns with limited resources to larger urban centers like Ancona and Pescara (each with over 100,000 inhabitants), include Ancona, San Benedetto del Tronto, and all coastal municipalities in the province of Teramo. This collaborative pathway involves establishing shared objectives for climate adaptation and improving local population quality of life and health, thereby identifying primary activities and interventions for each designated system and area. To facilitate knowledge exchange and foster adaptive climate change measures, the LIFE+ A_GreeNet project strategically implemented participatory processes—including workshops, focus groups, and the establishment of an innovative “Urban Forestation Contract”—aimed at engaging technical offices, associations, and diverse stakeholders, thereby ensuring comprehensive information dissemination, capacity building, and collaborative planning integration into local urban regulations. The article analyzes a critical component of the LIFE methodology: the determination of detailed projects, exemplified by a specific study area in the city of San Benedetto del Tronto, one of the sequential phases of the overall methodological framework of the LIFE+ A_GreeNet project. This phase builds upon earlier stages of the project, particularly those focused on constructing climate-adaptive design scenarios at a broader scale for 2030 and 2050 through the development of comprehensive GI systems, and based on participation and capacity building phases involving administrations, associations, and stakeholders.

2. Materials and Methods

2.1. Existing Literature Review

The existing literature identifies various barriers to Green Infrastructure (GI) implementation, ranging from limited resources and a lack of political and administrative leadership [50,51] to practical challenges in managing on-the-ground details. Numerous studies offer general guidelines [47,52,53], categorize solutions based on urban characteristics [54], or focus on specific technical aspects [55]. Some research proposes NBS categories characterized by their capacity to address particular climatic risks [56], while others prioritize categorizations based on ecosystem service provision [57]. Furthermore, numerous design manuals are tailored for climatic or urban contexts different from the Mediterranean [58], or predominantly focus on specific NBSs [59]. While valid, these approaches often address the problem from highly defined and compartmentalized perspectives. Significant examples, such as the historic city center market in Rimini and the Darsena in Ferrara (developed within the REBUS project [60]), or the Carrer del Consell de Cent of Barcelona’s Superilles [61,62], demonstrate the successful translation of general principles into high-quality design outcomes. However, a key limitation in these otherwise successful applications lies in the ad hoc nature of their context selection and the implicit, rather than explicit, transferability of their design process. This often hinders wider replication without significant reliance on individual expertise. It is noteworthy that the urban contexts for REBUS application were selected through collaboration with local administrations, rather than through a dedicated spatial analysis methodology focused on in-depth urban fabric understanding or identification of climatic and social vulnerability. These interventions are notably strong as applications of guiding principles, in environmental control and meticulous tree species selection, leading to remarkable urban regeneration and comfort improvement. In these cases, the results obtained are largely attributable to the careful interpretation and application of core principles by the actors involved in the design process, such as public space proximity, GI as a distributed infrastructure, access to services, and comfort optimization through the judicious use of vegetation and

materials. Similarly, other projects, like the Parco del Mare in Rimini, despite being structured on a comprehensive planning vision, are translated into detailed designs following a set of specific guidelines [63]. Despite a robust strategic vision aligned with overarching objectives and financial frameworks, projects like Parco del Mare often utilize sophisticated tools for technical analysis and microclimatic performance validation in a parallel, disconnected manner. This makes the workflow difficult to access for replication, thus creating a methodological gap in translating the strategic vision into specific design solutions. Additionally, some efforts attempt to identify holistic approaches capable of scientifically addressing the diverse variables affecting a project, yet they often maintain a strong detail-oriented focus, lacking a comprehensive vision of risks and vulnerabilities at the territorial scale [59].

Therefore, a critical analysis reveals a critical trans-scalar methodological deficit in these otherwise virtuous practices. Despite relying on sound principles and insightful design intuitions, they lack an explicit, replicable methodological process that coherently structures all phases, from territorial analysis to detailed design. This persistent methodological gap—defined as the absence of a comprehensive, codified framework that integrates crucial information on climatic risks, urban vulnerabilities, spatial-functional aspects, botanical-vegetational issues, and design guidelines up to simulation phases—compromises the transferability and standardization of such excellence. It effectively limits the replicability of projects without depending solely on individual designers' sensibilities, hindering a comprehensive design approach essential for complex urban outdoor spaces requiring integrated professional competencies [64] and site-specific knowledge.

2.2. Methodology

The article fits into this context, aiming to fill this specific methodological gap. It presents and details a key component of the overall framework developed within the European project LIFE+ A_GreeNet, which aims to illustrate how a structured and multi-disciplinary process can guide the generation of preliminary, detailed, and site-specific design proposals for GI. The contribution directly addresses the complexity of detailed design, aiming for an urgent transition towards the implementation of real pilot projects, and also by adopting modular and flexible approaches [65]. The main objective was to create a tangible methodological example directly applicable to specific urban areas. The different reference areas in the LIFE+ A_GreeNet project, while varying in physical characteristics, density, amount of greenery, and soil types, have been subject to a process developed in close collaboration with local municipalities, culminating in the creation of preliminary design proposals with economic estimates, serving as a replicable model for future GI initiatives.

The overall methodological approach is structured into five main phases (Figure 1):

1. Identification of Detailed Design Areas.

The identification of detailed design areas is the initial phase of the process, aimed at selecting representative sites for the application of the methodology, while simultaneously maintaining an overview of territorial network development by interpreting the individual contributions that each area provides. This selection occurs through an iterative and multi-criteria process, integrating the following:

- Pre-existing Data: Socio-demographic and morpho-climatic analyses derived from previous preparatory phases of the LIFE+ A_GreeNet project.

The synthesis of critical issues emerging from the cognitive framework is translated into the "Risk Map" (Carta del Rischio), a spatial correlation that elaborates and highlights areas subject to multiple vulnerability conditions, framing urban contexts and systems at risk on which to focus design attention.

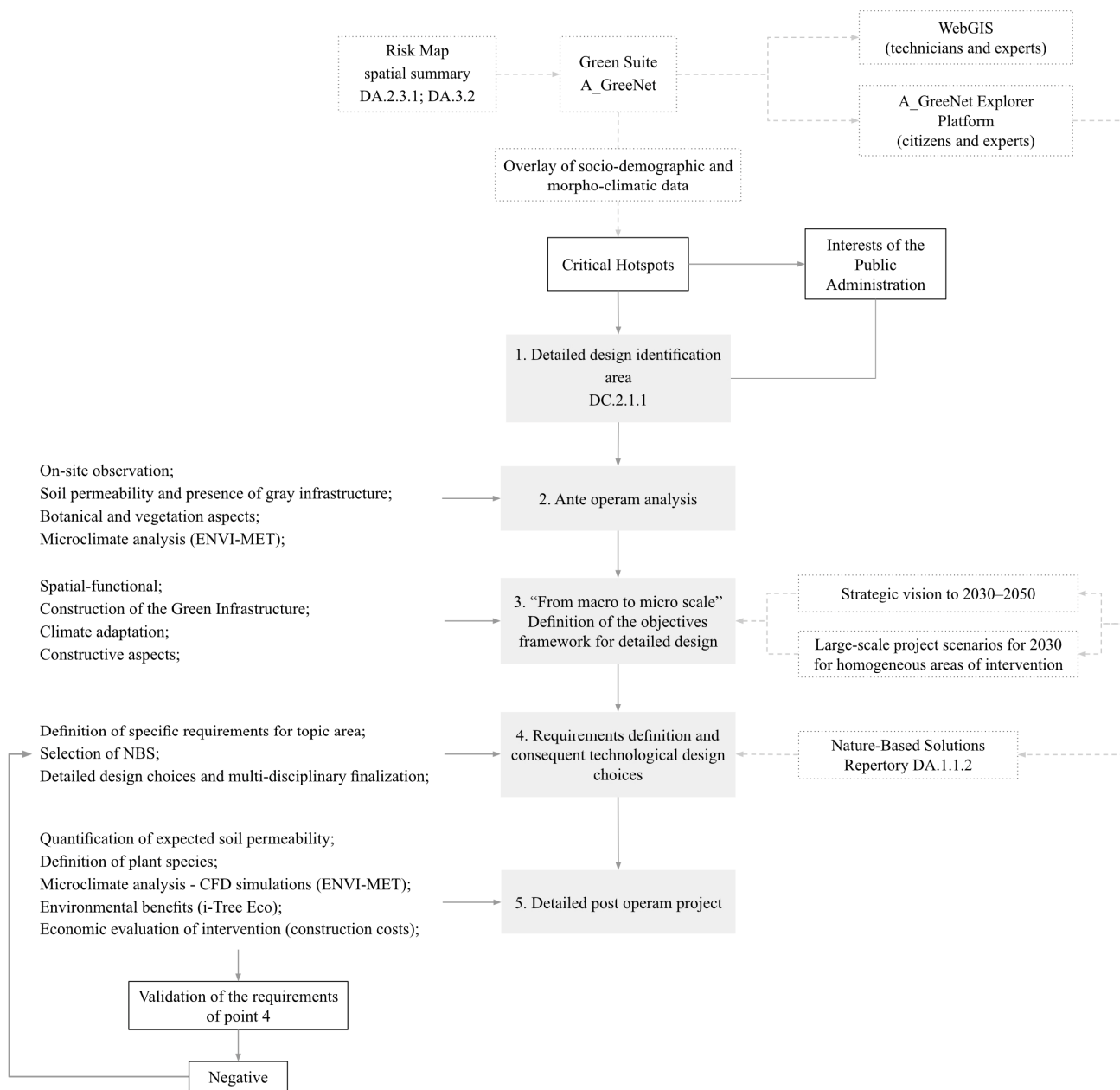


Figure 1. Methodological workflow for this stage of the project (antecedent and preparatory project phases indicated by dashed lines).

Specifically, the intersection between morphological and climatic analysis led to the identification and classification of 9 “Homogeneous Systems and Areas” (Sistemi e Ambiti Omogenei) recurrent in the context of the mid-Adriatic linear city, which serve as a matrix for intervention strategies, each associated with specific “type” of design solutions.

Starting from the available outdoor urban spaces within the urban fabric, the reading and evaluation of urban systems involved various settlement systems with reference to demographic and social fragilities, urban planning forecasts, and public works programming, as well as the recognition of recurrent typological settlement morphologies to understand their contribution to the creation of urban and territorial Green Infrastructure.

- **Local Consultation:** Active involvement of the project’s partner municipal administrations and stakeholders.

The primary objective of this phase is threefold:

- Identify areas with high climate vulnerabilities: Focusing on those projected to face the greatest climate risks in the 2030 and 2050 scenarios.
- Select exemplary and replicable sites: Prioritizing areas that represent the most common and recurrent criticalities in the coastal urban fabric, in order to maximize the transferability potential of the methodology to other similar contexts, by identifying specific strategies related to their belonging to a homogeneous area.
- Test the methodological approach: Provide real-world contexts for the validation of the proposed design methodology.

In collaboration with local administrations, two intervention areas were selected for the cities of Ancona, San Benedetto del Tronto, and Pescara, and one for each of the other coastal municipalities. Once these areas were identified, the subsequent phase focused on an in-depth understanding of their pre-existing conditions through the ante operam analysis.

2. Ante Operam Analysis.

For each selected area, a detailed analysis was conducted to understand the pre-existing conditions and associated criticalities. The analyzed parameters include the following:

- Use and distribution of space: The qualitative analysis of space use and distribution is conducted to identify urban outdoor spaces (both available and currently utilized) and their modes of use. This involves the following:
 - a. On-site Observations: Direct surveys to assess the actual use of spaces by different users and the presence/continuity of pedestrian and cycle paths.
 - b. Cartographic and Documental Analysis: Study of existing urban plans and consultation of current urban planning instruments, such as Sustainable Urban Mobility Plans (PUMSs), Bicycle Plan (Biciplan), and General Master Plans (Piano Regolatore Generale), to understand land use designations and mobility guidelines.
 - c. Dimensional Verification: Evaluation of the dimensions and continuity of areas designated for vegetation and vehicular infrastructure (e.g., roadways, parking areas) concerning their road category and supra-local regulations (e.g., Road Code).

This phase allows for the mapping the “empty spaces” between buildings, determining their predominant current function (vehicular traffic, parking, green areas), and detecting any oversized elements or conflicts of use that may indicate opportunities for GI implementation.

- Soil permeability and presence of gray infrastructure: The quantification of permeable surface area is performed to calculate the percentage of permeability relative to the total area, a key indicator for stormwater management (storage capacity and run-off reduction) and for mitigating temperature peaks. This is achieved through GIS analysis utilizing land cover maps, also leveraging remote sensing vegetation indices (i.e., SAVI), and on-site surveys of existing surface materials to refine the accuracy of permeability mapping. Concurrently, the existing gray infrastructure (e.g., conventional sewage networks) is mapped to identify current discharge points and potential future integration or upgrade points [66].
- Botanical and vegetation aspects: This phase involves a comprehensive census and characterization of existing tree species and vegetation, with the aim of identifying the green heritage and evaluating its suitability and coherence with the urban

context. The analysis, qualitative and quantitative in nature, is developed through the following:

- a. Field Surveys: Direct observation, cataloging of species and dimensional parameters, and assessment of the health status of existing plants (visual and, when available, using specific reports based on ultrasonic acoustic tomography).
- b. Aerial Image Analysis: Utilization of geographical data to support vegetation mapping.

In this phase, the resilience of species in relation to current and future climate scenarios is evaluated, and potential criticalities related to the position of the plants are identified, such as interferences with vehicular traffic or insufficient dimensions of tree pits. To quantitatively assess the ecosystem benefits of existing green spaces (e.g., pollutant removal, carbon storage, oxygen production), simulations are performed using i-Tree software (version 6), a tool that integrates vegetation data with local information on air pollution and meteorological data [67].

- Microclimate analysis: Simulations using ENVI-MET software (version 5.6) to understand and model current (2019) and projected microclimate conditions according to future climate scenarios (2030). This is a thermo-fluid dynamic tool that uses input data on the terrain, vegetation, urban topography, building structure, and meteorological conditions to simulate local microclimates.
3. “From Macro to Micro”: Objectives Framework Definition.

This phase defines a framework of specific and actionable objectives for each intervention site, translating the long-term strategic macro-objectives established by the LIFE+ A_GreeNet project. The process of translation from the macro to the micro scale occurs through the following steps.

- Macro-scale Context: In previous phases, the project conducted a comprehensive territorial analysis of the mid-Adriatic coastal cities. This allowed for their classification into homogeneous areas based on criteria such as the quantity of existing green areas, land use, building density (average building height), urban planning designations of the General Master Plans (PRG), main design proposals, and climate scenarios projected for 2030 and 2050, with reference to the UTCI index for identifying “Stress Categories” related to comfort conditions [49]. From this analysis, macro-scale guideline scenarios for the development of a robust Green Infrastructure network emerged.
- Disaggregation and Alignment: The central objective of this phase is to disaggregate these macro-objectives. This is achieved by aligning them with the specific peculiarities and local criticalities identified through the ante operam analysis (Phase 2) of each study area.
- Thematic Structuring: The translation of objectives from the macro to the micro scale is structured around four detailed design thematic areas:
 - a. Spatial-functional: Objectives related to space use and configuration.
 - b. Construction of the GI: Objectives related to the implementation and consolidation of Green Infrastructure.
 - c. Climate adaptation: Objectives for improving microclimatic comfort and water management.
 - d. Constructive aspects: Objectives related to technical and economic feasibility, and to foster the replicability of solutions.

This approach ensures that each detailed intervention is deeply rooted in both the strategic unitary vision of the project and the specific conditions and needs of the site.

4. Requirements Definition and Consequent-Detailed Technological and Design Choices.

The concrete implementation of the objectives defined within the four thematic areas (spatial–functional, construction of the GI, climate adaptation, and constructive aspects), as established in Phase 3, requires the definition of a specific framework of requirements. This framework systematically guides the selection of applicable design interventions. The process is structured as follows.

- **Definition of Specific Requirements per Thematic Area:** For each of the four thematic areas, detailed requirements are formulated that translate the general objectives into operational and measurable criteria.
 - a. For the spatial–functional area: Optimization of vehicular space to promote active mobility by increasing pedestrian and cycle areas, also intervening with traffic calming measures and speed reduction.
 - b. For the construction of the GI area: Continuity, effectiveness, and density of vegetation, consistent with the specificity of the location.
 - c. For the climate adaptation area: Increase in outdoor thermal comfort and improvement in stormwater management capacity.
 - d. For the constructive aspects area: Cost-effectiveness, replicability, and compatibility with existing infrastructure.
 - **Selection of Nature-Based Solutions (NBSs):** The requirements thus defined serve as guiding criteria for the selection of solutions. This phase leverages the “NBS Repertoire” (Deliverable DA 1.1.2), a catalog of Nature-Based Solutions developed by the LIFE+ A_GreeNet project, which proposes a range of applicable measures for various recurring urban fabric typologies of the Adriatic city. The selection is conducted through a comparative analysis of the repertoire options against the specific site requirements, ensuring a targeted and evidence-based application.
 - **Detailed Design Choices and Multi-disciplinary Evaluation:** The finalization of design choices requires the involvement of multi-disciplinary specialized competencies (e.g., architecture, engineering, botany, climatology). While the methodology provides a rigorous framework, the final decisions also incorporate a deep understanding of the context and the design team’s project sensitivity, which ensure the adaptability and effectiveness of the proposed solutions within the specific context.
5. **Detailed Post Operam Project.**

The final phase of the process consists of drafting the detailed design project, which is systematically supported by a series of validation analyses. These analyses are intended to verify the effectiveness of the proposed solutions, in conformity with the objectives and requirements defined in the preceding phases. Corresponding to a technical and economic feasibility study for public works in Italy, this phase includes project documents (e.g., plans, sections, construction details), economic estimates, and technical reports to be further elaborated in subsequent procedural phases.

The validation analyses comprise the following:

- a. **Quantification of Post-Intervention Soil Permeability:** Detailed maps of the post-intervention study area are produced, categorizing surfaces into permeable, semi-permeable, and impermeable. For each category, the surface extent is quantified, allowing for a direct comparison with ante operam conditions and an evaluation of the increase in permeable surfaces as a result of the design solutions (e.g., de-sealing interventions, creation of new green areas).
- b. **Validation of Plant Species Selection:** The selection of tree species and vegetation (carried out in Phase 4) is validated based on the expected ecosystem benefits, as described in the preceding botanical and microclimatic analyses (Phase 2). This includes verifying their suitability for future climate scenarios, their capacity to contribute to urban heat island mitigation (e.g., shading, evapotranspiration), stormwater

management, and oxygen production and carbon storage. The validation relies on scientific data, species technical sheets, and results from simulations (e.g., i-Tree Eco) that quantify the anticipated benefits.

- c. Microclimate Analysis—CFD Simulations and Environmental Benefits: New simulations are performed using ENVI-MET and i-Tree Eco software on the study area model with the implemented design solutions. These simulations allow for the evaluation of microclimatic impact (e.g., UTCI index) and ecosystem services (e.g., pollutant removal, carbon sequestration) resulting from the proposed solutions, comparing them with ante operam and projected future scenarios (2030). The analysis confirms the achievement of climate adaptation objectives.
- d. Economic Evaluation of Interventions (Construction Costs): Summary estimates of construction costs for the proposed interventions are elaborated. While these estimates do not possess inherent scientific value for the validation of environmental performance, they are essential for the technical and economic feasibility studies required for public works in Italy. They provide local administrations with a pragmatic tool for budget definition, financial planning, and the overall economic sustainability assessment of the project with a view to potential implementation.

The entire methodological workflow is conceived as recursive and iterative. Should the results of the validation analyses not confirm the full achievement of the objectives or if criticalities emerge, a revision of the design solutions in preceding phases is envisaged, with consequent refinements and new iterations, until the desired results are achieved.

3. Results

This section presents the main findings from the diagnostic phase of the methodology, applied to one specific pilot area in the Sant'Antonio district in the city of San Benedetto del Tronto. This particular area was selected for the article due to a series of characteristics recurrent in Adriatic cities, as indicated in point 1 of Section 2.2, making it relevant for both methodological insights and design articulation, for cities with temperate Mediterranean climates (Table 1) that are subject to the effects of climate change.

Table 1. Monthly summary of climatic data for the city of San Benedetto del Tronto, year 2019 [67].

Month	Average Max Temperature (°C)	Average Min Temperature (°C)	Rainfall (mm)	N° of Rainy Days	Relative Humidity
January	9.8	3.5	65	7	79%
February	12.1	4.2	48	6	76%
March	15.5	6.0	52	6	74%
April	18.2	9.5	60	8	75%
May	19.5	11.8	145	12	78%
June	28.5	18.2	35	4	68%
July	30.2	20.1	42	4	65%
August	30.5	20.5	55	5	69%
September	25.4	17.5	79	9	75%
October	21.0	13.2	85	7	78%
November	15.8	9.5	130	11	82%
December	11.5	5.2	80	8	80%

3.1. Identification of the Detail Area

The Sant'Antonio neighborhood constitutes the largest community within the city, spanning from the seafront toward the inland hills. It occupies a central position, intersected by primary access routes leading from the south to the historic center, including Viale De Gasperi, State Road n°16, the waterfront, and the railway line. This district accommodates key municipal administrative services, such as the Town Hall, schools, health facilities, and the nearby Civil Hospital. The neighborhood was developed rapidly between the 1960s and 1970s, characterized by high building and population density typical of that era. Consequently, it suffers from a pervasive lack of centralized public gathering spaces for residents, with the exceptions of Parco Wojtyla (between Via Asiago and Via Piemonte) and Pinetina Via Zara on the seafront—two isolated green pockets within an otherwise densely built environment.

The selected study area is located at the intersection of Viale de Gasperi and Via Lombardia, adjacent to the scientific high school and classical high school. This area is heavily trafficked and highly frequented, defined by the presence of mature trees lining the main avenue. Prior climate vulnerability reports, namely D.C. 2.1.1 and D.C. 2.1.2 [49], delineated the anticipated future comfort scenarios for 2030 and 2050. These analyses highlight that the area is subject to significant climate deterioration, projecting a shift from the current configuration of “strong heat stress—very strong heat stress” toward “very strong heat stress—extremely strong heat stress” in the coming decades. This highly delicate antecedent condition, coupled with the area’s elevated pedestrian activity due to the concentration of schools, activities and homes, confirmed the relevance of the site for intervention, a decision reached collaboratively with the local administration. Furthermore, analyses conducted during preceding phases of the LIFE+ A_GreeNet project defined this district of San Benedetto del Tronto as a compact city. In its previous phases, the Life+ AGreenNet project characterized the urban areas of cities of the mid-Adriatic region according to certain recurring parameters, such as building density and the amount of permeable soil present—leading to the articulation of a strategic vision and associated planning guidelines for 2030 and 2050. The strategic objectives defined for the GI construction and climate adaptation across the city are summarized in Table 2.

Table 2. Macro-scale objectives as previously described in D.C. 2.1.1 and D.C. 2.1.2 of the Life+ project, specifically referring to the compact portion of the city of San Benedetto del Tronto.

GI Construction Goals	Climate Adaptation Goals	Project Scenario 2030	Project Scenario 2050
Regeneration of public space and building fabrics through greening and micro-forestry interventions.	Cooling of the urban environment; Reduction in air pollution; Health and well-being of inhabitants.	Initiation of public space regeneration along the squares and the streets.	Interventions targeting small-scale public spaces and building courtyards through greening and de-sealing of existing parking areas.
		De-sealing interventions, installation of permeable paving, and qualitative improvement of existing public green spaces.	
		Introduction of new non-allergenic trees, micro-forestry interventions, and integration of NBSs.	

3.2. Ante Operam Analysis

The ante operam analysis focused on characterizing the existing conditions and vulnerabilities across spatial, botanical, and soil permeability aspects within the selected detailed design area (Figure 2).



Figure 2. General plan of the intervention area, ante operam. The buildings are white and the colored hatches refer to the outdoor urban space.

- Use and distribution of space.

The analysis was a qualitative evaluation of the current configuration of this part of the city, initiated by mapping the “void space”: the existing area between buildings dedicated to infrastructure, parking, and parks. This evaluation defines the available design settings, concentrating especially on public spaces. The evaluation highlighted that the vast majority of this outdoor space is currently allocated to vehicular traffic and parking. Notably, many of the surfaces designated for these activities are oversized: carriageways are frequently wider than necessary for the effective vehicle capacity as defined by the road category. This over-dimensioning is confirmed by observed driving patterns, such as double parking during peak hours (e.g., school dismissal), permitted precisely because of the large size of the vehicle spaces, which not only exacerbates vehicular flow but also creates hazardous situations for pedestrians and students. This data strongly suggests that the existing space can be optimized for more efficient and safer public use [68]. As highlighted by the literature, street space can provide considerable opportunities when searching to provide more efficient, alternative, or multifunctional street use [69]; therefore, these aspects suggest that these types of surfaces should be re-defined. Furthermore, while the nearby Parco Wojtyla provides some green space, it is disconnected and lacks functional continuity with other potential green systems. From the elaborated scenarios of the PUMS and Biciplan approved by the Municipality of San Benedetto del Tronto, it emerges that Via Lombardia and Viale De Gasperi are part of the Plan Network with a proposed “zone 30” typology. On Via Lombardia, road infrastructure can be modified to favor

promiscuity among users, and for both roads, measures can be envisioned to improve the safety of pedestrians and cyclists.

- Soil permeability and presence of gray infrastructure.

The soil permeability analysis revealed a critical condition: the vast majority of the outdoor space under study is impermeable. The only exceptions to this are the existing isolated green areas and narrow, linear strips of permeable soil situated along the avenue in correspondence with the tree pits. An evaluation of the existing parking areas revealed that they were found to be completely impermeable. A distinguishing characteristic of public buildings in this part of the city is their flat roofs, a feature that is particularly prevalent in schools. The materials employed in these systems are predominantly cement-based, asphalt, or bituminous, and their use has been observed to result in heat accumulation. This phenomenon has been identified as a contributing factor to adverse effects during periods of heightened temperature, particularly during the summer months, or to the exacerbation of the urban heat island effect. Via Lombardia has one underground conventional stormwater rainwater collection line, while Viale De Gasperi has two, located at the outer edges of the road.

- Botanical–vegetational aspects.

The distinctive botanical feature of the area is the presence of tree lines accompanying the main road. However, this green system is currently fragmented and discontinuous, and the width of this strip of land is undersized, unable to accommodate trees. The existing tree inventory is characterized primarily by species such as *Eucalyptus*, *Pinus halepensis*, and *Pinus pinea*, which are deemed unsuitable for the site's current ecological and microclimatic conditions, and especially ill-suited to thrive under projected future climate scenarios. In certain instances, the expansion of roots in proximity to the surface layer of asphalt, in conjunction with the age of the trees, gives rise to potentially hazardous scenarios stemming from the inherent instability of the tree itself. This configuration, when coupled with extreme weather events characterized by strong winds and rain, can result in the tree's failure. The i-Tree simulation results indicate tree coverage of approximately 6.8% of the study area, with a total of 39 trees surveyed.

- Microclimate analysis.

Analysis of the current state of the intervention area revealed critical microclimatic conditions, attributable to an urban morphology characterized by high building density and extreme soil sealing along road axes with marginal tree cover. This configuration influences urban heat island phenomena, as quantified by simulations using CFD “ENVI-MET” software for the pre-construction scenario (2019). The results show that, during a typical summer day (representative day), the Universal Thermal Climate Index—or UTCI, a universal climate index that assesses thermal stress on the human body in outdoor environments by accounting for air temperature, humidity, wind speed, and solar radiation—reaches peaks of around 41 °C, a value that classifies the environment as being at risk of heat stress, posing a significant risk to public health. This condition of severe thermal discomfort, aggravated by poor nighttime heat dissipation, establishes a baseline of deterioration in the absence of interventions for the 2030 projection scenario, demonstrating the need for the proposed Green Infrastructure interventions for climate mitigation and environmental comfort improvement. Data from the project's partner municipalities (data for 2011–2022 acquired from WorldWeatherOnline [70], and subsequently used to construct an EPW Weather Data File) were divided into four climatically homogeneous groups to calculate the “representative day” [71,72], defined as a real day (24 h) characterized by the smallest deviation from all real days within the considered time interval (2017–2022). For the ENVI-MET simulations, a common representative input day, 21 July 2019 (Table 3), was selected, with a deviation among the four groups ranging from 0.3% to 1% compared

to the specific representative days of each group. The projection for the year 2030 scenario was performed by conveying 2019 data into an EPW file and modifying it to account for “Representative Concentration Pathways” (RCPs) 2.6 and 4.5 emission scenarios. These scenarios represent a diverging range of future greenhouse gas concentration trajectories, spanning from RCP 2.6, which envisions strong climate change mitigation, to RCP 4.5, representing an intermediate emission pathway.

Table 3. Summary of climatic data for the representative day (21 July 2019) used for the ENVI-MET simulation.

Time	Temperature (°C)	Humidity (g/kg)	Precipitation (mm)	Wind Speed (m/s)	Wind Direction (°)
00:00	21.4	11.14	0	2.5	240
01:00	21.3	11.13	0	2.5	242
02:00	21.4	11.14	0	2.5	243
03:00	20.4	10.32	0	2.5	245
04:00	22.4	11.11	0	2.5	244
05:00	23.4	11.79	0	2.2	244
06:00	24.4	13.34	0	1.9	243
07:00	26.3	12.68	0	1.7	200
08:00	27.3	12.71	0	1.7	157
09:00	28.3	11.91	0	1.4	114
10:00	29.3	11.79	0	1.7	100
11:00	29.3	11.79	0	1.9	85
12:00	30.3	11.9	0	2.2	71
13:00	29.3	11.79	0	2.2	77
14:00	29.4	12.63	0	2.5	83
15:00	28.4	13.48	0	2.5	89
16:00	27.4	13.45	0	2.2	98
17:00	26.4	14.31	0	1.9	107
18:00	25.4	14.37	0	1.7	116
19:00	24.4	13.34	0	1.7	145
20:00	23.4	12.57	0	1.7	174
21:00	22.3	12.55	0	1.7	203
22:00	22.3	11.1	0	1.9	217
23:00	22.3	10.37	0	1.9	231

3.3. From Macro to Micro: Objectives Framework Definition

The site-specific objectives for the detailed design derive directly from the translation of the macro-scale goals (defined in Phase 3.1) in light of the ante operam criticalities.

- Spatial-functional objectives. Given the scarcity of available space in this part of the city, which has already been defined as a compact city in other phases of the Life+ project analysis, i.e., as a densely built-up city with little green space and public space in general, it is necessary to understand how outdoor spaces are currently used, potentially in order to gain surface area. Analyses of the current use and size of roads suggest that there is indeed the possibility of fostering the use of urban space by pedestrians and cyclists and increasing the amount and quantity of greenery without compromising vehicular traffic, as the roads are largely oversized. A similar principle applies to parking lots, which allow for the rationalization of maneuvering spaces to obtain areas that can be used for other purposes.

- GI construction objectives. Implementation and consolidation of widespread green intervention in public spaces in continuity with other portions of the city.
- Climate adaptation objectives. The objective of this study is to enhance the outdoor microclimate, with a particular emphasis on cooling measures. This initiative is driven by the recognition of the area's vulnerability to extreme heat stress, a condition that is anticipated to worsen in the future. The primary objective of this initiative is to promote sustainable rainwater management, with a dual focus on reducing flooding and runoff, minimizing sewage load, and enhancing the health and well-being of residents and users.
- Technological and construction objectives. In an effort to curtail expenditures while formulating an intervention that is not only economically sustainable but also replicable and expandable, the strategic objective is to identify cost-effective, replicable solutions that can be implemented expeditiously and without compromising the functionality (vehicular and pedestrian) of the area.

3.4. Requirements and Consequent-Detailed Technological and Design Choices

Following the definition of the objectives framework in Section 3.3, this section delves into the specific requirements derived from those objectives and the resulting technological and design choices. These elements represent the concrete translation of the project's goals, aligning with the structured approach outlined in Phase 4 of the methodology (Section 2). Table 4 provides a comprehensive framework, systematically outlining the progression from the initial needs to specific requirements and consequent technological design choices for each thematic area—spanning spatial-functional organization, the construction of Green Infrastructure (GI), climate adaptation, and constructive aspects—thereby defining the comprehensive design setting for the interventions.

Table 4. The table shows the framework described in Section 3.3 (Needs) and Section 3.4 (Requirements and design and technological choices).

Aspects	Needs Framework	Requirements	Technological Design Choices
Spatial-functional	Streets. Foster the use of urban space by pedestrians and cyclists and increase the amount and quantity of greenery without compromising vehicular traffic.	Minimum provision of comfortable, attractive, and safe outdoor urban space.	Via Lombardia can become one-way with a reduced carriageway of 3.30 m wide. Space is created for the insertion of a bioretention device and to increase space for pedestrians. In Viale De Gasperi, there can be a reduction in the carriageways to 3.80 m. This allows the creation of cycle lanes in both directions, and the insertion of a large vegetated flowerbed (from 1.60 m to 3.70 m) which can accommodate bioretention basins and large safe spaces for pedestrians to cross and stop, equipped with benches and street furniture. It is also planned to rationalize spaces designated for motor vehicle traffic in order to increase green pedestrian areas.
	Parking spaces. Rationalize maneuvering spaces and parking areas to obtain areas that can be	Reduction in parking area with total number of parking spaces unchanged.	Parking areas are rationalized, double access points are removed, and spaces are created for the purposes of the project. The number of parking spaces remains essentially unchanged (113 before and 114 after),

	used for other purposes.		while the space for maneuvering and accessing has been reduced. These changes do not affect drivers' ability to access and exit parking spaces, in line with current regulations and the urban planning instruments adopted.
Construction of the GI	Implementation and consolidation of widespread green intervention in public spaces.	Continuity of the GI to supplement the existing one.	The creation of new green spaces allows for increasing green capacity and integrating it into the existing network. Insertion and replacement of high-risk tree species. Wojtyła Park is located to the west of the project area. The extension and densification of the tree-lined avenue will serve as a connection to the park, promoting the creation of ecological networks. The selection of possible NBSs is made through Deliverable DA 1.1.2, the "NBS Repertoire," based on site characteristics and includes the following categories: Rain gardens; Tree-lined streets; Pergolas and green shading structures; Permeable surfaces; De-sealing; Green roofs.
	Effective tree cover.	Selection of trees and bushes based on current and projected climate, as well as site characteristics and distance from the sea. Selection also based on their adaptability, ability to withstand cold and especially hot and arid climates, as well as low maintenance requirements once established. Maximize tree canopy cover during hot periods and allow solar radiation to pass through during winter.	Trees: <i>Morus alba</i> ; Tree that has these characteristics and its widespread traditional use in neighboring territories. Bushes: <i>Solanus jasminoides</i> , <i>Rosa banksia arbustiva</i> , <i>Rosa chinensis</i> .
Climate adaptation	Improving outdoor microclimate comfort, particularly cooling and counter-acting the urban heat island effect; Sustainable rainwater management with a view to reducing flooding and runoff; Reducing sewage load; Health and well-being of residents and users.	Minimum number of trees along main roads; Use of materials suitable for hot temperatures and long, continuous exposure to solar radiation; Capacity of the sewerage system to cope with the effects of extreme events; Provision of green and blue infrastructure integrated with existing gray infrastructure; Capacity of urban bioretention basins capable of absorbing and slowing down rainwater runoff; Minimum provision of green space with trees to benefit from the effects of shade and evapotranspiration.	Allocating the highest possible number of tall trees along the road, in parks, and within newly created surfaces; Replacement of existing pavements with high albedo materials (cool pavement) in order to reduce surface temperatures; Creation of green roofs when feasible, for example, on flat roofs of schools and public buildings; Creation of road sections with slopes towards bioretention basins, which are specially sized according to the collection areas and extreme precipitation forecasts.
Technological	Economy; Replicability;	Easy to install; Easy to maintain;	Constructive systems with materials and components available on site and construction methods

construc- tive	Speed in the imple- mentation phase; Ability to carry out interventions with- out compromising the functionality (vehicular and pe- destrian) of the area; Compatibility with under services lines.	Possibility of implementation for modu- lar segments or phases.	implemented starting from knowledge not foreign to local workers; Identify modular technological solutions and materials easy to replace and maintain over time
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3.5. Detailed Post Operam Project

The detailed post operam project (Figure 3) demonstrates the significant impact of the adopted technological and design choices on outdoor urban spaces. As shown in Table 5, the allocation of GI brings a series of benefits deriving from increased tree cover, carbon storage and sequestration capacity, oxygen production, and runoff reduction, resulting from the general increase in permeability of the area.

The synthesis that emerges from this analysis is as follows.

- **Viale de Gasperi:** A notable augmentation in green space can be achieved through a substantial reduction in the width of the roadways without compromising traffic flows. The central flowerbed has undergone significant expansion, reaching almost three times its original width (Figure 4). This modification serves to mitigate the presence of overly elongated discontinuities. This approach enables the strategic planting of new trees and bushes and the replacement of those that are not well-suited to the local climate, urban configurations, and projected climate change scenarios. The primary option under consideration is *Morus alba*, a deciduous and adaptable tree with a long history in the region, suited to temperate climates and, once mature, able to withstand even prolonged periods of drought. The resized central strip becomes a linear bioretention basin, appropriately connected to the existing rainwater collection network. The changes to the road section are made in line with current urban planning regulations.
- **Via Lombardia:** The project involves the implementation of a one-way system for automobiles, with a roadway measuring 3.30 m in width (Figure 5). The design incorporates the implementation of a vegetated bioretention basin that is to be situated along the entire length of the thoroughfare. The basin has been meticulously designed to serve as a collection point for rainwater during inclement weather, while ensuring that the pedestrian thoroughfare remains accessible. The position of the bioretention basin, developed longitudinally with respect to the road, follows the current gray infrastructure layout in order to facilitate connections in the event of actual implementation. The changes to the road section are made in line with current urban planning regulations.
- **Parking and pavements:** The parking area can be optimized, particularly the spaces designated for maneuvering and the redundant entrances and exits, without compromising driver usability. This can create widespread space for new greenery. These spaces are scheduled to undergo de-sealing and replacement of the surface layer with materials conducive to drainage.
- **Pedestrian and cyclist Space:** Pedestrian and cyclist-designated spaces have been augmented and made safer, crossings have been shortened, making them easier to use, especially for those with mobility issues, and cycle paths now run seamlessly throughout the area. Despite the lack of direct correlation with greenery, these measures are regarded as essential climate mitigation strategies aimed at enhancing

the comfort of outdoor spaces. This enhancement is defined by their capacity to welcome individuals, encourage movement, and consequently exert a positive influence on both physical and psychological well-being. Consequently, these measures can potentially lead to a reduction in automobile presence, accompanied by the associated benefits.

In greater detail using ENVI-MET software (Table 6), it was finally possible to highlight the difference in UTCI in the current scenarios, and in 2030, to highlight the difference between before and after (Figures 6 and 7). Specifically, the ENVI-MET simulations, demonstrate a substantial impact on thermal comfort, with the interventions resulting in an average reduction of 0.61 °C in the UTCI index (peaking at 4.45 °C) in the present scenario and an average reduction of 1.17 °C in the projected scenario for 2030. The cumbersome visualization and comparison of multiple simulation outputs with conventional tools (e.g., Leonardo) were addressed by employing specifically developed tools. For enhanced speed and efficiency in data consultation and comparative analysis, the EnviReader tool was utilized [73]. The augmentation of the tree population (from 39 to 59 specimens) and the resultant escalation in coverage (from 6.1% to 15.1%) demonstrate significant environmental benefits, which are quantifiable through the utilization of i-Tree software. Specifically, there is a twofold increase in pollutant removal capacity (from 2.26 to 4.52 kg/year) and an enhancement in carbon sequestration, which escalates from 1163 kg to 1849 kg/year (Table 5).

On a total area of 21,100 sq. m. under study, the total permeable surface area is expected to increase from 1750 sq. m. to 2850 sq. m., along with an additional 2300 sq. m. of semi-permeable surface area (+194%). Additionally, an estimated 1150 sq. m. of green roofing can be installed on public buildings (Figure 8). The project culminated in the evaluation of summary estimates of construction costs. This was performed with the objective of elucidating the economic complexities of the ongoing interventions. The estimates have been developed to provide municipal administrators and technicians with useful tools for programmatic assessments to be carried out in the area. Moreover, the reference can be utilized for analogous projects in order to assess the relative weight of individual interventions (Table 7).

Table 5. Comparison table before and after; data extrapolated using i-Tree software.

	Ante	Post
Number of trees	39	59
Tree cover	6.1%	15.1%
Pollution removal	2.26 kg/year (EUR 18/year)	4.52 kg/year (EUR 31.7/year)
Carbon storage	20.390 kg (EUR 3280)	23.370 kg (EUR 3760)
Carbon sequestration	1163 kg (EUR 187/anno)	1849 kg (EUR 297/anno)
Oxygen production	3101 kg/year	4931 kg/anno
Avoided runoff	1.82 m ³ /year (EUR 3.45/year)	3.47 m ³ /year (EUR 6.61/year)

Table 6. UTCI comparison table ante and post operam, representative day, years 2019 and 2030, 21 July 2019; data extrapolated using ENVI-MET software and referred to the point indicated on the output maps (Figures 4 and 5).

	UTCI ANTE (°C) in Case of No Intervention	UTCI POST (°C) in Case of Implementing the Design Proposal
21 July 2019 at 2:00 PM	41°	37°
21 July 2030 at 2:00 PM	47°	43°

Table 7. Summary and indicative estimation of construction costs. The estimation does not take into account substantial changes to existing sewerage systems, electrical systems, or road finishes.

Brief Description of the Intervention	Summary Cost (Euro)
Interventions aimed at creating bioretention basins	
De-sealing and restoration of the surface layer of soil	13,800.00
Construction of rain gardens, sub-bases, drainage systems, soil, fabrics, and rainwater collection systems	51,700.00
Interventions aimed at creating lawns	
De-sealing and restoration of the surface layer of soil	14,500.00
Soil preparation and sowing operations	2500.00
Interventions aimed at creating permeable parking lots	
De-sealing and restoration of the surface layer of soil	38,200.00
Soil preparation, ballast, sand bed, etc.	59,100.00
Drainage paving in interlocking elements	76,300.00
Interventions aimed at creating extensive green roofs	
Preparatory works, supply, installation of green roofing	230,000.00
Maintenance and connection works on sidewalks	20,000.00
Total	506,100.00



Figure 3. General plan of the intervention area, post operam. The codes refer to a previous deliverable of the Life+ project called DA.1.1.2 Repertoire of NBS interventions and tree species for the physical and mental well-being of the urban community.

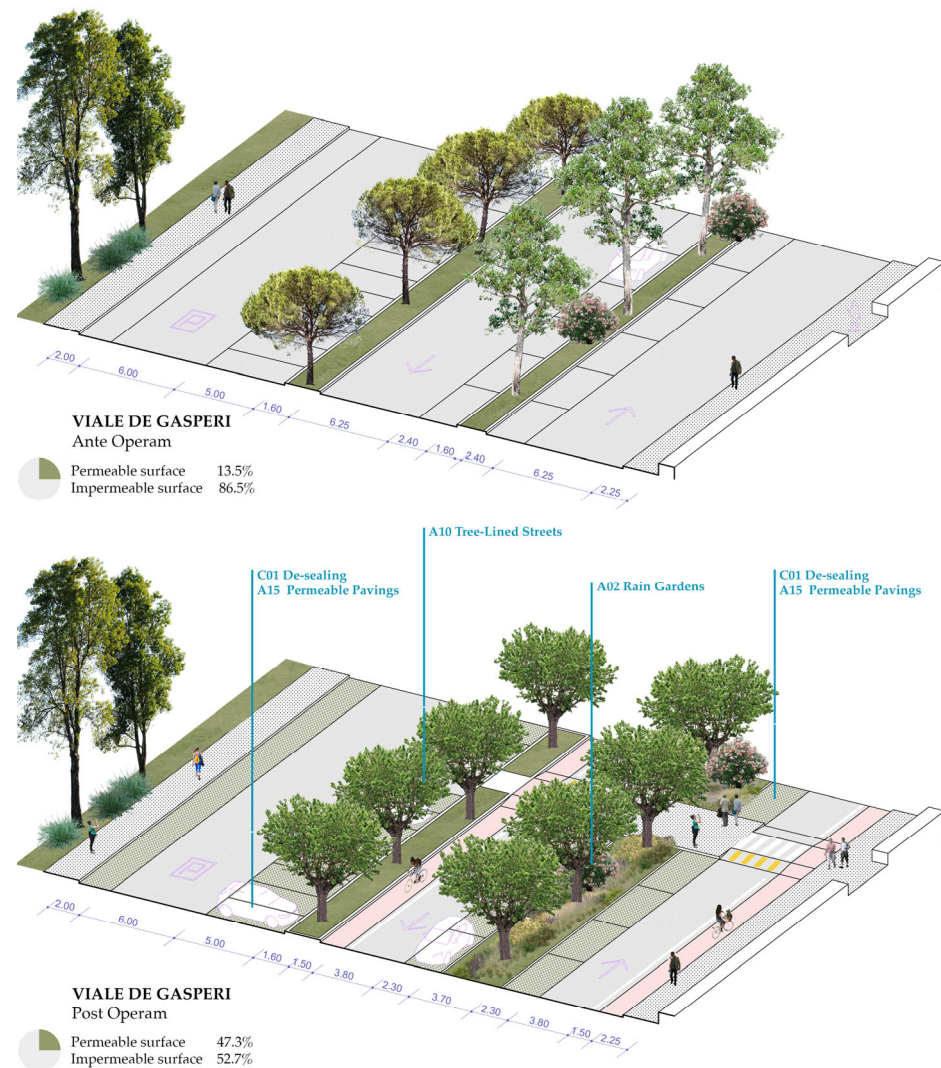


Figure 4. Cross-sections of Viale De Gasperi ante operam and post operam. The codes refer to a previous deliverable of the Life+ project called DA.1.1.2.

The overall effectiveness of the proposed methodology in addressing the identified challenges and achieving the project objectives for the Sant'Antonio pilot area is summarized in Table 8, demonstrating the successful alignment of post operam results with the established methodological requirements.

Table 8. Synthesis of post operam results aligned with methodological requirements.

Thematic Area	Specific Requirement (from Phase 4)	Operam Result (from Section 3.5)	Validation Status
Spatial-functional	Optimization of vehicular space for increased pedestrian/cycling areas.	Significant increase in pedestrian/cycling areas, reduced roadway widths, optimized parking; substantial gains in space allocated for trees and vegetation;	Fulfilled
Construction of GI	Continuity and density of vegetation.	Tree canopy cover increased from 6.1% to 15.1%; new green areas connected to Parco Wojtyła.	Fulfilled

Climate Adaptation	Reduction in UTCI index; improved stormwater management capacity.	Average UTCI reduction of 0.61 °C (peaks of 4.45 °C) in 2019, 1.17 °C in 2030; +194% permeable surface area.	Fulfilled (microclimatic and hydrological benefits confirmed)
Constructive Aspects	Cost-effectiveness, replicability, infrastructure compatibility.	Estimated construction costs EUR 506,100; modular solutions; no substantial alteration to existing infrastructure.	Fulfilled (for the case study)

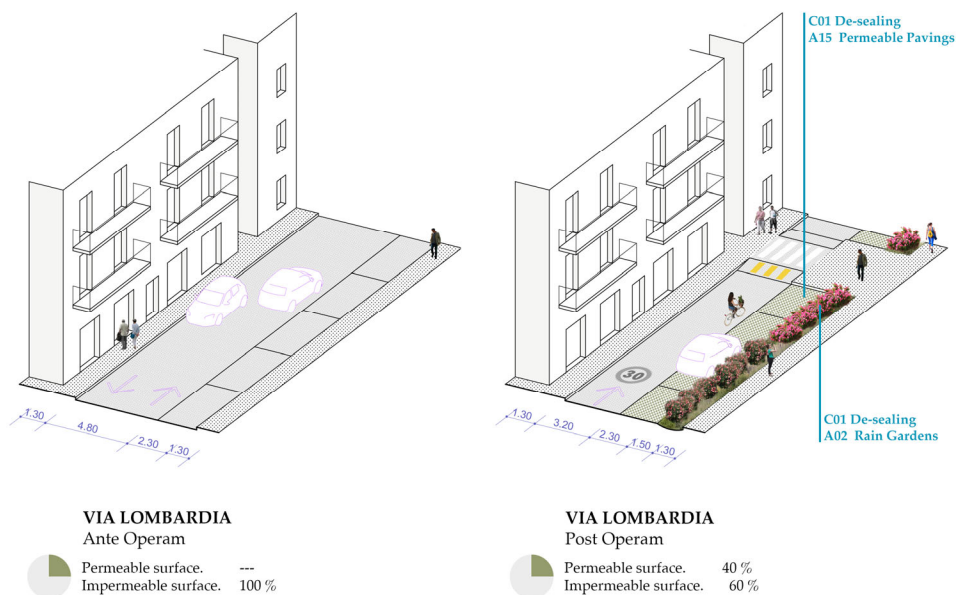


Figure 5. Cross-sections of Via Lombardia ante operam and post operam. The codes refer to a previous deliverable of the Life+ project called DA.1.1.2.

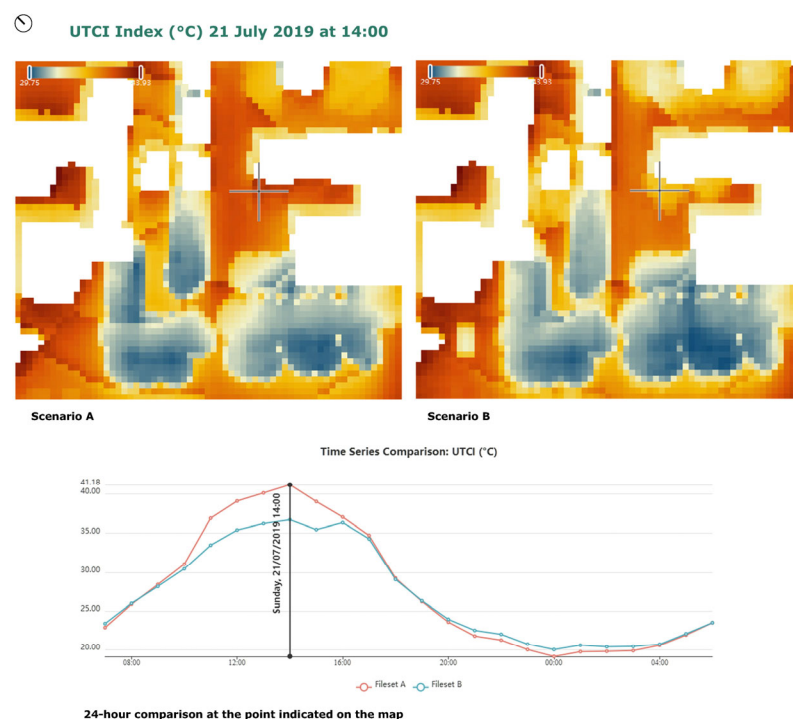


Figure 6. ENVI-MET output maps, year 2019. UTCI comparison table ante (Scenario A) and post operam (Scenario B); data extrapolated using the EnviReader tool (version 1.5) [73,74].

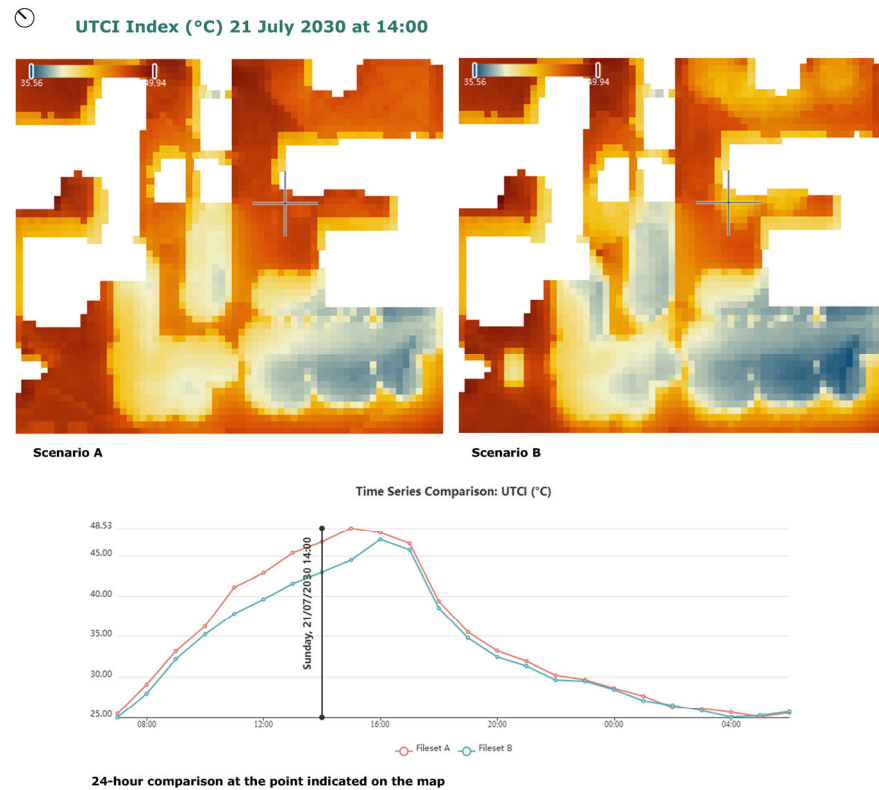


Figure 7. ENVI-MET output maps, year 2030. UTCI comparison table ante (Scenario A) and post operam (Scenario B); data extrapolated using the EnviReader tool [73,74].



Figure 8. Plans ante operam and post operam, highlighting permeable surfaces. There is a 194% increase in permeable soil (permeable + semi-permeable soil).

4. Discussion

This study's application of the proposed design methodology in the Sant'Antonio neighborhood exemplifies the potential for significant urban transformation. The post-intervention scenario reveals several key improvements: a substantial increase in tree coverage with climate-resilient species, enhanced soil permeability, augmented public space for active mobility, and notably, improved outdoor thermal comfort, projected to persist even under future climate scenarios. These outcomes, detailed in Section 3, underscore the tangible benefits achievable through a structured GI implementation.

This project holds particular significance when viewed through the lens of climate vulnerability and the urgent need for action in mid-Adriatic cities. The Sant'Antonio district, characterized as a "compact city" with inherent limitations for intervention, was identified as a critical climate vulnerability hotspot. Our projections, aligning with the 2050 scenario, predict extremely strong heat stress by 2050, highlighting the severe consequences if left unaddressed. The robust ante-post analyses demonstrate the efficacy of the proposed GI interventions in reducing peak temperatures and improving UTCI values, particularly during the hottest periods. Beyond thermal comfort, direct benefits were quantified, including enhanced runoff management, increased carbon storage and sequestration, and oxygen production. These outcomes highlight the imperative for prompt action, even within densely populated urban areas, validating the site's selection as a paradigmatic case study for similar dense urban regions across the Middle Adriatic [2,21]. Crucially, the analysis revealed that, in many analogous urban contexts, vehicular infrastructure and parking spaces are often oversized [75]. This pervasive over-dimensioning offers a significant and replicable opportunity: despite the apparent saturation of space, areas can be "liberated" and reallocated for de-sealing and Green Infrastructure implementation, demonstrating that spatial constraints are not insurmountable barriers to GI.

The article delineates a component of the LIFE+ A_GreeNet project, which transitions from the urban macro-scale to the detailed scale, thereby establishing a methodological detailed design approach, capable of incorporating the necessary sensibilities that every site-specific project should have. The five phases adopted facilitate the translation of macro-scale analyses and objectives into requirements, and consequently, into design choices that are informed by an understanding of the specific issues of the site. The key contribution proposed by this part of the project lies in its ability not only to adopt a holistic approach capable of integrating the diverse variable factors of a project, but also, and more importantly, in guiding designers from the urban scale to the detailed design scale. This allows for overcoming some of the criticalities identified in the literature or in reference case studies, which acknowledge the role of GI but do so either at the urban scale [18,29,51], or at the detailed project scale [55,59], or intervene specifically on only certain aspects or by interpreting guiding principles [47,48,55,60,61]. Such an integrated approach necessitates a high degree of multi-disciplinary expertise (architecture, engineering, botany, climatology), orchestrated by a clear methodological framework that supports and synthesizes these diverse professional skills. Crucially, the methodology eschews a "pre-packaged recipe" or a mere checklist of standardized solutions. Instead, it advocates for a needs-driven design process where performance-based and technological choices (e.g., specific materials or plant elements) are consequential to a rigorous initial analysis and objectives framework (Phases 1–3). This structured pre-selection ensures that NBSs are not applied indiscriminately but are strategically tailored to specific urban fabric typologies—such as the "compact city" identified here. The method explicitly addresses the identified "discrepancy" in existing practices, which often leave the selection of solutions to individual designer sensibility without a clear, codified link between the solution, the city's morphological form, and broader urban planning objectives for GI network development.

The methodology, as demonstrated through the “compact city” characterization for Sant’ Antonio, is directly replicable for other coastal cities in the Middle Adriatic that share similar urban typologies and climate challenges. Its strength lies in providing a transferable methodological framework, rather than a prescriptive set of design outcomes. It is crucial to emphasize that the analysis presented here represents one component of a larger, integrated methodological framework (LIFE+ A_GreeNet project), which, by its very nature, cannot be disassociated from its antecedent and subsequent phases for full implementation. However, a key limitation of this approach stems from its intrinsically integrated and sequential nature: full implementation necessitates adherence to all its various phases, including the preparatory stages not explicitly detailed in this paper. This demands significant multi-disciplinary coordination and can entail substantial time and resource investments, requiring diverse competencies and dedicated development periods. Furthermore, while the methodological process is transferable, the actual design results and their quantified benefits are highly site-specific. The effectiveness of the proposed solutions is intrinsically linked to the particular morphological characteristics, selected botanical species, and local climatic conditions of each site. Therefore, successful application in different urban contexts mandates a careful calibration of input parameters and a preliminary evaluation of local microclimatic and hydrological responses, preventing a direct “copy–paste” of solutions.

While the LIFE+ A_GreeNet project aims to disseminate these tools and methodologies to other Italian coastal municipalities, the economic analysis in this study focuses solely on initial implementation costs. For a holistic assessment of economic sustainability and long-term replicability, a comprehensive Life-Cycle Cost Analysis would be essential, encompassing operation and maintenance expenses over the project’s lifespan. Beyond technical design, the LIFE+ A_GreeNet project’s framework also critically addresses institutional and managerial sustainability. Partner municipalities have formalized their commitment through memoranda of understanding, and the project’s preliminary urban planning guidelines are intended for integration into municipal regulations (Action C4 [49]). This proactive engagement ensures continuous political–administrative support, crucial for the widespread and sustained adoption of GI. The detailed designs developed have been submitted to local administrations, who, driven by the collective benefit and their civic responsibility, are expected to proceed through phases of communication and participatory evaluation to advance these proposals or explore suitable alternatives, ultimately facilitating the real-world impact of the methodology.

5. Conclusions

The critical urban vulnerability of the Middle Adriatic region to climate change necessitates a decisive shift from conceptual GI planning to practical, detailed implementation. This paper addressed the pervasive challenge of translating high-level strategic visions into executable, site-specific projects—a gap particularly pronounced in dense, spatially constrained Mediterranean urban environments [76]. This article highlights how one of the root causes for the limited dissemination of real-world case studies across urban territories lies in the difficulty of translating strategic visions, conceived at the territorial and urban scales, into detailed projects by the various stakeholders involved.

The core contribution of this research is the presentation and application of a replicable, multi-disciplinary, five-phase methodology developed within the framework of the LIFE+ A_GreeNet project, to provide designers with a structured, scientific-based approach to guide them through the design process. This methodology operationalized strategic GI goals by integrating macro-scale climate risk assessments with detailed on-site diagnostics (ante operam analysis) to define a robust framework of technical requirements and specific Nature-Based Solution choices.

The pilot study in the Sant'Antonio district of San Benedetto del Tronto provided empirical evidence of the methodology's efficacy. Despite being a highly dense urban hotspot projected to face "extremely strong heat stress," the analysis revealed significant opportunities for spatial optimization through the re-appropriation of oversized vehicular areas and the targeted introduction of climate-adapted GI. This demonstrates that precise GI design allows municipalities to reclaim seemingly saturated urban space, creating urban environments that are fundamentally more resilient against an evolving hotter and drier climate. Crucially, the outcome transcends mere technical adaptation, resulting in environments that are measurably safer, more comfortable, and actively human-centered. Quantifiable gains from the GI implementation and de-impermeabilization strategies include a substantial average reduction in the UTCI index (0.61 °C in the current scenario, peaking at 4.45 °C; 1.17 °C in the 2030 scenario), a significant rise in canopy cover from 6.1% to 15.1%, and tangible ecosystem benefits such as a doubling of pollutant removal capacity (from 2.26 to 4.52 kg/year) and an increase in carbon sequestration (from 1163 kg to 1849 kg/year). Hydrologically, increased permeability significantly reduces overall surface runoff across the area. As demonstrated in the literature, these ecosystem services generate not only environmental value but also indirect economic benefits in terms of reduced infrastructure strain, enhanced property values, and improved public health, leading to long-term savings for municipalities and citizens.

This detailed planning framework serves as a tangible, transferable trans-scalar model for the partner municipalities of LIFE+ A_GreeNet and other Mediterranean coastal cities facing similar socio-spatial and environmental pressures. This approach could be particularly useful for designers or technicians working for public bodies who are seeking to identify the most appropriate, science-based design choices within broader analytical frameworks and guidelines that refer to a comprehensive approach, such as that of the Life+ project. The subsequent step should be the physical realization of these detailed interventions. Only through the concrete implementation of these projects can the expected efficacy of the NBSs be validated over time, allowing for long-term monitoring of their microclimatic and ecosystem performance.

Future research could particularly address the persistent challenges in integrating new GI and NBSs with existing "gray" urban infrastructure, notably concerning subsurface complexity and stormwater management systems. The lack of detailed historical knowledge regarding existing underground networks and the frequent under-dimensioning of current infrastructure present significant barriers. Further efforts should focus on securing resources for the construction phase, developing comprehensive Life-Cycle Assessment tools, and promoting interdisciplinary collaboration to overcome these subsurface integration challenges, thereby ensuring the widespread and effective adoption of climate-resilient solutions.

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Abbreviations

The following abbreviations are used in this manuscript:

GI	Green Infrastructure
NBSs	Nature-Based Solutions
PUMS	Piano Urbano Mobilità Sostenibile (Sustainable Urban Mobility Plan)
UTCI	Universal Thermal Climate Index
RCP	Representative Concentration Pathways

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