# Introducing Indicators for Assessing the Readiness of Buildings for Greening Interventions

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**Abstract.** The adaptation of the built environment to climate change requires strategic interventions that enhance urban resilience against increasing environmental risks. Adaptation measures emphasize targeted solutions to minimize climate-related vulnerabilities. Among these, Nature-Based Solutions (NBS), such as green roofs and vegetated facades, play a crucial role in improving thermal regulation, storm water management, and urban biodiversity. However, their effectiveness depends on large-scale implementation guided by systematic evaluation criteria rather than isolated applications. This study presents a methodological framework for assessing buildings' suitability for green roof implementation, integrating technical feasibility, environmental impact, and economic viability. The approach consists of defining intervention areas, categorizing relevant parameters, and prioritizing buildings through a multi-criteria evaluation model. Advanced tools, including Geographic Information Systems (GIS) and environmental modeling, support data-driven decision-making. A structured weighting system, based on literature review, field observations, and expert consultations, ensures an objective evaluation of key feasibility indicators such as structural capacity, roof conditions, and accessibility. The methodology facilitates the identification of high-priority buildings where green roofs can be most effectively implemented, optimizing both environmental benefits and economic investments. By providing a scalable decision-support tool, this study contributes to advancing climate adaptation strategies and promoting sustainable urban transformations. The proposed methodology is applied on a case-study area in the city of Naples (Italy).

**Keywords:** Greening intervention · Transformability indicators · Technical Feasibility · Decision support system

## 1 Introduction

Adapting the built environment to climate change represents an increasingly urgent and complex challenge, requiring diversified strategies to address the multiple risks associated with the alteration of climatic balances. Unlike mitigation, which for many years has been linked to a model of sustainable development—widely promoted in global

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policies but with evident limitations in effectively slowing global warming—adaptation focuses on targeted interventions aimed at reducing the vulnerability of urban and built systems to climate impacts. However, the adaptation measures, to be truly effective, must address a broad range of risks that currently undermine urban resilience, extending beyond the management of heat waves and the improvement of building energy efficiency and system performances. A comprehensive, multi-risk urban perspective must also consider the increasing risks of flooding, the rise of vector-borne diseases favored by changing temperatures, declining air quality, and negative effects on public health. These interconnected challenges highlight the need for integrated, multi-sectoral solutions that can enhance the overall sustainability and resilience of urban environments.

In this context, the widespread application of Nature-Based Solutions (NBS) [1] emerges as a particularly effective approach to climate adaptation. Such an approach is not merely reactive but also proactive and multifunctional. Green infrastructure interventions, such as green roofs, vegetated walls, and the integration of urban green spaces, contribute not only to thermal regulation of buildings and the reduction of the urban heat island effect [2] but also to sustainable storm water management, reduction of air pollution, enhancement of urban biodiversity, and overall improvements in public health [3]. To ensure that these interventions generate a significant and systemic impact, however, it is essential that they be implemented on a large scale and guided by strategic selection criteria. A fragmented and uncoordinated approach, where these solutions are applied in isolated instances without urban planning considerations based on structured large-scale greening strategies, risks reducing them to virtuous but ultimately insignificant measures. The large-scale implementation of greening solutions in urban contexts must address multiple challenges, ranging from the need for adequate public space to accommodate interventions, to the integration of measures across both public and private buildings, and the securing of funding necessary to initiate such strategies.

A crucial aspect in guaranteeing the effectiveness and large-scale adoption of greening interventions is the development of tools that can assist decision-makers in the strategic selection of the most suitable areas and buildings for transformation, as well as support designers in the various phases of project definition.

Over the past decades, numerous support tools have been developed to assist decision-makers in assessing the effectiveness of retrofitting efforts affecting the existing built environment, particularly through multi-criteria evaluation approaches. One of the first notable tool is EPIQR [4, 5], which assesses retrofitting strategies, costs, and activities aimed at reducing energy consumption while improving indoor environmental quality. Similarly, the Design Quality Indicator (DQI) [6] employs user questionnaires to provide qualitative evaluations of building quality, drawing inspiration from Vitruvius' classical principles [7].

While widely recognized certification systems like LEED, BREEAM, GREEN GLOBES, and CASBEE [8–11] provide valuable frameworks for evaluating and accrediting building interventions, they primarily focus on assessing retrofitting measures rather than offering precise recommendations on optimal strategies and intervention timelines.

Future advancements of such kind of tools should integrate multiple variables, including climate vulnerability, available surface areas, potential for heat island reduction, water management capacity, and economic feasibility. Advanced technologies, such as

Geographic Information Systems (GIS), can play a fundamental role in storing and managing built environment data, facilitating informed decision-making processes. Furthermore, environmental simulation models and artificial intelligence-based optimization algorithms can provide valuable support in assessing intervention priorities and developing tailored design strategies for urban contexts. Additionally, the integration of climatic, morphological, and energy-related data through digital platforms enables a more dynamic and adaptive approach, enhancing the effectiveness of design choices and streamlining the implementation of impactful greening strategies.

This article aims to contribute to these objectives by implementing a methodological framework based on specific indicators designed to assess buildings' suitability for the adoption of greening strategies. The objective of this paper is to define indicators and their integration into an effective tool designed to support and guide the selection of buildings that should be considered for greening interventions, based on their technical feasibility and readiness for implementation. The interpretation of results obtained across large urban areas or extensive real estate assets allows for the prioritization of interventions, while the detailed analysis of individual cases provides valuable insights for practical, site-specific, architectural design applications. By adopting such an approach, urban adaptation strategies can be optimized to maximize resilience, sustainability, and overall environmental performance in the face of ongoing climate challenges.

## 2 Methodology

The methodology adopted to achieve the established objectives is structured into several phases (Fig. 1):

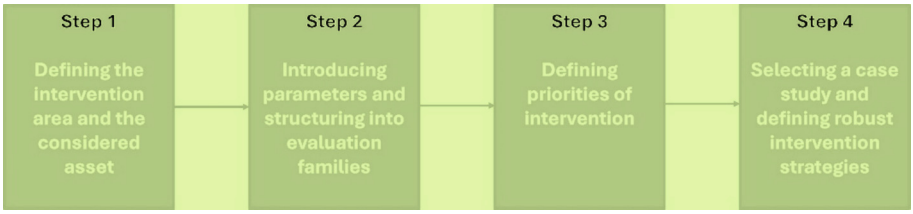


**Fig. 1.** Workflow of the various phases on which the methodology of the research is based.

### 2.1 Step 1: Defining the Intervention Area and the Considered Asset

The first methodological step involves identifying the intervention area. This area must possess specific urban, landownership, typological, and morphological characteristics that allow for the implementation of comprehensive strategies capable of generating an overall benefit for the selected site. The selection process must consider the broader urban context, ensuring that the proposed interventions align with the existing spatial and regulatory framework.

Depending on the characteristics of the context—whether urban or peri-urban—its primary function, and the ownership structure (public, private, or mixed), different strategies can be implemented to optimize the intervention's effectiveness. A well-defined intervention area enables a targeted approach that maximizes the potential impact of greening strategies while addressing the specific constraints and opportunities present in the built environment.

Once the area has been defined, an extensive data collection and documentation process must be initiated. This step involves storing key information regarding the urban environment that will be subject to greening interventions, whether open spaces or buildings. For instance, in cases where implementing greening strategies in open spaces is impractical—such as in dense urban fabrics with narrow streets and limited public spaces—attention may shift exclusively to buildings. In this scenario, the collected data should be referred to the case study buildings and include general information (year of construction, ownership, function), geometric attributes (building height, covered surface area, plot perimeter), construction characteristics (building materials, structural typology, percentage of openings in facades, overall state of maintenance), and environmental factors (local climatic conditions, surrounding urban morphology).

The collected data, recorded for each building through structured survey forms, can be systematically stored on a Geographic Information System (GIS) platform. This digital archive facilitates rapid visualization and analysis of the gathered information, supporting an informed decision-making process and enabling a more strategic and data-driven approach to the planning and implementation of greening interventions.

### 2.2 Step 2: Introduction of Parameters and Structuring into Evaluation Families

In the second methodological phase, a structured list of parameters is established, serving as a fundamental tool for comprehending the predisposition of buildings to undergo transformative interventions that consider the integration of green areas or vegetated portions. Subsequently, these parameters are rigorously determined for the analyzed buildings. When greening interventions are considered, the main possible interventions to be considered are the implementation of green roofs, the installation of vertical green facades, or the replacement of impermeable paving materials with permeable alternatives, thereby fostering a more ecologically attuned built environment. For the sake of brevity and analytical clarity, the present paper exclusively focuses on the realm of green roof applications.

From an operational point of view, the definition of these parameters, aimed at assessing the readiness of buildings to undergo greening interventions based on green roofs, originates from the theoretical framework introduced by Sommese and Diana [12]. This framework delineates the context, environmental, and urban parameters, as well as those directly referred to the architectural and technological characteristics of the buildings, that show the most profound influences on the definition of the design variables associated with green roof systems. The specificities of this framework, alongside the intricate ontologies between parameters and variables, are comprehensively illustrated in Figs. 2 and 3.

Starting from the assumptions established by [12], this paper explores a possible implementation of the framework. Building upon the established ontologies within this

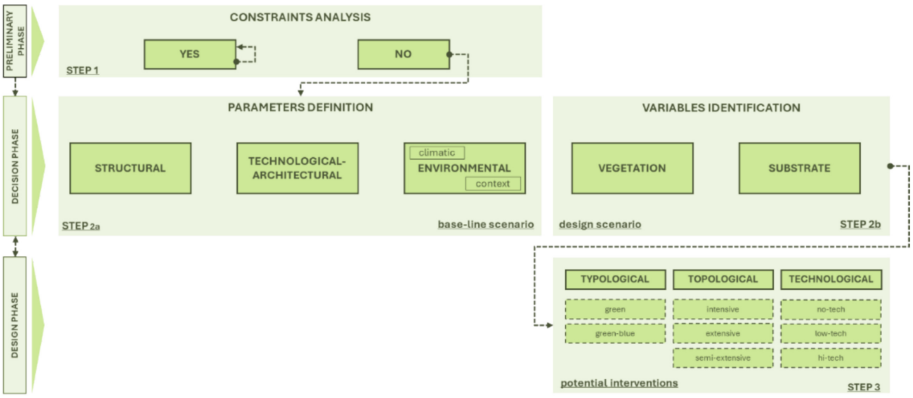


**Fig. 2.** Framework for green roofs (Picture taken from [12]).

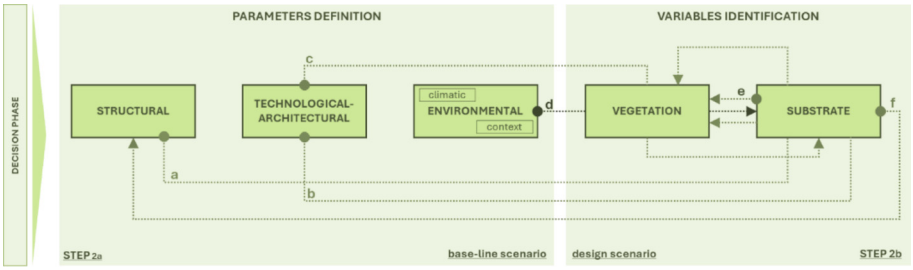


**Fig. 3.** Ontologies between parameters and variables (Picture taken from [12]).

conceptual structure connecting the dependencies between parameters and design variables, a diversified set of indicator families is formulated to delineate the readiness of buildings for green roof interventions. Parameters are measurable entities while indicators are synthetic measures derived from one or more parameters to represent or evaluate an aspect or phenomenon in a comparable way [13]. These categories encompass technical feasibility indicators, environmental feasibility indicators, economic feasibility indicators, as well as indicators assessing the environmental, economic, and social benefits derived from such interventions. While all these indicator families collectively contribute to the formulation of a synthetic index of transformability, the present study is limited solely to the aspects related to the technical feasibility (Table 1).

Concerning especially the indicators constituting the evaluation of technical feasibility, these are further categorized into two principal domains: structural and construction-related aspects on the one hand, and technological and architectural characteristics on the other. Within the structural and construction-related domain, particular attention is paid to indicators related to the year of construction (unit: year), the construction technology of the roof slab (Vaults without tie rods, Vaults with tie rods, Beams with a deformable slab, Beams with a semi-rigid slab, Beams with a rigid slab), and the load-bearing capacity of the roofing structure (unit: %). Meanwhile, within the technological and architectural domain, the main indicators include the slope of the roof surface (unit: °),

**Table 1.** Indicator families for the definition of an index of transformability for green roofs.

| | | |
|---|---|---|
| Technical Feasibility | | Tot |
| Environmental Feasibility | | Tot |
| Economic Feasibility | | Tot |
| Environmental Benefits | | Tot |
| Social Benefits | | Tot |
| Economic Benefits | | Tot |
| | ***Index of transformability*** | ***TOT*** |

its state of maintenance (very poor, poor, sufficient, good, excellent/recently renovated), the overall height of the roof (unit: m), the incidence of usable roof area (unit: %), the incidence of accessible roof area (unit: %), the presence and the mean effective drainage area for a single downspout (unit: $m^2$), as well as the existence of a water supply system on the rooftop (yes/no). Some indicators are considered as costs, where a lower value is considered better, while some others are considered as benefits, where a higher value is considered better. The various indicators with the reference ID are listed in Table 2.

These parameters collectively delineate the potential and constraints inherent in the implementation of green roofing solutions, thereby fostering a more nuanced understanding of their applicability in existing buildings.

**Table 2.** Indicators' ID and Name for the technical Feasibility family

| Indicator family | Indicator domain | Indicator code | Indicator Name | Weight |
|---|---|---|---|---|
| Tech. Feasibility | Structural and construction | In01 | YEAR | 0.08 |
| Tech. Feasibility | Structural and construction | In02 | CONST. TECH | 0.11 |
| Tech. Feasibility | Structural and construction | In03 | LOAD CAPACITY | 0.16 |
| Tech. Feasibility | Technological and architect | In04 | SLOPE | 0.08 |
| Tech. Feasibility | Technological and architect | In05 | MAINTENANCE | 0.12 |
| Tech. Feasibility | Technological and architect | In06 | HEIGHT | 0.07 |
| Tech. Feasibility | Technological and architect | In07 | USABLE AREA | 0.14 |
| Tech. Feasibility | Technological and architect | In08 | ACCESSIBILITY | 0.13 |
| Tech. Feasibility | Technological and architect | In09 | DRAINAGE | 0.07 |
| Tech. Feasibility | Technological and architect | In10 | WATER SUPPLY | 0.04 |

### 2.3 Step 3: Defining Priorities of Intervention

Based on what was discussed above, the various technical feasibility indicators, briefly introduced in Sect. 2.2, can be employed—if calculated for the various buildings selected within the studied area—to establish a priority scale for interventions. This priority scale is based on an objective comparative evaluation of the various buildings analyzed. The

evaluation method follows a analytic hierarchy process (AHP) multicriteria approach [14], which allows results expressed in different units of measurement to be converted into comparable numerical values, enabling assessments and comparisons.

This approach is particularly advantageous because it facilitates the comparison between purely quantitative indicators—expressed as numerical values with defined measurement units—and qualitative indicators, which do not inherently deliver numerical values. The ability to integrate these two types of data within the same assessment framework ensures a more comprehensive and structured decision-making process, allowing for a nuanced and multidimensional evaluation of feasibility.

The transformation of the various indicators' results follows a standardized normalization process. Quantitative indicators are adjusted to a scale ranging from 0 to 1, while qualitative indicators are aligned to the same scale through the definition of preference relationships. For instance, for the indicator "roof maintenance condition", a qualitative judgment of "very poor" corresponds to a score of 0, a "poor" condition corresponds to 0.25, a "sufficient" condition to 0.50, a "good" condition to 0.75, and an "excellent/recently renovated" condition to 1. The same approach is followed for the indicator "construction technology of the roof slab" and "existence of a water supply system on the rooftop". The assessment of the indicators relies on in-situ measurements as well as the retrieval of information from municipal technical departments and the heritage preservation authority.

Since the various indicators hold different levels of significance, a refined weighting system has been developed based on pairwise comparison matrix [15]. The assigned weights are derived from established literature in the field of large-scale rapid visual screening assessments, empirical field assessments, and expert deliberations and can be seen in Table 2, last column. The multicriteria method thus ensures that each building is assessed on a harmonized scale, enabling decision-makers to prioritize interventions in a rational and structured manner. This process is particularly beneficial in urban planning and architectural decision-making, where multiple conflicting factors—such as cost, technical feasibility, and long-term durability—must be considered simultaneously. On this basis, buildings that obtain higher overall scores will be those with a greater readiness for green roof installations, as they demonstrate higher values in terms of feasibility and benefits. Focusing solely on the study of technical feasibility, buildings with higher results indicate greater potential for green roof implementation, as these interventions would be easier to carry out and, intuitively, more cost-effective.

### 2.4 Step 4: Selecting a Case Study and Defining Robust Intervention Strategies

The application of the selected indicators to the various buildings within the study area allows, as established in Sect. 2.3, for the definition of a priority intervention scale. This procedure is essential for a strong and sustainable planning of greening interventions at the neighborhood scale, ensuring that resources are allocated effectively. However, beyond providing a broad framework for the definition of the priority of intervention based on technical feasibility, the interpretation of the specific results for each individual building offers designers valuable support in formulating precise, robust, and context-sensitive green roof intervention strategies.

For instance, a given value of "load-bearing capacity of the roofing structure" provides the designer with a clear indication of the most suitable type of green roof for that specific building—whether it should be an intensive green roof, an extensive one, or a combined green/blue roof system [16]. Additionally, factors such as the accessibility of the roof surfaces further influence the choice for a green roof typology that requires intensive maintenance interventions over time. In this way, the proposed methodology serves a dual purpose: on one hand, it aids decision-makers in establishing intervention priorities at a large scale, and on the other, it provides architects and engineers with a flexible, data-informed tool to optimize their design choices based on both structural, technological, and typological feasibility and long-term maintenance considerations.

## 3 Case Study

The area selected for the application of the methodology introduced in Sect. 2 is located in the historic center of the city of Naples. The historic center of Naples notably lacks ample, pedestrian-accessible green areas making it an ideal case study for implementing the proposed approach. The presence of many historic public buildings with large internal courtyards, cloisters, open spaces, and roof surfaces allows for considering potential integration of various greening strategies on horizontal building components or paved surfaces. The area is situated within the Forcella district (Fig. 4) and is enclosed by Piazza Garibaldi, Via D. Cirillo/Via Carbonara/Via A. Poerio, Via Foria, Via Duomo, and Corso Umberto. This area covers approximately 400,000 $m^2$ and has an estimated built coverage of approximately 60%, with a total constructed surface of 244,600 $m^2$. The buildings selected for the application of the methodology reach a total surface area of around 50,000 $m^2$, representing 12% of the overall study zone. These buildings are typically arranged around large, open courtyards or cloisters, which, on average, account for 25% of each lot's footprint. Many of the examined public buildings exhibit considerable wear and deterioration, with some possessing noteworthy historical and architectural value, officially recognized by the Ministry of Cultural Heritage. Due to these architectural and cultural constraints, interventions on vertical façades and monumental courtyards' paving for many buildings should be excluded. Within the studied area, the buildings considered for the assessment here presented are shown in Fig. 5.

The application of the indicators to the various buildings selected in the case study area are depicted in Table 3. The values in the second-last column represent the Technical Feasibility Index, obtained by averaging the results of the individual indicators weighted according to the values shown in Table 2. The Technical Feasibility Index for the analyzed case studies ranges from 0.38 for case study ID04 – Castel Capuano to 0.68 for case study ID08 – Ex Ospedale della Pace – Lazzaretto.

Based on the obtained results—although limited to the family of indicators related to technical feasibility—a priority scale for intervention can be established. This priority scale of intervention supports a generalized definition of measures across the entire study area, ensuring substantial results in terms of adaptation to climate change. Within this framework, buildings with a higher T.F. Index should be given higher priority for intervention (corresponding to lower values in the last column of Table 3). It is important to note that due to a lack of available data, some values for Indicator "In03 – load



**Fig. 4.** The case study area of the historical center of Napoli (Picture taken from [17]).

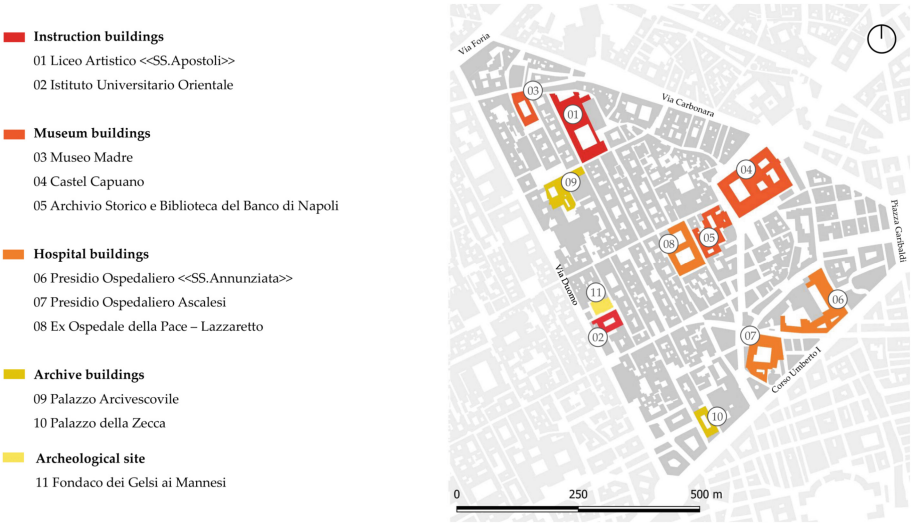


**Fig. 5.** List of the buildings studied in the area considered.

capacity" could not be determined. Consequently, a default value of 0 was assigned in these cases.

Among the various analyzed buildings, case study ID06 – Ospedale dell'Annunziata has been selected for a deeper analysis related to the design interventions, previously partially published in [12, 18, 19]. A site plan of the green roof intervention can be seen in Fig. 6. An intensive and walkable green roof has been designed on the portion of the building facing via A. Ranieri (east side). This choice is supported by the value of indicator "In08 – Accessibility" (0.67 points, resulting from an accessible surface area of the roof equal to 75%), indicator "In03 – Load Capacity" (0.85 points, based on the ratio between the design moment induced by a hypothetical intensive green roof and the resistant moment of the main current structural roof section, which is 65%),

**Table 3.** Results of the various indicators for the calculation of the index of technical feasibility

| Buil ID | In01 | In02 | In03 | In04 | In05 | In06 | In07 | In08 | In09 | In10 | T.F index | Priority |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 01 | 0.91 | 0.25 | 1 | 0 | 0.75 | 0.5 | 0 | 0.15 | 0.09 | 0 | 0.40 | 8 |
| 02 | 0.52 | 0.25 | 0* | 1 | 1 | 0.67 | 0.33 | 1 | 0.59 | 1 | 0.58 | 2 |
| 03 | 1 | 0.50 | 0* | 1 | 1 | 0.83 | 0.12 | 0.47 | 0.21 | 1 | 0.53 | 3 |
| 04 | 0.52 | 0.44 | 0* | 0.42 | 0.25 | 0.58 | 1 | 0.11 | 0.40 | 0 | 0.38 | 10 |
| 05 | 0.39 | 0.25 | 0* | 1 | 0.75 | 0.58 | 0.40 | 0 | 0.46 | 1 | 0.40 | 9 |
| 06 | 0.82 | 0.25 | 0.85 | 0.47 | 0.75 | 0 | 0.29 | 0.67 | 0 | 1 | 0.53 | 4 |
| 07 | 0.59 | 0.37 | 0* | 1 | 0.75 | 0.25 | 0.39 | 0.71 | 0.40 | 1 | 0.49 | 6 |
| 08 | 0.91 | 0.25 | 1 | 0.75 | 0.25 | 0.75 | 0.93 | 1 | 0.32 | 0 | 0.68 | 1 |
| 09 | 0 | 0.50 | 0* | 0.38 | 0.25 | 1 | 0.76 | 0.19 | 0.78 | 1 | 0.42 | 7 |
| 10 | 0.48 | 0.50 | 0* | 1 | 0.25 | 0.75 | 0.48 | 1 | 1 | 0 | 0.52 | 5 |

and indicator "In10 – Water Supply" (YES). The last substantial intervention on the roof structure dates back to the post-World War II period ("In01 – Year" is equal to 0.87 point, derived from the year of last intervention 1950) when a system of steel beams and hollow brick blocks was implemented. On the other hand, the portion of the building facing via Egiziaca features an extensive and non-walkable green roof due to the presence of sloped roof, demonstrated by the value of the indicator "In04 – Slope" (0.47 points, resulting from a value of the slope of the roof of 11° 54′ 0") and the indicator "In07 – Usable Area" (0.29 point, due to a low usable surface area of 29%).




**Fig. 6.** Green roof intervention for Ospedale dell'Annunziata (Picture taken from [12]).

## 4 Conclusions

In conclusion, this paper presents a methodological approach for the evaluation of the technical feasibility of implementing green roofs on buildings located within dense central urban areas. The primary aim was to develop a decision-support tool that can assist stakeholders—such as urban planners, architects, and public administrators—in assessing the suitability and prioritization of green roof interventions. This tool is particularly relevant in highly dense urban areas, where the availability of open and green spaces is severely limited, and strategies for enhancing urban sustainability are urgent.

To reach this goal, a set of indicators, that have been derived from a framework of both urban and building-specific parameters and design-related variables, was defined to enable the assessment and comparison of the various case studies examined using a multicriteria method. The evaluation is grounded in technical feasibility of installing green roofs. The proposed methodology has been applied to a representative central area of Naples, characterized by the presence of numerous public buildings and properties managed by large institutions, such as the curia.

At a more detailed level, the interpretation of the results of the various indicators for the individual case study supports designers in defining the most suitable design intervention solutions at the building scale.

It is particularly significant that this approach addresses the potential of underutilized rooftop surfaces of historic buildings, where conventional greening strategies on monumental facades and open spaces may be infeasible, due to cultural and urban constraints. On the contrary, the roofs, often hidden behind large and tall parapets, tend to be poorly maintained or covered exclusively with dark rubber membranes. These surfaces still represent a preferred target for intervention, opening new avenues for the ecological enhancement of heritage-sensitive areas. Whitin the various buildings that have been analyzed, the “Ex Ospedale della Pace – Lazzaretto” (ID08) emerges as the most transformable, with a technical feasibility index of 0.68. A detailed analysis of Ospedale dell’Annunziata (ID06), ranked as the fourth priority building, along with the proposed greening project, has been presented.

While the current set of indicators provides a solid foundation, further refinement is needed, particularly regarding the improvement of normalization techniques and the refinement of the weighting system. Nonetheless, any potential errors in the normalization process are distributed across the various case studies, thus preserving the overall comparability of results. This comparability is essential for establishing a clear and objective priority scale among the examined buildings. The proposed prioritization scale serves as a strategic planning tool, enabling guidance for future interventions and a more effective and targeted deployment of green roofs in urban contexts. By identifying the most technically feasible and impactful solutions, this approach contributes to a more resilient and sustainable urban environment.

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