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Rossano Albatici · Michela Dalprà ·
Maria Paola Gatti · Gianluca Maracchini ·
Simone Torresin *Editors*

Envisioning the Futures - Designing and Building for People and the Environment

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Effect of Green Roofs on External Microclimate and Runoff Mitigation: Do They Work in Historical Contexts? A Case Study in Naples

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Abstract. In cities characterised by a dense urban fabric and high population density, the lack of green spaces is a critical problem, despite their well-known environmental and social benefits. However, the creation of new green spaces for public use is often complex. This study proposes an innovative solution by creating a green roof on the internal terrace of SS. Apostoli, an art high school in the historic centre of Naples.

The analysis was carried out using a framework that integrates the parameters of technical-environmental feasibility that are related to the baseline scenario, and the design variables related to substrate and vegetation of the green roof. The design of the greening strategy was validated through urban microclimate simulations, assessing its impact on air and surface temperatures, as well as through calculations of rainwater management, evaluating its effectiveness by analysing retention times and storage capacity in response to low permeability of urban soils.

The results show a significant improvement in terms of temperature reduction and stormwater management. The chosen approach is a pioneering model that can be replicated in similar urban contexts and shows that greening strategies, if carefully planned, can integrate sustainable solutions without compromising the historical-architectural value of the buildings on which they are applied.

Keywords: Green Roof · Urban Microclimate · Historical Building · Temperature Mitigation · Runoff

1 Introduction

In the current context of rushing climate change, the unsustainable nature of the built environment has become an issue of growing urgency, requiring immediate and systematic intervention to mitigate its negative environmental, social, and economic impacts [1]. This necessitates targeted interventions on existing building stocks, not merely from the perspective of energy efficiency of buildings but through comprehensive strategies aimed at adapting cities to evolving climatic conditions. Over the past decades, climate change mitigation has largely remained an aspirational goal, failing to produce significant

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reduction effects in global warming. Consequently, the resilience to emerging climate-induced risks – most notably extreme precipitation events and heat waves – has become a critical challenge, particularly in historic urban centers characterized by high-density development and a pronounced scarcity of green and open spaces for implementing nature-based solutions.

In cities such as Naples, where the historic center is defined by a compact urban fabric, the effects of climate change are particularly pronounced. The increasing frequency of heavy rainfall events exacerbates the pressure on an already overburdened stormwater drainage system, while extreme heat events amplify the urban heat island effect [2]. These phenomena place considerable stress on buildings, particularly on non-structural elements such as building envelopes, drainage infrastructure, and HVAC systems. The lack of vegetated areas, coupled with limited available space for greening interventions, further exacerbates these challenges in dense urban contexts.

Contrary to the current scarcity of green space, the historical evolution of Naples offers valuable insights into the role of greenery in the urban environment [3]. Historically, vegetation was an integral component of city life, as exemplified by the courtyards and cloisters that once facilitated a direct relationship between built and green open spaces. The city's ancient layout, established during the Greek and Roman periods (6th and 4th centuries BC), followed a structured Hippodamian grid of *cardines* and *decumani*, shaping a network of *insulae* (urban blocks) that has persisted despite centuries of transformations. Successive layers of construction have resulted in a highly articulated urban fabric, wherein buildings are closely juxtaposed, forming a compact and dense built environment.

Due to the geometric constraints imposed by the original urban layout and the saturation of the *insulae*, expansive public green spaces were never a characteristic feature of Naples' historic center. Instead, green areas traditionally emerged as enclosed, inward-facing courtyards primarily associated with monastic and ecclesiastical complexes, providing essential microclimatic benefits within a low-rise urban morphology [4, 5]. However, with increasing population density and the progressive intensification of the built environment, vertical expansions and significant alterations to spatial configurations have led to the substantial reduction of private green spaces, diminishing their functional and environmental role [6]. The progressive urbanization and extensive paving of open spaces have further contributed to the loss of vegetation, adversely affecting environmental quality and urban resilience.

Addressing contemporary climate issues necessitates the reintegration of greenery into the historic city, prioritizing the restoration of pre-existing internal green spaces without resorting to disruptive and unsustainable modifications to the historic urban grid. In this regard, a viable strategy involves the reactivation of vegetated spaces within large institutional and public buildings in the historic center, restoring them as collective green areas that can enhance urban resilience and social well-being.

The implementation of Nature-Based Solutions (NbS) [7] within this context offers the opportunity to restore courtyards and cloisters as fundamental urban green infrastructures, recovering their original ecological functions while accommodating contemporary urban needs [8]. These interventions hold significant potential in terms of stormwater management, thermal regulation, and overall environmental comfort [9, 10]. Given the scale of historic buildings – characterized by extensive courtyards and substantial roof surfaces – targeted yet widespread greening initiatives within these structures could yield transformative effects, transcending the individual building scale to influence broader neighborhood- or city-scale resilience.

Proposed interventions – such as the installation of green roofs, the replacement of impermeable paving with permeable surfaces, and the creation of small-scale gardens – must be carefully adapted to the constraints imposed by historic preservation frameworks, particularly given the cultural and architectural significance of buildings in heritage districts. However, these interventions do not necessarily require highly technological approaches; in many cases, self-constructed, community-driven architectural strategies can offer viable, simple, and contextually appropriate solutions. A pertinent example is the Giardino per Renato project [11] at the historical Faculty of Engineering of Sapienza University in Rome, where a DIY architecture initiative successfully transformed a residual space of a secondary courtyard into a community garden, simultaneously enhancing microclimatic conditions and fostering social cohesion. Building upon these principles, the present study implements a methodological framework for the realization of greening interventions in historic urban centers. By focusing on existing buildings, the objective is to enhance their resilience and habitability in response to contemporary environmental challenges without altering the historical nature of contexts and buildings. The research outlines a set of analytical parameters for the description of the urban and environmental context and the current condition of the building suitable for green transformation, alongside a series of design variables and their ontological connections. This framework aims to facilitate the identification of the most sustainable and context-sensitive greening strategies, ensuring their effective integration within the historic built environment. The main goal of the paper is to apply the proposed holistic framework for the implementation of a green roof on a historical building in the center of the city of Naples assessing the benefits of the intervention in terms of outdoor microclimate (mitigation of temperatures) and water regulation (water retention capacity).

Although scientific literature offers several studies on the implementation of green roofs in new buildings or in urban redevelopment projects, specific research on the application of this solution to protected buildings in the historic centers of large cities is lacking. Therefore, the proposed approach represents a novel contribution to existing scientific literature.

2 Methodology

The following section describes the methodological approach adopted to achieve the aims of this manuscript and to answer the research questions by providing reliable and meaningful results that contribute to the existing scientific literature.

After defining the objectives and research questions, the monumental complex of the Santi Apostoli in Naples, currently used as a high school, was selected as a case study for applying the proposed framework for implementing green roofs on existing buildings. The considered framework is organized in several phases (preliminary, decision, design). Determining the parameters for the baseline scenario, defining the variables for the design scenario, and establishing their ontological relationships are essential steps of the decision phase for shaping the effective design proposal.

Following the design phase the approach was validated through: (i) simulations using the ENVI-MET fluid dynamics modeling software [12] to assess the mitigation of environmental factors, including potential air temperature reductions and mean radiant surface temperatures; (ii) calculations to evaluate the potential benefits for stormwater management.

2.1 Holistic Framework

The holistic framework for the implementation of green roofs [13] (Fig. 1), organised in three successive phases that are presented below, is configured as a general framework that takes into account all the necessary parameters and variables and ensures applicability in different climatic contexts and on different types of buildings.

Phase 1: Preliminary analysis.

In this first phase, the feasibility of a green roof is assessed on the basis of the historical-architectural knowledge of the building and the analysis of any regulatory or legal restrictions.

- No constraints: move on the decision phase.
- Insurmountable obstacles: the project is interrupted.
- Overcomeable obstacles: the most suitable solutions are evaluated.

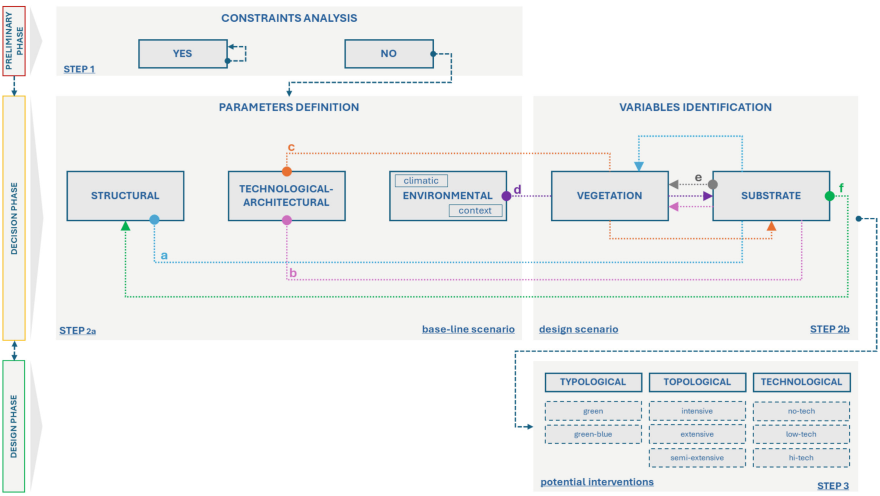

Fig. 1. Framework for green roof implementation. Source [13].

Phase 2: Decision-making.

This phase consists of defining the parameters of the reference context and identifying the key variables for the realisation of the green roof. It is divided into two sub-phases based on the baseline scenario and the design scenario:

2a) Base-line scenario. Parameters definition:

- Structural: load-bearing capacity.
- Technological: geometry and building typology.
- Environmental, subdivided into:

– climatic parameters: Precipitation, wind, temperature, solar radiation.
– context parameters: Shading elements, distance to neighbouring buildings and facilities or other interfering elements.

2b) Design scenario. Identifying variables:

- Vegetation: Selection of plant species based on local climatic conditions and the type of substrate that determines the type of green roof (also based on the load-bearing capacity of the building).
- Substrate: Determination of the type, properties and thickness in relation to the needs of the vegetation, the climate and the structural and technical constraints of the roof.

The variables identified in this phase depend strictly on the reference scenario and the associated constraints.

Fase 3: Design phase.

Once all the information has been gathered, the type of green roof that is best suited to the building in question can be determined: extensive, intensive or semi-intensive, based on the parameters and variables defined in the previous phases. At the same time, the complexity of the functional layers required for the green roof is determined, thus establishing the required technological level (hi-tech, low-tech, no-tech) [9].

2.1.1 Ontological Connection Between Parameters and Variables

The analysis of the different phases of the framework highlights a close dependence of the design variables on the parameters that define the baseline scenario. This interdependence is not accidental but reflects an ontological link between parameters and variables. Variables arise directly from the environmental, structural, and technological characteristics of the reference context, as determined by the parameters.

This relationship implies that the design variables cannot be considered as autonomous entities but are constrained by the parameters that limit the set of possible design configurations. In other words, the definition of the parameters conditions guides the design decisions and determines the available options for the realisation of the green roof.

Although the parameters exert a direct influence on the variables, their relationship is not linear but cyclical, configuring a complex system of interactions. This dynamic is illustrated graphically in Fig. 2, which shows six key relationships (lines from a to f) between parameters and variables:

- Line a (cyan): links structural parameters with substrate selection, which in turn influences vegetation selection.
- Line b (magenta): establishes a link between technical-architectural parameters and substrate and vegetation variables, considering factors such as accessibility and roof slope.

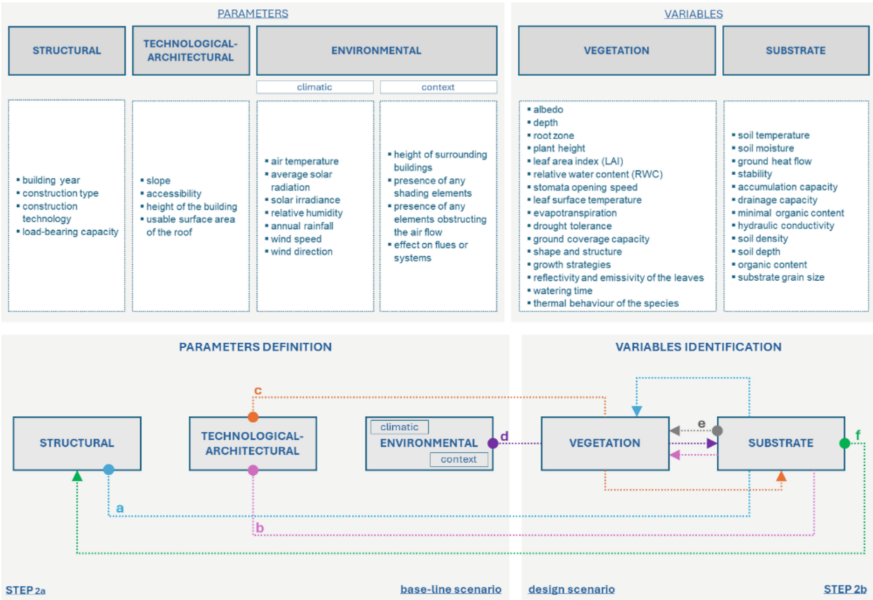

Fig. 2. Top: parameters and variables. Down: ontological interconnections between parameters and variables. Adapted from [13].

- Line c (orange): illustrates the influence of the functional configuration of the roof on the choice of vegetation and substrate (e.g. sensory gardens).
- Line d (purple): shows how environmental and climatic parameters determine the optimal vegetation and substrate characteristics.
- Lines e (grey) and f (green): represent relevant interactions for new buildings and underline the need to integrate structural, environmental and design aspects from the outset.

Furthermore, there are internal correlations at every level of the parameters. The structural aspects, for example, are interdependent: the year of construction affects the materials and building techniques used and influences the load-bearing capacity. A brick building from the 16th century will have a different structural behaviour than a modern reinforced concrete building. Similarly, the choice of vegetation depends not only on the type of substrate, but also on factors such as evapotranspiration capacity, albedo, and reflectivity. The interdependence between the parameters and variables configures a dynamic system in which each design choice influences the others. Recognising this non-linear decision logic is crucial for optimising the implementation of green roofs to ensure a balance between technical feasibility, environmental conditions, and functional objectives. Understanding this ontological relationship is crucial for the development of a holistic and rational design approach, where the selection of each variable is made according to the specific characteristics of the context in order to optimise the effectiveness of the chosen solutions and ensure the sustainability and integration of the green roof into the built environment.

2.2 Definition of the Area of Intervention

The application of the framework described above was carried out on one of the identified buildings in an area of the historic centre of Naples. The study area, bordered by Corso Umberto, Via Duomo, Via Foria, Via D. Cirillo/Via Carbonara/Via A. Poerio and Piazza Garibaldi in the Forcella neighbourhood, was selected as a test area for the implementation of greening strategies. The main objective is to remodel existing courtyards, roofs, and façades of large public buildings, to increase the number of public green spaces for pedestrians in a strategic central area in order to promote environmental and social sustainability. In fact, these measures aim to have a positive impact on urban resilience, urban health, and soil permeability.

The area in question covers approximately 400,000 m^2 and is characterized by a significant lack of green spaces. Within this area, the spatial distribution of the public buildings of significant historical-artistic value was analysed using GIS software, which facilitates the systematic collection, storage, analysis, and visualisation of spatial data. Figure 3 shows the identified buildings, classified according to their function: education, museums, hospitals, archives, archaeological sites.

The dimensional characteristics of the involved urban blocks allow for an expansion beyond intervention at the individual building scale, promoting broader scope of urban transformation. Simultaneously, their typological features – such as courtyards, cloisters, or large roofs – enhance their transformability and feasibility for intervention. In line with the objectives of this study, the proposed framework is implemented on the case study of the monumental complex of SS. Apostoli, which currently houses the Liceo Artistico dei SS. Apostoli (ID 01 in Fig. 3).

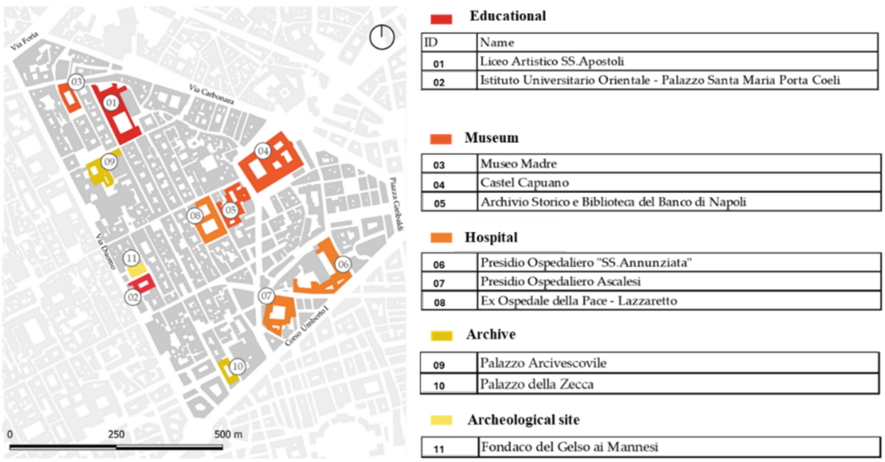

Fig. 3. Identification of public buildings of historical-architectural interest.

3 Case Study

The monumental complex of the SS. Apostoli, located in the north-eastern part of the Greco-Roman center of Naples, dates back to the middle of the 5th century AD when the church, on the ancient site of a temple, was erected. This historic site is characterised by an architecture that reflects the various layers and transformations that have taken place over the centuries, culminating in a configuration that expresses the Neapolitan Baroque taste [14]. The building was originally designed by Francesco Grimaldi in 1610. In the course of its history, the complex was severely damaged by the earthquake of 1688 but repaired in a short time. In 1809, during the reign of Gioacchino Murat, the convent was dissolved, and the building was used for various purposes, including as a notary's chamber and later as barracks for the "Real Napoli" regiment. In 1860, it became the site of a tobacco factory, but after more than a century, the factory was moved to another location in 1972, leaving the building to fall into disrepair. Thanks to the intervention of the Dean of the Academy of Fine Arts Architect Mario Rispoli the complex was

Fig. 4. Photos of the internal courtyard: (a) terrace taken from the southern side; (b) terrace taken from the northern side; (c) garden taken from the southern side; (d) garden – lower left corner; (e) garden – lower right corner.

assigned to the Liceo Artistico Statale of Napoli in 1976. Rispoli played a decisive role in the restoration of the building, the first significant intervention in the historic centre of Naples to preserve and enhance its historical and cultural heritage.

The building is organized around a cloister structured on two levels (Fig. 4). The rectangular courtyard is articulated through a sequence of arcades, marked by Tuscan pilasters on the ground floor and Doric ones on the first level, as originally designed by Francesco Grimaldi. The cloister, with its rectangular layout, is divided into two distinct sections. The southern portion, which is lower in elevation, directly opens onto the entrance from Largo Santi Apostoli and is designed as a green garden with trees.

The northern portion features a terracotta-paved terrace on the first floor supported by a vaulted structure, housing a gymnasium and a parking area, where several skylights provide natural illumination. These two areas exhibit contrasting climatic conditions. However, due to the considerable height of the surrounding building wings, both spaces remain partially shaded, particularly in the afternoon. The lower garden plays a crucial role in providing a cooling effect, especially during summer, enhancing not only the comfort of both the outdoor space itself and the internal areas – as classrooms or corridors – facing the courtyard. In contrast, the elevated terrace is fully exposed to solar radiation during peak summer hours, leading to significantly high temperatures both on its surface and within the adjoining spaces, such as the long-glazed corridor on the first floor. The proposed greening intervention involves the installation of an extensive and intensive green roof on the first-floor terrace. This solution aims to enhance the usability of such an important external space, particularly during periods of intense solar exposure and high temperatures. Additionally, it seeks to mitigate stormwater runoff by reducing the volume of rainwater to be managed, thus alleviating the load on the existing drainage system during heavy rainfall events.

3.1 Applying the Framework to the Case Study

With the goal of defining a proper green roof intervention, the framework introduced in Sect. 2.1 is applied to the horizontal terrace of the internal courtyard of the SS. Apostoli building.

Tables 1 and 2 present the parameter values identified for the case study, addressing technical and environmental feasibility, respectively. The proposed approach follows a phased structure, strategically integrating the relationships between contextual and building parameters and design variables. By analysing the determined parameter values, a coherent set of design variables can be established, ensuring a robust foundation for the subsequent design phase.

The terrace, like the entire building after the last strong reconstruction, dates back to 1860. However, due to recent maintenance interventions, it is currently in a medium state of conservation. The construction technology is based on a vaulted structural system. Approximately 95% of the terrace surface is accessible and usable. The terrace is situated at a height of 7 m and has a slight slope ranging between 2% and 3%.

These characteristics support the selection of an intensive green roof, which necessitates accessibility for maintenance and benefits from the terrace's low slope. However, certain constraints must be considered, including limited direct sunlight – approximately

80% of the perimeter of the terrace is surmounted by obstacles – and structural limitations, which permit additional loads up to 0.65 MPa only in vertical correspondence to the piers of the lower vaulted system. Nevertheless, the shading constraint is mitigated by the terrace's open southern side, allowing significant direct sunlight during the fall, spring, and summer months. From a structural perspective, the bearing capacity of areas not directly supported by the piers must be carefully considered in the design phase.

Further constraints arise from urban planning and heritage protection regulations. As the building is designated as a listed heritage site, any intervention must respect its historical and architectural integrity. Consequently, only reversible, minimally invasive solutions with limited functional and aesthetic impact can be considered.

Based on the parameters outlined in Tables 1 and 2, along with the aforementioned considerations, Tables 3 and 4 detail the vegetation and substrate variables for intensive and extensive green roof systems, respectively. The proposed intervention incorporates both intensive and extensive green roof solutions across the terrace. As illustrated in Fig. 5, the intensive green roofs are strategically positioned in vertical alignment with the piers of the vaulted system at the lower floor while the lighter extensive green roofs are

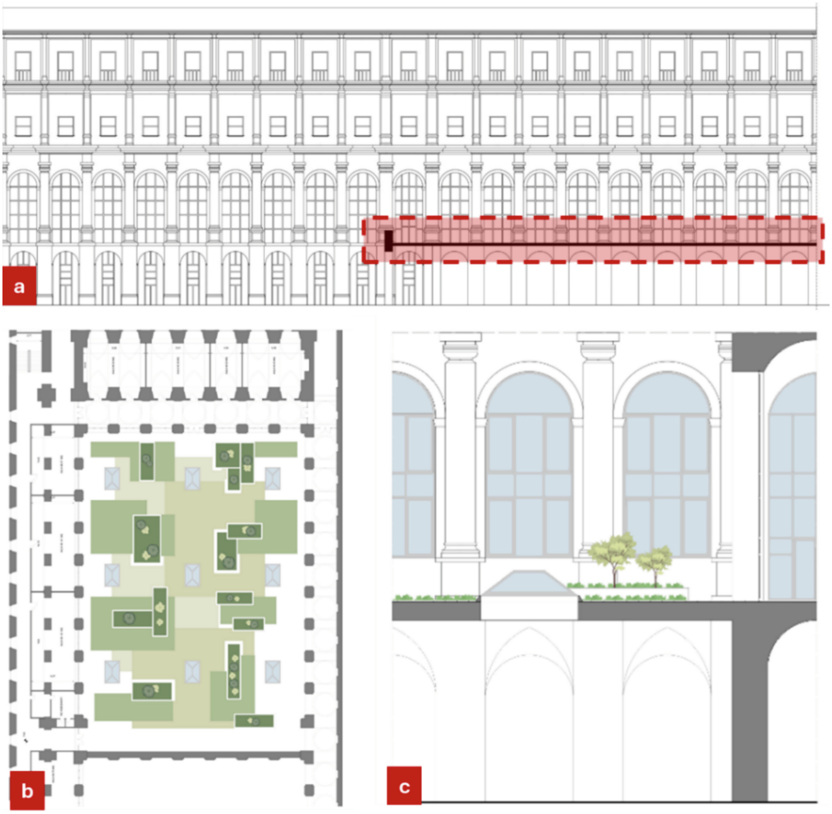

Fig. 5. a) base-line scenario section and highlighting of the terrace; b) Design of the green roof on the terrace; c) Design section.

placed directly above the vaults. This configuration is dictated by structural constraints: the piers, with their higher load-bearing capacity can accommodate the increased weight of intensive green roofs, which require a substrate depth of 30 cm. Conversely, the structural limitations of the vaults restrict the extensive green roof system to a maximum substrate thickness of 6 cm.

To comply with cultural heritage constraints, the green roof intervention may involve the creation of wooden boxes with a small steel structure for soil containment and plant growth. These structures are designed to be easily constructed and assembled, allowing the direct involvement of the school's students through an eventual DIY architecture process.

Table 1. Parameters for technical feasibility of green roof.

Technical feasibility		
Structural - construction parameters		
Construction year	1860	[year]
Construction technology	vault	[-]
Pier resistant capacity	0,65	[MPa]
Technological - architectural parameters		
Slope	2–3	[%]
State of conservation	medium	[-]
Terrace height	7	[m]
Usable surface	95	[%]
Accessibility	95	[%]
Water users	No	[Yes/No]
Urban planning and regulatory parameters		
Regulation	Yes	[Yes/No]

Table 2. Parameters for environmental feasibility of green roof.

Environmental feasibility		
Climate parameters		
Average air temperature	25,7	°C
Average solar irradiance	298,7	W/m^2
Relative humidity	56,4	%
Annual precipitation	1005	mm/year
Wind speed	1,78	m/s
Wind direction	N	[N,S,O,E]
Context parameters		
Presence of shading objects	80	%
Presence of chimneys	No	[Yes/No]

Table 3. Vegetation variables for intensive and extensive green roof.

Design variables - vegetation				
	EXTENSIVE		INTENSIVE	UNIT
Number of essences	2		1	[n°]
Type of essence	Myrtle	Little lime	Sedum	[-]
Height of plants	1	1,5	0,15	[m]
Shape and structure of plants	Compact and ornamental shrub	Erect and branched	Low and compact	[-]
Plant growth time	2–3	1–2	1–2	[years]
Leaf Area Index	1,5–3	2–4	2–4	[LAI]
Leaf surface temperature	30–45	30–45	30–45	[°C]
Stomata opening speed	20 –40	20–40	5–15	[µmol $CO_2/m^2/s$)]
Evapotranspiration	2–4	2–6	0,5–2	[mm/day]
Drought tolerance	3–4	1–2	3–4	[weeks]
Reflectivity	0,20	0,40	0,35	[-]
Emissivity of leaves	0,90	0,96	0,95	[-]
Soil coverage capacity	60 -80	40–60	80–100	[%]
New Albedo	85	85	50	[SRI]
Watering time	15	15	7	[min/day]
Thermal behavior of species	{min -5 °C; max 40 °C}	{min 0 °C; max 38 °C}	{min -10 °C; max 40 °C}	[°C]
Root zone	0,3	0,3	0,05	[m]
Vegetative maintenance cycles	Medium	Medium	Low	[-]

Table 4. Substrate variables for intensive and extensive green roof.

Design Variables - Substrate				
	INTENSIVE		ESTENSIVE	
Substrate Thickness	0,3	[m]	0,06	[m]
Substrate Mix Design	50;30;20	%	50;30;20	%
Root zone	0,3	0,3	0,05	[m]

(*continued*)

Table 4. (*continued*)

Design Variables - Substrate				
	INTENSIVE		ESTENSIVE	
Vegetative maintenance cycles	Medium	Low	[-]	
Substrate temperature	10–35	[°C]	15–40	[°C]
Substrate humidity	20–60	[%]	10–40	[%]
Heat flow in the substrate	0,3–1,5	[W/m^2]	0,2 - 1	[W/m^2]
Stability	moderate	[-]	high	[-]
Storage capacity	40	[l/m^2]	20	[l/m^2]
Drainage capacity	0,05–0,2	[l/s/m2]	0,05–0,1	[l/s/m^2]
Minimum organic content	10–20	[%]	5–10	[%]
Hydraulic conductivity	1–5	[mm/min]	1–10	[mm/min]
Substrate density	1,100–1500	[Kg/m^3]	900–1300	[Kg/m^3]
Irrigation system	No	[Yes/No]	No	[Yes/No]

3.2 Applying the Framework to the Case Study

After applying the framework, the entire building and part of the surrounding area were modelled using Envi-Met software, starting from a map (bmp file). After modelling the baseline scenario (Fig. 6) and the project design (Fig. 7), the simulations were started by inserting the climate data and some input data, which are listed in Table 5.

After creating the models and entering all the necessary climate data, the simulation was started to obtain the output data for both the current model and the proposed design model. From the large amount of climate data generated by the simulations, two specific indicators were extracted using the ENVI-Met plug-in "Leonardo", which were considered particularly relevant for the validation of the proposed environmental measures. These indicators are potential air temperature and mean radiant surface temperature.

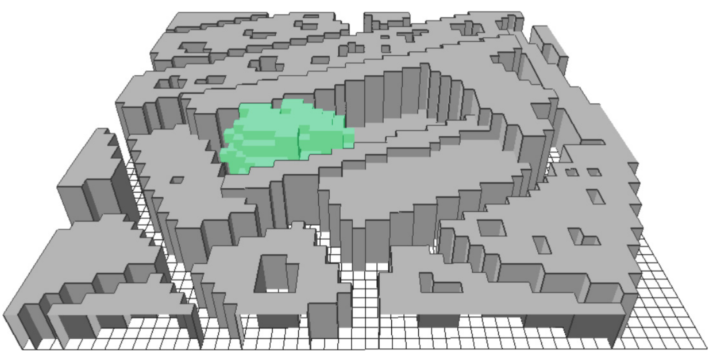

Fig. 6. Envimet model related to base-line scenario.

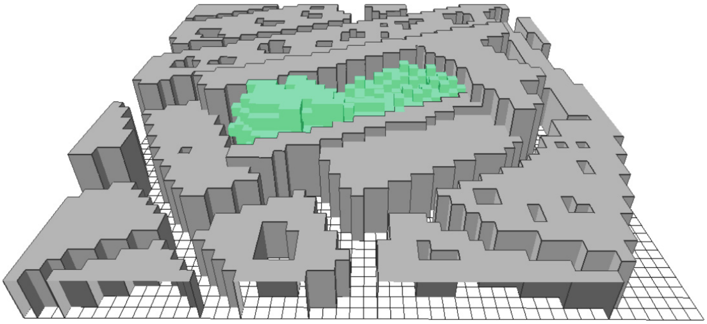

Fig. 7. Envimet model related to design scenario.

Table 5. Input data in Envi-met software simulation.

Data	Description	Values
Date and Time	Start data Start time Simulation time	26 July 2024 14:00 1 h
Meteorological data	Initial temperature Average temperature Temperature range Specific humidity	26 °C 30 °C 24 °C–36 °C 8.00 g/kg

For the baseline scenario, the case study was modelled considering the building's morphological and material characteristics in its current state. As for the outdoor areas, the courtyard was modelled by including vegetated areas with lawn and existing trees, mainly conifers, reflecting the current conditions.

In the project scenario, a greening strategy for the terrace was implemented, based on the modelling of the current state. In particular, a mixed substrate (silty-loamy) without an air gap was chosen, as the main objective of the intervention is to create a healthy and favourable environment from a microclimatic point of view. This choice makes it possible to maintain an optimal moisture content of the substrate, which favours evaporative cooling and contributes to lowering outside air temperatures. In other words, the substrate absorbs a greater amount of heat and, through the process of evaporation of the vegetation, facilitates the dissipation of heat, resulting in a more effective solution for mitigating the urban microclimate.

As far as the plant component is concerned, the entire surface of the green roof was covered with a 25 cm layer of grass. In the areas with intensive plant growth, thicker substrates and the planting of hedges and small shrubs were provided. In order to ensure adequate shading, the planting of trees with a moderate root system was also planned in order to avoid interfering with the building structures. The chosen species is the "Little Leaf Lime Rancho", a medium-sized essence chosen for its adaptability to the conditions of the environment.

3.2.1 Base-Line Scenario Results

The potential air temperature within the simulation area under consideration fluctuates between a minimum of 25.12 °C and a maximum of 26.50 °C. In particular, in the area of interest for this study (marked by the red box in Fig. 8), the potential air temperature measured on the terrace is between 25.81 °C and 26.50 °C, indicating a prevalence of high thermal conditions. This is also confirmed by the colour distribution of the map, which shows a prevalence of reddish tones compared to blue.

As far as the main radiation temperatures of the surfaces are concerned, the values vary between a minimum of 24.56 °C and a maximum of 74.36 °C in the entire simulation area under consideration. On the terrace in particular (marked by the red box in Fig. 9), the average radiation temperatures fluctuate in the same interval between 24.56 °C and 74.36 °C. The distribution of these temperatures is almost balanced, as shown by the red box in Fig. 9. Their distribution is almost balanced, as the colour representation shows, in which the shades tending towards red and light blue appear to be evenly distributed.

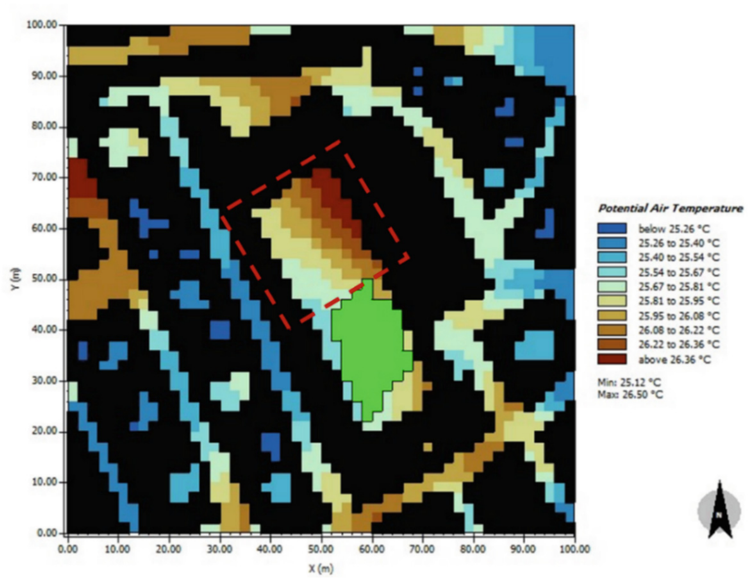

Fig. 8. Potential Air Temperature related to base-line scenario.

3.2.2 Design Scenario Results

The simulations in connection with the project scenario, which include the application of the greening strategies described above, show considerable advantages regarding the microclimate.

Particularly concerning the potential air temperature, the improvement on the terrace can be clearly seen in the colour comparison between Fig. 8 and Fig. 10. In quantitative

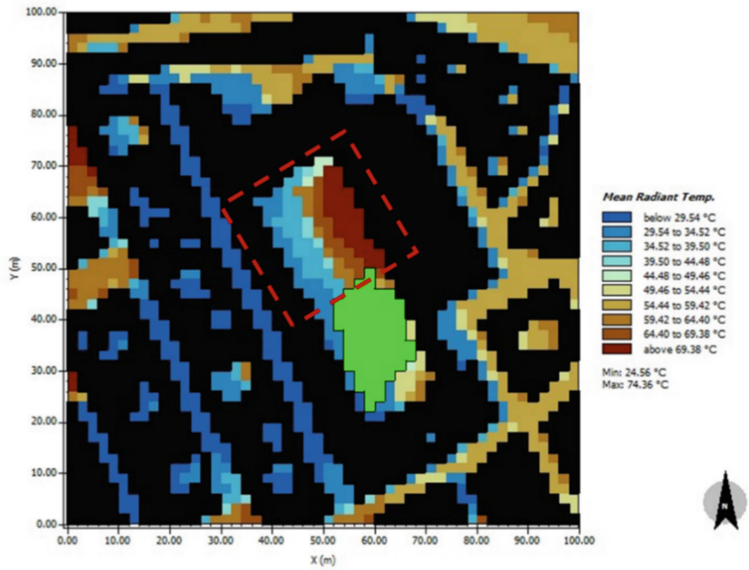

Fig. 9. Mean Radiant Temperature related to base-line scenario.

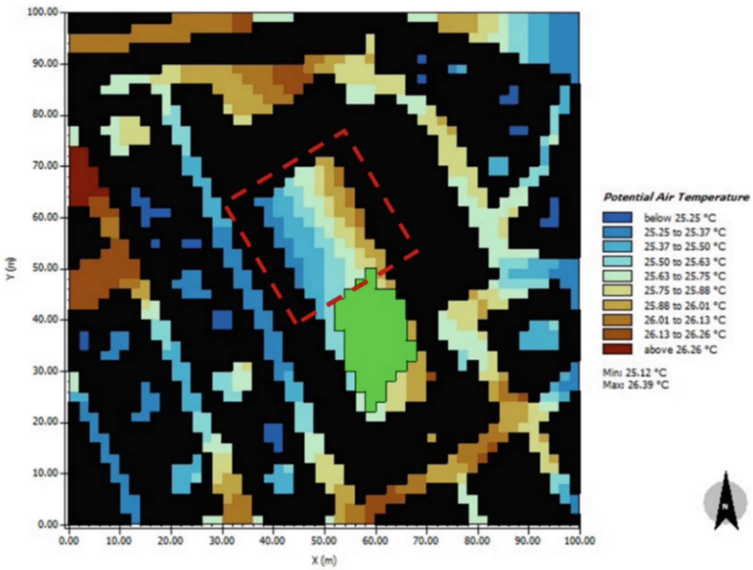

Fig. 10. Potential Air Temperature related to design scenario.

terms, the application of the greening strategies in the project scenario leads to a fluctuation in the potential air temperature between 26.01 °C and 25.12 °C in the terrace area (characterised by the red box in Fig. 10).

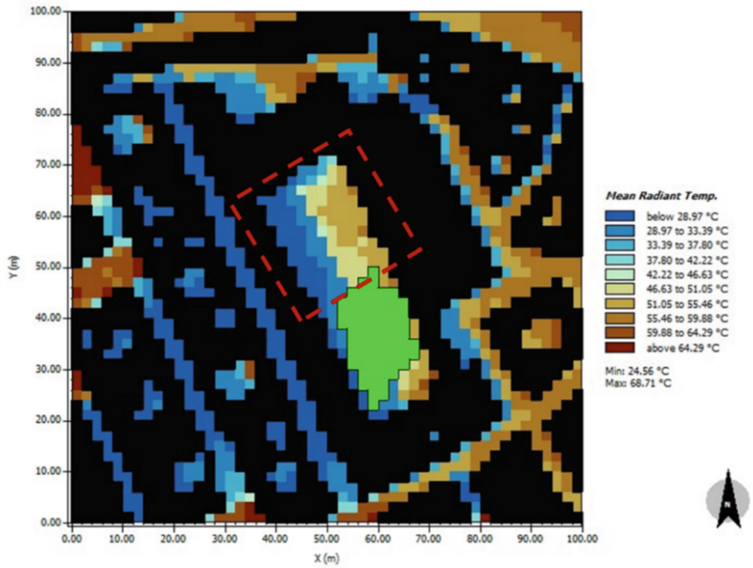

Fig. 11. Mean Radiant Temperature related to design scenario.

Similarly, the effect of the greening strategies can also be seen in the average radiant temperatures of the surfaces, whose values on the terrace lie between 55.46 °C and 24.56 °C (Fig. 11).

3.3 Hydrological Analysis

In addition to the positive effects of greening linked to the fight against urban heat islands, green roofs are important tools for stormwater management. This effect is due to the presence of the substrate necessary for support and obtaining water and nutrients for the plants [15]. The effect occurs through the natural infiltration process of the soil, when rainwater infiltrates the substrate of the green roof it ends up being retained instead of being discharged into the drainage system, helping to avoid overloading the system in cases of heavy rain.

To measure the effect, it is necessary to calculate the rainwater volume will infiltrate these green structures, but also how long it will be retained. Retention time is important because after the water passes through the layers of the green roof, it also needs to be discharged into the drainage system, and thus it is possible to know the water discharge in the system as a function of time.

To calculate the effects of stormwater management, the rain of 17/09/24 in Naples was chosen to represent a real example. The rain had a total precipitation of 22.9 mm [16], and the average intensity of 30 mm/h was chosen because, according to the World Meteorological Organization [17], it represents high intensity rain. These parameters are consistent with the intensity and characteristics of that period's rains in Naples and result in a rain lasting 45.8 min.

The terrace of SS. Apostoli has a total area of 1576.9 m^2 of which 157 m^2 will be composed of intensive roofs and 335 m^2 extensive with depths of 30 and 6 cm, respectively. The chosen rainfall generated a discharge of 788.45 L/min in the area, which was immediately directed to the drainage system, however, with the intervention of these green roofs, the same rainfall would represent a lower discharge in the drainage system. This intervention would result in a capture of 246 L/min in this case, determining a substantial reduction in the discharged water. As previously stated, it is also important to consider the retention time because once this time is reached the water will be discharged back into the building's drainage system. To obtain this value in this case, it is necessary to know the hydraulic conductivity (1–5 and 1–10 mm/min for intensive and extensive green roof respectively) and thus know the time for the water to cross the soil of the green roofs.

4 Discussing the Benefits

The application of greening strategies on the terrace in the inner courtyard of the historic school building shows a significant improvement in microclimatic conditions. The comparison between the baseline scenario and the design scenario shows clear benefits, both in terms of air temperature and surface radiation temperature, which contribute to overall thermal comfort and environmental sustainability.

The baseline scenario shows that the thermal conditions on the terrace are high, with possible air temperatures between 25.81 °C and 26.50 °C. Surface radiation temperatures also show extreme variations, ranging from 24.56 °C to 74.36 °C, with a relatively even distribution between warm and cold surfaces.

In contrast, the greening strategies implemented in the design scenario lead to a significant improvement in temperature regulation. The potential air temperature in the terrace area is reduced to a range between 25.12 °C and 26.01 °C, which indicates a general cooling effect. In addition, the radiant temperatures on the surface drop considerably, from 24.56 °C and 55.46 °C.

The observed temperature gradients between the baseline and design scenarios emphasise the effectiveness of the greening measures (Fig. 12 and Fig. 13). The reduction in air and surface temperatures contributes to an improved thermal environment, which is particularly beneficial in urban areas with high population density, where heat build-up can lead to discomfort and increased cooling energy demand. Reducing peak surface temperatures by almost 19 °C and potential air temperatures by around 0.5 °C not only improves outdoor comfort, but also indirectly reduces the need for cooling inside the building, thereby promoting the building's energy efficiency.

These results suggest that vegetation acts as a natural cooling agent by providing shade and improving evapotranspiration, thus mitigating the urban heat island (UHI) effect in the courtyard.

Indeed, trees contribute to the reduction of surface overheating by creating shaded areas and limiting the absorption of direct solar radiation. Moreover, in combination with the green roof substrate, they increase the specific humidity (as can be seen in Fig. 14), which favours evapotranspiration and cooling, thus lowering the potential air temperature.

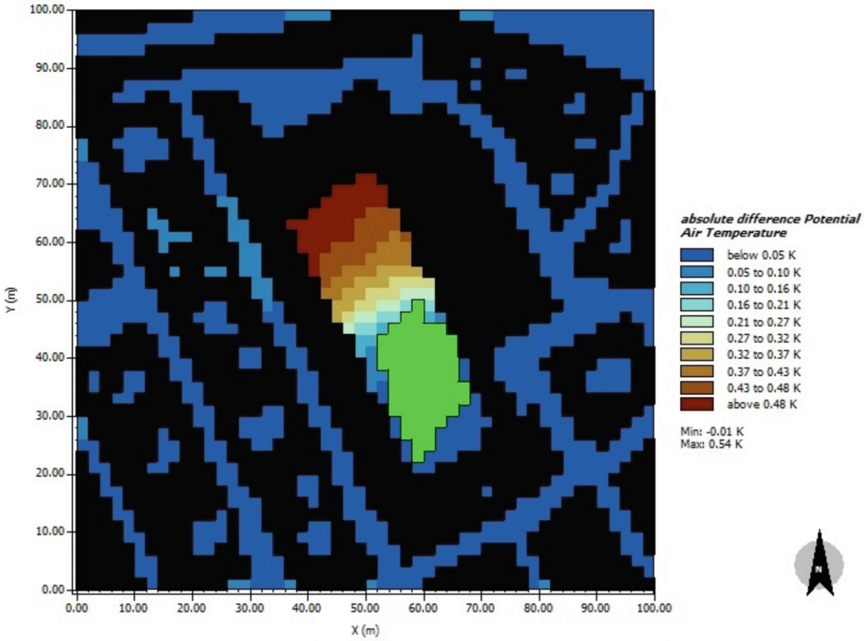

Fig. 12. Absolute difference Potential Air Temperature.

The proposed greening measure for an existing building, and in particular for a terrace located in an enclosed courtyard bounded by high walls, may have some limitations in terms of its effectiveness due to two main factors:

- Restricted air circulation: the enclosed configuration of the patio can hinder natural ventilation and reduce the ability of the wind to disperse the trapped hot air [18], which has less impact on mitigating the heat island effect compared to a more open area.
- Impact of shading: The presence of enclosing walls could limit the total solar radiation on the cloister and thus reduce the contribution of shading to regulating the temperature of the surrounding air.

Despite these potential limitations, the simulation results confirm the effectiveness of the intervention in lowering temperatures. In particular, the 0.5 °C reduction in air temperature observed is consistent with the data from recent ENEA studies [19], which show that the implementation of green roofs and walls over a total area of 6,000 m^2 can cause a drop in outdoor temperatures of around 0.5 °C during the summer season. In addition, these studies show that these solutions can reduce indoor temperatures by up to 3 °C thanks to the combined effect of shading and increased evapotranspiration [19].

To measure the hydraulic benefit of installing green roofs first it was necessary to check the drainage capacity to understand if the soil would be able to absorb all the water that fell on it. Both terrains have an infiltration rate of at least 0.05 l/s/m^2 (Table 4), which results in a minimum drainage capacity of 180 mm/h, sufficient absorption to support

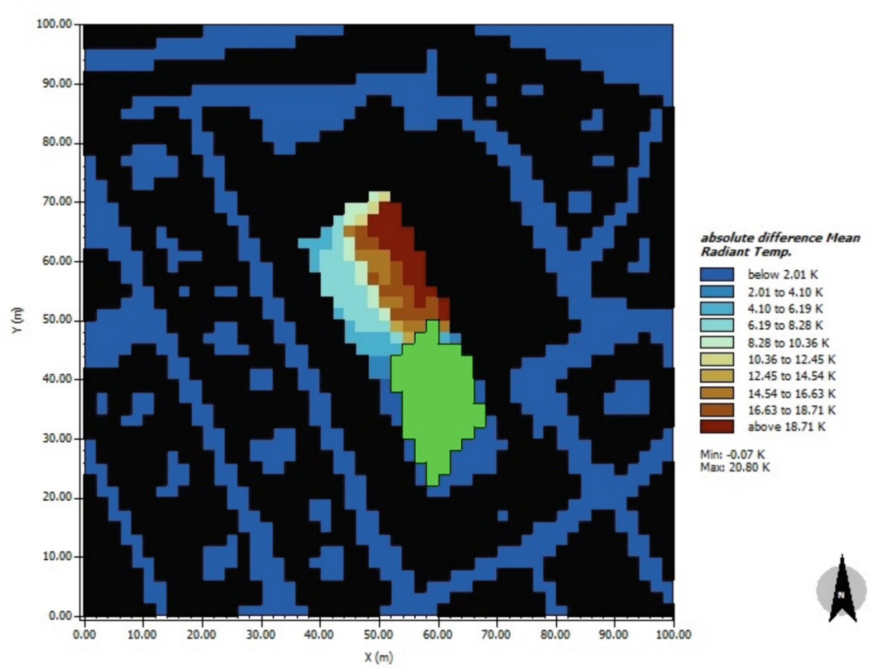

Fig. 13. Absolute difference Mean Radiant Temperature.

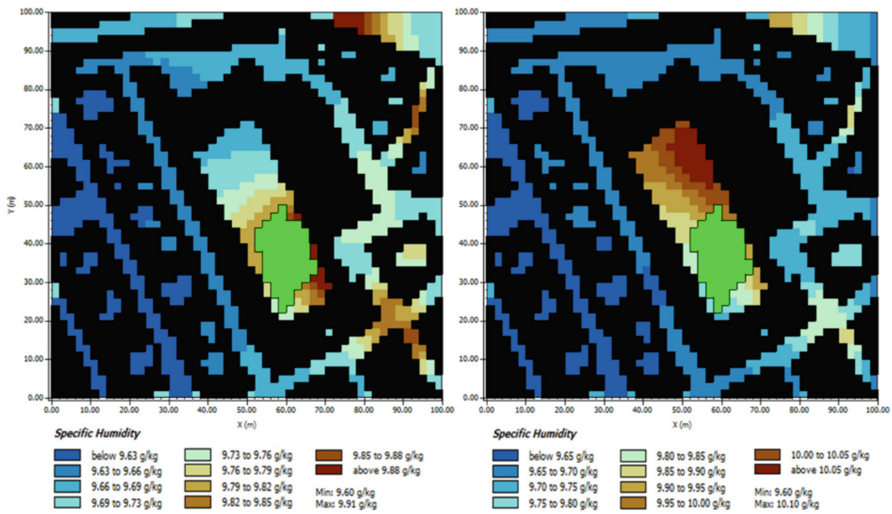

Fig. 14. Specific humidity. Left: base-line scenario; right: design scenario.

the intensity of 30mm/h of rain in green areas. Therefore, the discharge if the green structure were designed would be equal to 542.45 L/min, a reduction of 31.20% since all the water that rained on the terrace would be infiltrated (Table 6).

However, it is necessary to know when this water will pass through the green roof structure. With hydraulic conductivity equal to 3 mm/min (Table 4), intensive roofs would begin to discharge the water infiltrated into them after 1 h 40 min, while extensive roofs would begin to discharge the water infiltrated into them after 20 min. Therefore, after 20 min the water that infiltrates the extensive roofs will be discharged into the drainage system, increasing from 542.45 L/min to 709.95, which still represents a reduction of 9.96% compared to the case without green roof (Table 6).

Table 6. Discharge into the drainage system.

	Without green roof	With green roof	Reduction [%]
Rain Discharge [L/min]	788.45	542.45	31.20
Rain Discharge [L/min] after 20 min	788.45	709.95	9.96

In addition to the direct thermal and hydraulic benefits, terrace greening also offers considerable social and ecological advantages. Transforming a previously heat-stressed area into a cooler, more inviting space encourages community interaction, recreation, and outdoor learning opportunities for students. This is in line with contemporary urban design principles that encourage multifunctional green spaces to improve wellbeing and social cohesion.

Furthermore, greening promotes biodiversity by creating new habitats for birds, insects, and other urban wildlife. The integration of green infrastructure into a historic school building is an educational tool that raises students' awareness of climate adaptation and sustainability. Furthermore, to respect cultural heritage constraints, the proposed green roof structures should be designed for ease of assembly, removability, and simplicity in construction, thereby allowing direct student participation in the building process. In this regard, DIY construction workshops can be organized to promote practical engagement. In addition, the presence of greenery can have positive psychological effects by reducing stress and improving cognitive function, which is particularly important in an educational environment. The aforementioned benefits confirm the suitability of the proposed design solution for the case study.

5 Conclusions

This study has shown the potential of greening strategies in the dense urban fabric of historic cities. The case of Naples serves as just one example of many large historic cities with a compact, high-density structure. The implementation of greening solutions on existing buildings is not a paradox: as shown, through a careful preliminary analysis, including the assessment of technical feasibility, it is possible to preserve the structural integrity of the building, its history and its architectural features, while adding value in the fight against climate change.

The design of a green roof on the terrace of the complex of SS. Apostoli showed positive effects on the external microclimate, helping to moderate air and surface temperatures and creating a more liveable environment. In addition, water retention analyses confirmed the role of green roofs in the sustainable management of rainwater.

In addition to these environmental benefits, the intervention created new spaces for socialising and recreation, providing opportunities for outdoor lessons during school hours and social activities for students and teachers.

Although the proposed solution aimed to improve the external microclimate and create new recreational spaces, the green roof also provides indirect benefits to the building's internal microclimate. It helps enhance thermal insulation, regulate indoor humidity through the substrate and plants that retain rainwater, and protect the roof from atmospheric agents, extending its lifespan.

The case study presented here represents a pioneering model for the greening of a compact historic centre such as that of Naples and offers a methodology with a high replicability, although it requires a thorough preliminary assessment, especially of the structural parameters that will influence the design variables. By applying the proposed approach, it is possible to assess the feasibility of the interventions while ensuring the protection of the architectural and historical heritage. However, the role of maintenance and costs remain critical factors to be investigated in the future continuation of research. Moreover, this study can provide guidelines for the application of green roofs in historic centers and protected areas, promoting innovative and replicable solutions in other historic cities with similar construction characteristics. At the same time, this approach can influence urban policies, encouraging incentives for the adoption of green infrastructure, as already happens in other European cities.

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