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HERITAGE MANAGEMENT

- Book of Papers -

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(11th REHABEND Congress)

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PERMANENT SECRETARIAT:

UNIVERSITY OF CANTABRIA

Civil Engineering School

Department of Structural Engineering and Mechanics

Avenue Los Castros 44, 39005 SANTANDER (SPAIN)

Tel: +34 942 201 761 (43)

Fax: +34 942 201 747

E-mail: rehabend@unican.es

www.rehabend.unican.es

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EDITORS:

IGNACIO LOMBILLO
HAYDEE BLANCO
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BUILDING FACADES FOR CLIMATE ADAPTATION. AN EXPERIMENTAL INTEGRATED METHOD FOR INDOOR AND OUTDOOR EVALUATIONS OF ENERGY BUILDING ENVELOPE RETROFITTING

Iommi, Matteo¹; Figliola, Angelo²; Viviani, Nazzareno³; Losco, Giuseppe⁴

1: School of Architecture of Ascoli Piceno.
University of Camerino.

e-mail: matteo.iommi@unicam.it, web: <https://saad.unicam.it/>

2: Department Planning Design Technology of Architecture.
University of Sapienza of Rome.

e-mail: angelo.figliola@uniroma1.it, web: <https://www.architettura.uniroma1.it/>

3: School of Architecture of Ascoli Piceno.
University of Camerino.

e-mail: nazzareno.viviani@unicam.it, web: <https://saad.unicam.it/>

4: School of Architecture of Ascoli Piceno.
University of Camerino.

e-mail: giuseppe.losco@unicam.it, web: <https://saad.unicam.it/>

ABSTRACT

The urgent need for cities and urban areas to increase climate adaptation efforts, requires new approaches and more integrated strategies. To address the Climate Change (CC), the energy retrofitting of buildings needs to be more aware of the correlations among outdoor and indoor. The buildings and the building envelopes play a double role, influencing the energy consumption, the greenhouse gas emissions, and the thermal outdoor conditions. The energy retrofitting of existing buildings is still an essential element of climate adaptation. Evaluating building envelope retrofit solutions at the same time in relation to indoor and outdoor effects will be increasingly important in near future. This study proposes a novel methodology for building envelope retrofitting, integrating evaluations for both indoor and outdoor with the aim to highlight the relationships between building performances and outdoor microclimate. The proposed method is based on a cohesive sequence of activities, analysis and simulations, focused in particular on opaque facades. It starts from the definition of a reference scenario, as current status, including architectural and technological inquiry, climate data and a common 3D model. A set of energy metrics is selected: Universal Thermal Comfort Index (UTCI) and Mean Radiant Temperature (MRT) about outdoor and CO₂ emissions and Overall Heating Transfer Coefficient (H'T) about indoor. Simulations for each metric are performed and replied for the intervention scenarios, using energy parametric design tools.

As an applicative case study, an urban residential block, in San Benedetto del Tronto, a coastal city in central Italy is chosen.. Two non-invasive intervention scenarios on opaque facades have been tested. By means of the methodology application, comparisons of different interventions can be directly evaluated in relation to their effects on indoor and outdoor. Results side by side from analysis and simulations on outdoor microclimate and indoor energy performances can support the decision process, improving energy and environmental outcomes and impacts by building envelope retrofitting. The application of the methodology by the case study show its usefulness, facilitating the identification of differences, strengths, or opposing effects among the intervention scenarios.

KEYWORDS: Energy efficiency; Building envelope; Outdoor comfort; Energy building design tools.

1. INTRODUCTION

The worsening climate crisis makes the development of innovative architectural and environmental adaptation strategies increasingly urgent, particularly in Mediterranean urban contexts, which are experiencing high levels of overheating, frequent heatwaves, and a pronounced urban heat island effect [1]. The typical morphological characteristics of these areas, such as high building density, limited vegetation, and widespread use of high thermal inertia materials contribute to the deterioration of the urban microclimate and negative public health outcomes [2] [3]. At the same time, indoor environments are facing increasing thermal discomfort and rising cooling energy demand, exacerbated by the inefficiency of the existing building stock. Current research highlights the importance of integrated strategies, in which the building envelope design needs to be more informed about the contributions on outdoor comfort [4]. The adoption of new building envelopes represents a key lever for enhancing the energy and environmental performance of buildings and outdoor spaces [5] [6]. From an energy perspective, these solutions significantly reduce thermal losses and cooling demand, thus contributing to CO₂ emissions reduction. In addition, they improve indoor thermal-hygrometric comfort and can help mitigate the urban heat island effect through the use of innovative materials, ventilated systems, or vegetated cladding. Beyond the environmental and energy benefits, façade retrofitting also positively impacts urban aesthetics, property value, and structural durability, reducing the need for future maintenance interventions. A distinctive feature of this research is the analysis of the thermal behaviour of building envelopes, conceptualizing façades as dynamic interfaces between indoor and outdoor environments, capable of influencing outdoor thermal exchanges and affecting indoor energy demand at the same time. Although several urban-scale solutions have already been proposed—such as NZEB buildings, positive energy districts, smart technologies, and nature-based solutions—the specific role of building envelopes has often been overlooked or limited to highly invasive interventions. This research instead proposes a “soft” and non-invasive approach aimed at quantifying the climatic and energy effects of lightweight technological solutions. The objective is twofold: to address environmental challenges through operational and replicable tools, and to contribute to the implementation of European directives, particularly EPBD IV, which promotes zero-emission buildings (ZEmB) and a progressive decarbonisation of the building sector.

2. AIMS AND OBJECTIVES

The main objective of the following activities is to outline a method for the analysis and evaluation of building envelopes, aimed at supporting climate change mitigation and adaptation through integrated environmental and architectural retrofit solutions. Building envelopes are conceived as interface elements that influence both the environmental behaviour of outdoor spaces and the energy performance of buildings. The proposed method relies on specific tools and resources, including environmental data acquisition and parametric energy simulation models. In particular, the specific targets of the research include: providing simulations and results related to both outdoor and indoor energy behaviour; delivering simulations of retrofit scenarios for building envelopes, to support informed evaluations on both indoor and outdoor effects and make comparisons; validating the application of the proposed methodology.

3. METHODOLOGICAL FRAMEWORK FOR ADAPTIVE CLIMATE BUILDING ENVELOPE DESIGN

In order to develop a replicable approach to energy assessment and design in urban contexts, a structured and cyclical methodological framework has been defined, capable of addressing the complexity arising from the interaction between different disciplinary domains. The methodology is articulated in sequential phases, starting from the climatic and energy analysis of the current state and leading to the simulation and evaluation of alternative design scenarios, with a foundational principle of comparative assessment between solutions. The first phase involves the construction of a reference

scenario through: high-fidelity three-dimensional digital modeling of the urban fabric at the current status, obtained via satellite map extraction and manual refinement; the development of a validated climatic “Typical Year” based on historical datasets and in-situ measurements; material-performance surveys of the built environment aimed at identifying homogeneous building typologies through clustering techniques; microclimatic and energy simulations, both indoor and outdoor. Outdoor evaluations are based on climatic and morphological indicators such as UTCI and MRT, while indoor assessments focus on metrics such as CO₂ emissions and H'T, the global heat transfer coefficient. The simulation results are presented as thematic maps, graphical representations, and tables to integrate indoor/outdoor analyses and support informed decision-making processes. Data outputs are converted into formats compatible with decision support systems (DSS). The cyclical structure of the method allows the iterative application of the process to each alternative design scenario, enabling direct comparison with the existing condition. As such, the methodological framework serves as an adaptive operational tool, capable of evaluating the effectiveness of climate-responsive strategies applied to building envelopes across diverse urban settings.

4. CASE STUDY AND DESIGN SCENARIOS

As part of the research, the Sant’Antonio neighborhood in San Benedetto del Tronto was selected as case study in central Italy, as it exemplifies the characteristics of a consolidated coastal city. The area under analysis corresponds to an urban block, bounded by Bianchi street, SS16, Voltattorni street, and Forlanini street. It presents an autonomous spatial configuration composed exclusively of residential buildings constructed in the 1970s as part of public housing programs. The urban fabric is characterized by low-rise buildings, high horizontal density, and open spaces primarily designated for private use. The building typologies are homogeneous and representative of large segments of the local built heritage. The area also presents environmental and infrastructural challenges typical of the evolving dynamics of Italian coastal cities (Figure 1). The selection of this block as case study aims to apply and validate the proposed analytical and design methodology in a contemporary, dense, and residential urban environment, assessing the interactions between the urban microclimate and the energy performance of buildings. In particular, building envelopes are investigated as active interfaces between indoor and outdoor environments. The physical, social, and climatic specificities of the neighborhood make it an ideal context for implementing the planned simulations, both microclimatic and energy-related.



Figure 1: Map with identification codes of the buildings into the urban block case study and the energy model of the urban block located in San Benedetto del Tronto (Ascoli Piceno) (Italy).

Based on the surveys conducted in the study area, real data on the existing building envelopes, such as construction materials, thermal properties, and optical parameters of surface finishes were integrated into the digital model. The resulting reference scenario was then compared with two intervention

scenarios, both designed to test the proposed methodology and to analyze the impact of different retrofit strategies on improving energy and microclimatic performance. The first intervention, named Design scenario 01, involves the implementation of an insulated ventilated façade, consisting of a 15 cm layer of rock wool insulation, a breathable waterproof membrane, an 8 cm ventilated air cavity (600 mm²/m opening), and an external cladding of fiber-reinforced lightweight concrete panels. Key thermal and optical parameters were defined for each material, including emissivity ($\epsilon = 0.92$), total solar absorptance ($\alpha = 0.42$), visible absorptance ($\alpha_{vis} = 0.36$), and surface roughness. The second intervention, named Design scenario 02, consists of a green façade system, including a 15 cm layer of rock wool insulation, a waterproof membrane, a 6 cm unventilated air gap, PVC planting modules, 10 cm of substrate, and vegetative coverage. Vegetation characteristics were defined through specific parameters: plant height (40 mm), Leaf Area Index (LAI = 2.5), reflectivity (0.10), emissivity (0.95), and stomatal resistance (200.0). These scenarios were modelled to evaluate the effects of different technological solutions on the climate-energy interaction between buildings and the urban environment. A detailed analysis was conducted on thermo-optical performance and the potential benefits in terms of comfort improvement and mitigation of climate change effects.

5. INDOOR ENERGY MODEL

The data used for the indoor simulation of the buildings were obtained through on-site surveys aimed at identifying the typological and construction characteristics of the buildings, as well as from satellite-based surveys using WebGIS tools. For this specific building cluster, a site inspection was conducted, during which a survey form was compiled, assigning a unique identification code to each building. This form included key parameters required for the development of the energy model: structural typology, opaque and transparent envelope components, and primary energy generation systems. The characteristics of the building envelopes were determined based on the year of construction, geographic location (province), local construction practices, and relevant scientific literature. The buildings were found to be constructed using load-bearing masonry and hollow brick systems with reinforced concrete frames. For research purposes, exclusively aimed at identifying the overall energy performance class of each building, only the heated thermal zones (residential units) and unheated zones (cellars, stairwells, attic spaces) were considered.

The stratigraphy of both vertical and horizontal building components was identified, including the following performance parameters for each material layer: thickness (mm), thermal conductivity (λ W/(mK)), thermal resistance R (m²K/W), density ρ (kg/m³), specific heat capacity C (kJ/(kg·K)), and water vapor diffusion resistance factor (μ). These parameters were selected to support simulations of the physical performance of the envelope, with particular focus on thermal transmittance (U-value) and thermal inertia, which are critical to determining the envelope's performance during both winter and summer conditions. As for the transparent envelope components, in most cases, the window frames are made of wood with double-glazed insulating glass units. Regarding the energy generation systems, condensing combination gas boilers were assumed methane-fueled, rated at 22 kW, and classified with a three star efficiency rating for both space heating (delivered through thermal radiation systems) and domestic hot water (DHW) production. The construction of base models for the existing buildings constituted the next phase of the study, aimed at calculating the following indices and indicators: CO₂ emissions to the atmosphere and the global heat transfer coefficient (H'T). After generating the baseline model (Reference Scenario) for the different building typologies, additional envelope layers were applied to define the two retrofit scenarios (Design Scenario 01 and Design Scenario 02). For all three scenarios, the same set of indices and indicators was extracted. The comparative analysis of these data enabled the evaluation of the effectiveness of each intervention.

6. PERFORMANCE BASED MODEL FOR OUTDOOR THERMAL COMFORT

In the present study, the Universal Thermal Climate Index (UTCI) [7] and the Mean Radiant Temperature (MRT) were employed as the main parameters to evaluate the impact of building envelopes on thermal comfort in outdoor spaces. The UTCI, expressed in °C, integrates the combined

effects of air temperature, relative humidity, wind speed, and MRT, providing a comprehensive index of human thermal exposure in outdoor environments. The MRT, also expressed in °C, measures the radiant energy incident on a human body and depends on the radiative properties of surrounding surfaces and the components of direct, diffuse, and reflected solar radiation. Variations in UTCI and MRT derive exclusively from the different configurations of the buildings' opaque façades, while all other variables were kept constant. To ensure greater climatic representativeness, a customized EPW weather file was generated, derived from the city's Typical Meteorological Year (TMY) and adapted to the morphological characteristics of the case study block. The simulation days, corresponding to the annual thermal extremes, were selected as July 29 (summer) and January 12 (winter), covering both daytime (08:00–18:00) and nighttime (20:00–06:00) periods. The energy model was developed in the parametric environment of Grasshopper (Rhino) using the Honeybee plugin from the Ladybug Tools suite, in combination with EnergyPlus 22.2.0. The HB UTCI Comfort Map component was used to calculate UTCI and MRT, integrating hourly climatic data (via Ladybug) with surface thermal outputs (via EnergyPlus) [8]. The simulations incorporated detailed geometric and performance parameters, including window-to-wall ratio, shading elements, optical-radiative properties of materials, and modeling of the outdoor pavement (asphalt). At the urban scale, the surrounding built context was also included to account for its influence on shading conditions. For UTCI calculations, a horizontal analysis grid was defined at 1.5 m above ground level (the average height of the human body), with a resolution of 1 m × 1 m, resulting in a total of 6,929 analysis points. In total, 18 simulations were performed: 9 for UTCI analysis and 9 for MRT (Figures 2-3).

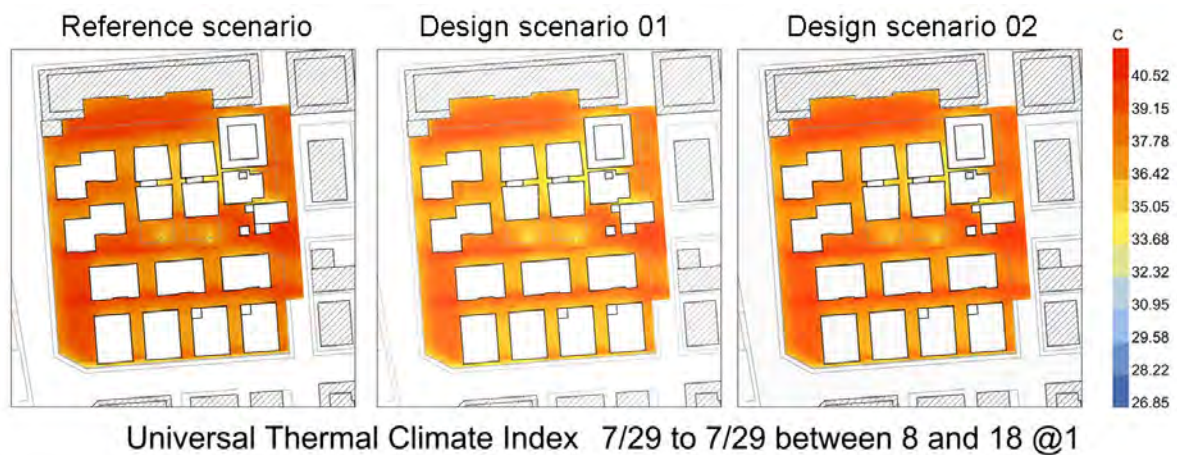


Figure 2. Maps of simulations for UTCI (°C). Maps show, outdoor condition in the three scenarios, side by side, for the hottest day in the day period

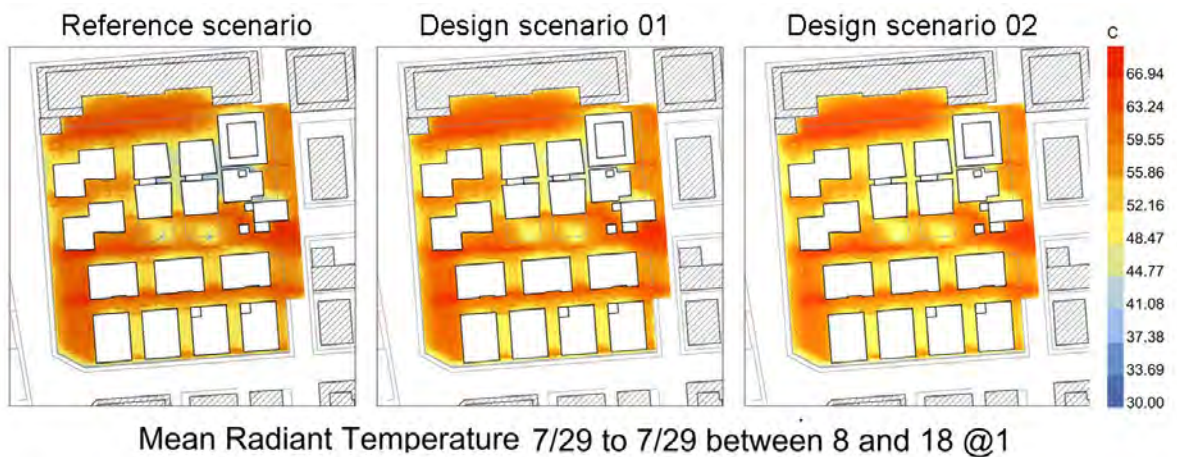


Figure 3. Maps of simulations for MRT (°C). Maps show outdoor condition in the three scenarios, side by side, for the hottest day in the day period

Each simulation produced a thematic map and a corresponding set of numerical data. Since differences between scenarios are sometimes limited, the comparative analysis prioritized numerical data, with particular attention to minimum, maximum, average, and median values, in order to provide a detailed interpretation of the spatial distribution of thermal comfort in the urban outdoor space.

7. RESULTS AND DISCUSSION

The indoor and outdoor results (Tables 1-2) show the data from the simulations, according to the above criteria.

Table 1: Summary of the three scenarios results for indoor metrics: CO₂ Emissions and Global Heat Transfer Coefficient (H'T).

BUILDINGS CODE	REFERENCE SCENARIO		DESIGN SCENARIO 01		DESIGN SCENARIO 02	
	CO ₂ Emissions (Kg/mq)	H'T	CO ₂ Emissions (Kg/mq)	H'T	CO ₂ Emissions (Kg/mq)	H'T
SBT 01	40,0	1,34	26,7	0,29	26,0	0,29
SBT 02	38,3	1,34	23,3	0,32	27,3	0,31
SBT 03	37,3	1,36	24,4	0,29	23,4	0,29
SBT 04	39,9	1,35	26,4	0,29	25,7	0,29
SBT 05	47,2	1,43	30,9	0,34	29,8	0,34
SBT 06	46,6	1,44	30,7	0,35	30,7	0,34
SBT 07	46,6	1,44	30,8	0,36	29,8	0,36
SBT 08	44,4	1,46	30,6	0,34	29,5	0,33
SBT 09	45,0	1,43	30,5	0,34	30,6	0,33
SBT 10	44,0	1,42	29,8	0,33	28,7	0,33
SBT 11	41,8	1,35	27,3	0,25	26,2	0,25
SBT 12	27,2	0,58	22,8	0,43	22,1	0,42
SBT 13	67,4	1,34	29,3	0,42	28,4	0,42
SBT 14	55,6	1,51	30,3	0,25	28,4	0,25

The application of the proposed methodology has highlighted the added value of an integrated and performance-based approach to building envelope design in urban contexts, able to provide aligned indoor and outdoor analysis. Rather than limiting the analysis to a punctual quantification of thermal reductions, the model enabled a systemic evaluation of the interaction between buildings and the urban microclimate, offering both spatial and temporal insights into the climatic phenomena induced by different façade configurations. The use of parametric modeling, integrated with advanced climatic tools, made it possible to map thermal comfort conditions in the urban space with high precision, providing a deeper understanding of the retrofit solutions' effects on radiative exchange, thermal accumulation, and natural ventilation. In particular, the ability to simulate alternative design scenarios dynamically has underscored the active role of the building envelope as an interface capable of significantly modulating energy flows between the built environment and the urban atmosphere. The 1.5 meter high horizontal calculation grid enabled the representation of outdoor comfort in relation to human perception, making the results technically robust while also accessible from a user-centered perspective. Simulations conducted under extreme climatic conditions allowed for the identification of spatial discomfort patterns and potential zones of mitigation resulting from the technological solutions applied to façades.

This approach proved especially effective in supporting decision-making processes, offering a comparative tool capable of highlighting the environmental implications of design choices, going beyond the mere presentation of numerical indicators. The integration of localized climatic data, high-fidelity 3D modeling, and thermo-radiative analysis established a robust evaluation framework, overcoming the limitations of isolated indoor analyses and introducing a replicable logic of climate-sensitive façade design for diverse urban contexts. The modular structure of the methodology and its compatibility with open-source climatic datasets and accessible simulation tools further enhance its transferability.

Table 2: Summary of the three scenarios results for outdoor metrics: UTCI and MRT.

REFERENCE SCENARIO				
UTCI SIMULATION (Universal Thermal Comfort Index) (°C)				
	Summer Date (29 July – Hottest Day)		Winter Date (12 January – Coldest Day)	
	Day (08:00-18:00)	Night (20:00-06:00)	Day (08:00-18:00)	Night (20:00-06:00)
Min	26,8 °C	25,0 °C	-2,7 °C	-6,7 °C
Max	40,5 °C	27,9 °C	5,2 °C	-3,8 °C
Average	37,0 °C	25,5 °C	0,6 °C	-5,6 °C
MRT SIMULATION (Mean Radiant Temperature) (°C)				
Min	35,6 °C	23,8 °C	4,2 °C	-4,0 °C
Max	66,9 °C	28,8 °C	26,8 °C	3,6 °C
Average	52,8 °C	25,5 °C	10,2 °C	-0,9 °C
DESIGN SCENARIO 01				
UTCI SIMULATION (Universal Thermal Comfort Index) (°C)				
Min	25,5 °C	25,0 °C	-3,1 °C	-6,5 °C
Max	40,4 °C	27,8 °C	4,8 °C	-3,7 °C
Average	36,9 °C	25,7 °C	0,5 °C	-5,2 °C
MRT SIMULATION (Mean Radiant Temperature) (°C)				
Min	35,2 °C	24,0 °C	2,9 °C	-4,2 °C
Max	66,5 °C	28,5 °C	25,1 °C	3,8 °C
Average	52,3 °C	25,3 °C	9,1 °C	-1,1 °C
DESIGN SCENARIO 02				
UTCI SIMULATION (Universal Thermal Comfort Index) (°C)				
Min	25,5 °C	25,1 °C	-2,8 °C	-6,5 °C
Max	40,1 °C	27,6 °C	2,1 °C	-3,2 °C
Average	36,7 °C	25,8 °C	-0,5 °C	-5,4 °C
MRT SIMULATION (Mean Radiant Temperature) (°C)				
Min	27,1 °C	24,0 °C	3,9 °C	-3,7 °C
Max	65,4 °C	29,4 °C	21,6 °C	4,8 °C
Average	51,7 °C	25,2 °C	9,7 °C	-0,3 °C

In parallel, the application of the methodology to the indoor scale allowed for an in-depth exploration of how internal comfort conditions evolve based on façade characteristics, material properties, and architectural geometry. Energy modeling, integrated with site-specific climatic data, enabled the mapping of indoor thermo-hygrometric conditions, offering both spatial and temporal readings of occupant comfort and potential energy savings. A key insight emerging from the analysis is the capacity of the building envelope to function as a dynamic interface between external and internal environments, modulating heat transfer, radiation, and natural ventilation. The analysis of alternative scenarios, including retrofit interventions and the adoption of nature based solutions, demonstrated that even small variations in surface finishes, thermal inertia, or air permeability can produce significant effects on indoor comfort conditions during both summer and winter. The comparative results summarized in the table show that external insulation applied directly to the wall (ETICS) has the most substantial impact on energy performance, whereas the external finish layer of the ventilated façade results in marginal improvements in the Design scenario 01 and, in some cases, slightly worsened outcomes in Scenario 02 compared to the baseline. From an energy standpoint, the results indicate a notable improvement during the summer period, which is increasingly considered the most critical season in light of emerging climate change dynamics. Furthermore, the simultaneous adoption of both outdoor and indoor parameters enabled a fast and effective comparison between different building envelope configurations, yielding an integrated overview of thermo-energy performance and comfort at both the urban and architectural scales. This made the methodology particularly suitable for supporting fast-track decision-making processes, especially during the early planning phases of retrofit interventions. In conclusion, the results confirm that a systemic and performance-driven approach to

building envelope design offers a more nuanced and climate-responsive understanding of the relationship between architecture and the urban climate, contributing to the development of effective strategies for enhancing environmental comfort and energy sustainability.

8. CONCLUSIONS

The adoption of an integrated methodology for the combined analysis of indoor and outdoor effects of building envelopes has proven to be highly effective in assessing and optimizing climate performance in urban environments. The results confirm that design strategies tailored to the local climatic context can deliver significant benefits in terms of thermal comfort, reduced energy impact, and informed decision-making support. The model's ability to provide a dynamic and multiscale representation of microclimatic phenomena and indoor energy performances reinforces its potential as a replicable tool for resilient design. In this regard, the proposed methodology constitutes an operational contribution to adaptive retrofit planning, oriented toward the integration of environmental quality, energy sustainability, and user well-being.

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