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An Integrated Decision-Support Framework for Sustainable Retrofitting of Post-War Residential Buildings to Support Urban Heat Island Mitigation

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Abstract

In recent decades, the intensification of the urban heat island (UHI) phenomenon has emerged as a critical challenge for European cities, exacerbated by climate change, dense urban morphologies, and the aging performance of the existing building stock. In this context, the renovation of post-war residential heritage represents a strategic opportunity to simultaneously enhance buildings' energy performance and contribute to urban-scale thermal mitigation. This study investigates sustainable and integrated retrofitting strategies applied to residential buildings constructed between 1945 and 1990 in the metropolitan area of Milan. The research aims to evaluate how targeted refurbishment interventions can improve building energy performance and potentially support UHI mitigation through improved envelope performance and material selection. The methodology combines field surveys, archival data from public housing authorities, energy simulations, and multiple-criteria decision-making (MCDM) analysis, integrating economic, environmental, and performance-based indicators. Several retrofit scenarios are assessed across different building typologies. Results highlight that low-invasive and cost-effective measures, such as advanced glazing systems, roof insulation, and efficient heating system upgrades, achieve a favorable balance between energy performance improvement, economic feasibility, and intervention-related criteria. For buildings with larger dispersing surfaces, envelope insulation solutions using sustainable materials demonstrate increased effectiveness. Beyond individual building performance, the study discusses the potential indirect contribution of large-scale retrofit strategies to UHI mitigation through reduced building energy requirements and potentially lower HVAC-related anthropogenic heat emissions. The proposed operational framework supports public stakeholders in prioritizing interventions across a large building stock, offering a replicable decision-support tool for climate-resilient urban regeneration and for supporting UHI mitigation strategies.

Keywords: urban heat island (UHI); building energy retrofit; public housing; multiple-criteria decision-making (MCDM); TOPSIS

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1. Introduction

In recent decades, the intensification of the urban heat island (UHI) phenomenon has emerged as one of the major environmental challenges affecting European urban contexts, exacerbated by the combined effects of climate change, high building density, soil sealing, and the growing energy inefficiency of the existing building stock. The UHI phenomenon

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causes an increase in both air and surface temperatures in urban areas compared with peri-urban and rural surroundings, with significant impacts on thermal comfort, public health, energy consumption, and urban climate resilience. Recent studies have shown that, during extreme heat events, UHI intensity can exceed 6–8 °C in the densest metropolitan areas, amplifying health risks, particularly for vulnerable populations such as older adults and frail individuals [1,2]. Within the European context, a significant share of greenhouse gas emissions and energy consumption is attributable to the building sector. According to the European Commission, buildings account for approximately 40% of final energy consumption and 36% of energy-related CO_2 emissions [3]. The building stock constructed during the post-war period represents a particularly critical component, as it was developed in a historical phase characterized by limited performance standards, low attention to thermal insulation, and a strong priority given to construction speed rather than energy efficiency. In Italy, and particularly in the metropolitan area of Milan, public residential buildings constructed between 1945 and 1990 represent a substantial portion of the urban building stock. These buildings share recurring characteristics, including poorly insulated envelopes, widespread thermal bridges, obsolete window systems, inefficient centralized HVAC systems, and energy performance levels that are inconsistent with current decarbonization targets. At the same time, Milan's urban morphology, characterized by high density, limited ventilation, and reduced vegetation cover in several districts, makes climate adaptation and urban overheating mitigation particularly relevant. In this context, the energy retrofit of the existing residential stock plays a dual strategic role. On the one hand, it enables improvements in building energy performance; on the other hand, it may indirectly contribute to UHI mitigation by potentially reducing anthropogenic heat released into the urban environment. Although building retrofit does not directly affect the main urban microclimatic variables, such as urban albedo, canyon geometry, vegetation, or ventilation, a reduction in summer energy demand may translate into lower heat emissions from HVAC systems, thereby potentially contributing to UHI mitigation [4,5]. The scientific literature shows that sustainable retrofit interventions can generate significant benefits in terms of reduced energy consumption, improved indoor comfort, and lower emissions. However, selecting the optimal retrofit strategy remains a complex and inherently multiple-criteria decision problem. Design decisions require the simultaneous evaluation of often conflicting criteria, including energy performance, initial cost, lifecycle economic convenience, intervention invasiveness, reversibility, and environmental sustainability of materials. As a result, purely mono-objective approaches based exclusively on minimizing energy demand or costs are insufficient to support robust design decisions at a large scale. In this context, multiple-criteria decision-making (MCDM) methods have emerged as effective decision-support tools in technical architecture, urban regeneration, and energy retrofit planning, enabling the integration of quantitative and qualitative indicators and the ranking of alternatives according to trade-offs between performance, cost, and sustainability. Several studies have applied methods such as AHP, ELECTRE, VIKOR, and TOPSIS to building-related and energy retrofit decision problems [6–8]. Among these methods, TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) is particularly suitable when a large number of design alternatives and heterogeneous evaluation criteria must be considered, as it provides an interpretable quantitative ranking based on the relative distance of each alternative from the ideal and anti-ideal solutions [9]. Previous applications have demonstrated its suitability for integrating technical, environmental, economic, and stakeholder-related criteria in building-related decision-making, including sustainable façade selection [8] and residential building renovation [10]. TOPSIS can therefore be regarded as an established decision-support method in this field. Accordingly, the methodological contribution of the present study does not lie in the TOPSIS method itself, but in its integration within an archetype-based and portfolio-oriented framework that uses representative buildings to assess retrofit alternatives and translate their multi-criteria prioritization into differentiated strategies for a large public housing stock. Despite the substantial literature on sustainable building renovation, important methodological challenges remain when retrofit decisions are extended from individual buildings to large and typologically repetitive housing portfolios. Existing MCDM-based approaches have demonstrated the value of integrating energy, economic, environmental, and stakeholder-related criteria in the assessment of renovation alternatives [8,10]. However, many applications remain centred on individual buildings or limited case-study sets, whereas portfolio-oriented methods primarily address the prioritization of buildings, investment pathways, or renovation schedules across multiple assets [11–13]. In parallel, archetype-based building-stock models have proven effective in representing heterogeneous residential stocks and estimating the effects of retrofit strategies at broader scales [14–16]. A methodological opportunity therefore remains to connect these approaches more explicitly, using representative archetypes not only for stock-level energy assessment but also as the basis for a multi-criteria comparison of retrofit alternatives that can inform portfolio-scale intervention strategies. A further research challenge concerns the integration of building retrofit within broader UHI mitigation strategies. Previous studies have demonstrated that building-envelope properties, building energy demand, anthropogenic heat emissions, and urban thermal conditions are interconnected [5,17,18]. This relationship provides a relevant basis for considering building-stock retrofit as part of an integrated approach to urban overheating mitigation. However, before its urban-scale thermal effects can be quantitatively assessed, retrofit strategies must first be identified and prioritized at the building and portfolio scales according to their energy, economic, environmental, and technical performance. The present study addresses this decision-support stage, providing a structured basis for identifying retrofit strategies whose building-scale benefits can subsequently be investigated in terms of cooling-demand reduction, HVAC-related anthropogenic heat emissions, and resulting effects on urban thermal conditions. Against this background, this study proposes an integrated decision-support framework for the sustainable retrofit of the post-war public residential building stock of Milan. The framework combines building-stock typological classification, selection of representative archetypes, standardized energy simulation, generation and assessment of retrofit scenarios, and multiple-criteria prioritization through TOPSIS. The main objective is to identify, for each representative building archetype, retrofit strategies that provide the most favourable balance among energy performance, economic feasibility, environmental impact, invasiveness, and reversibility, and to use these archetype-level assessments to support differentiated intervention strategies across a large public housing portfolio. The original contribution of the study does not lie in introducing a new MCDM algorithm, TOPSIS variant, or building-stock classification method, all of which are established approaches. Rather, it lies in their integration within a single scalable workflow that connects typological building-stock characterization with detailed retrofit-scenario assessment and multi-criteria prioritization. In this way, representative archetypes are used as an operational bridge between detailed building-scale analysis and portfolio-scale decision support, allowing retrofit priorities to account for the morphological and constructional heterogeneity of the existing public housing stock. The contribution should therefore be understood as an incremental methodological and operational advancement based on the structured integration of established methods rather than as the introduction of a new individual method. Within this framework, the relationship with UHI mitigation is conceived as a progressive building-to-urban assessment pathway. The present study establishes its building- and portfolio-scale decision-support component by identifying retrofit strategies capable of reducing building energy requirements while balancing their economic, environmental, and technical implications. These results provide the basis for a subsequent quantitative assessment of how the selected strategies may affect summer cooling demand and HVAC-related anthropogenic heat release when implemented across the building stock, and ultimately how these changes may influence urban thermal conditions. The proposed framework can therefore support UHI mitigation planning by identifying and prioritizing the building retrofit strategies to be carried forward into subsequent district-scale microclimate or urban canopy modelling.

2. Materials and Methods

The overall methodological framework is summarized in Figure 1. The workflow follows a sequential process from the characterization and typological classification of the public residential building stock to the identification of representative archetypes, the definition and assessment of retrofit scenarios, and their multiple-criteria ranking through TOPSIS. The resulting framework translates building-scale evaluations into differentiated retrofit strategies that can support decision-making at the building-stock portfolio scale.

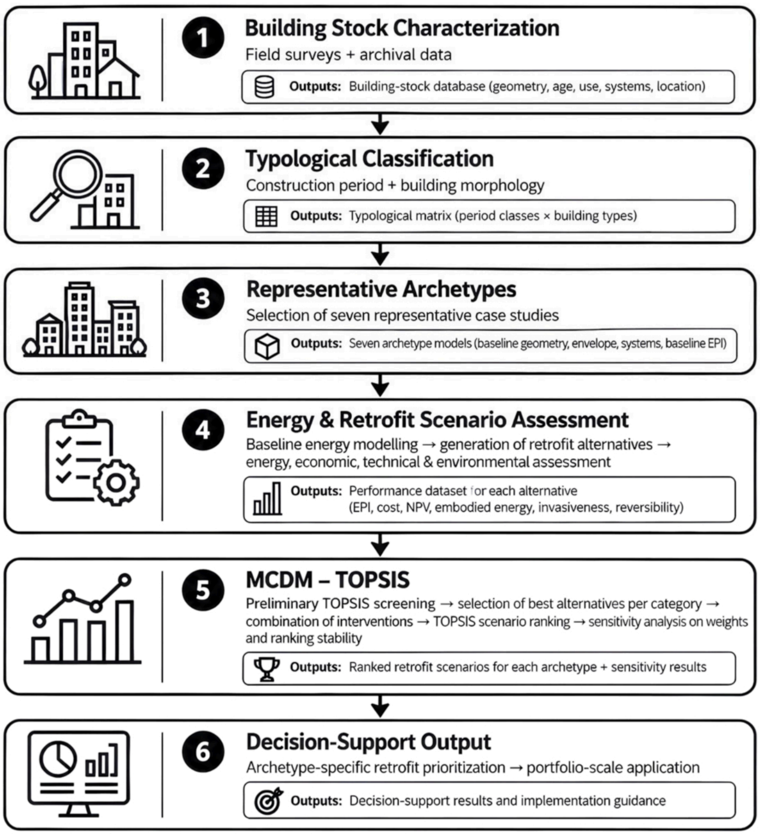

Figure 1. Overall research framework and methodological workflow. (Authors' original elaboration, 2026).

2.1. Study Area and Building Stock

The study area (Figure 2) corresponds to the public residential building stock located in the metropolitan area of Milan and managed by ALER (Azienda Lombarda per l'Edilizia Residenziale), the public body responsible for the management of social housing in the Lombardy region [19]. Milan was selected as the case study due to its relevance from both building and climatic perspectives, representing one of the Italian urban contexts where the combination of high urban density, aging building stock, and vulnerability to urban overheating makes energy retrofitting particularly strategic [2,20]. From a climatic perspective, Milan belongs to climatic zone E, with 2404 heating degree days, and is characterized by a temperate subcontinental climate, with cold winters and hot, humid summers [21,22]. Its geographical location within the Po Valley, combined with limited natural ventilation and high building density, makes the city particularly susceptible to urban heat accumulation phenomena and prolonged summer heat stress [5,23]. For this reason, Milan provides an appropriate context for investigating how building retrofit strategies may contribute, albeit indirectly, to reducing summer energy demand and the consequent release of anthropogenic heat into the urban environment. The analysed building stock consists of public residential buildings constructed between 1945 and 1990, corresponding to the period of greatest expansion of social housing in the post-war era. This construction period reflects the rapid urban growth experienced by Milan during the economic boom, when large residential districts were developed to respond to increasing housing demand [24]. The overall stock includes approximately 95,700 housing units, distributed across neighbourhoods characterized by different morphological and construction configurations, ranging from linear blocks to tower buildings and courtyard-based typologies. Buildings belonging to this stock exhibit recurring characteristics typical of post-war construction, including opaque envelopes generally lacking thermal insulation, poorly insulated roofs, window frames with limited thermophysical performance, obsolete glazing systems, and centralized HVAC systems with low energy efficiency. These characteristics are consistent with the energy performance limitations commonly reported for Italian residential buildings constructed before the widespread adoption of thermal regulations [25,26]. As a consequence, these buildings show high energy demand for both winter heating and, increasingly, summer cooling. This trend is becoming particularly relevant in Southern and Central Europe, where climate change is progressively reducing heating demand while increasing cooling loads and overheating risk [27,28]. Therefore, this building stock represents a priority target for retrofit interventions aimed not only at improving energy efficiency and reducing emissions, but also at supporting urban-scale climate adaptation strategies. Moreover, the high degree of typological repetition within the ALER stock enables the adoption of archetype-based analytical approaches, allowing results obtained from individual case studies to be transferred to broader clusters of buildings with similar characteristics.

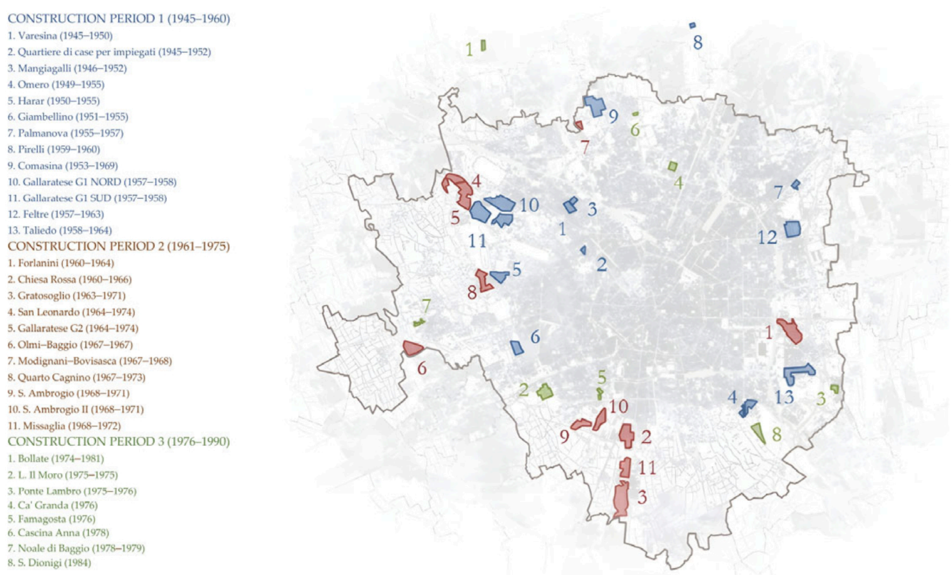

Figure 2. Spatial distribution of the Milan public housing districts considered in the building-stock analysis, grouped by construction period. (Authors' original elaboration, 2022; reproduced from preliminary research conducted within a currently embargoed thesis).

2.2. Typological Matrix

To enable the systematic analysis of a large and heterogeneous building stock, a typological matrix was developed to classify the entire public residential stock into representative archetypes. The approach is based on the assumption that buildings sharing similar morphological, construction, and chronological characteristics exhibit comparable thermo-energy behaviour and, consequently, may benefit from similar retrofit strategies. This assumption is consistent with the archetype-based approach widely adopted in building stock modelling and energy retrofit studies, where representative building typologies are used to reduce complexity while preserving the main performance-related characteristics of the stock [14,15]. The typological matrix was constructed through a double classification based on construction period and building morphology. The construction period was considered a proxy for the main technological and construction characteristics of the building, as buildings erected in the same historical period generally share similar materials, construction techniques, regulatory constraints, and plant systems [15,16]. Building morphology was instead selected because of its direct correlation with the surface-to-volume ratio (S/V ratio), which strongly influences heat losses and overall energy performance of the envelope [29]. Three main historical periods were identified within the Milan ALER building stock: 1945–1960, corresponding to the first phase of post-war residential expansion; 1961–1975, characterized by the strong industrialization of construction processes and rapid growth of public housing; and 1975–1990, associated with greater typological diversification and the introduction of more complex construction solutions. In parallel, buildings were classified into three macro-morphological categories: multi-family buildings (C), low- to medium-rise residential buildings, generally characterized by predominantly horizontal development; multi-storey buildings (D), multi-storey buildings with higher volumetric compactness and intermediate vertical development; and tower buildings (E), high-rise tower buildings characterized by strong vertical development and high exposure of dispersing surfaces. The intersection of the three temporal classes and the three morphological classes generated a 3×3 typological matrix of building types (Table 1). At the end of the statistical survey, a real building was associated with each building type showing sufficient representation within the analysed ALER stock. Consistent with the general building-stock modelling principles adopted in the TABULA/EPISCOPE framework, the classification combines construction-period and morphological classes and associates representative example buildings with sufficiently recurrent building types. In the present study, a threshold of more than 1000 housing units per type was adopted as a study-specific operational criterion to exclude marginal typological combinations and retain archetypes representing a substantial share of the analysed public housing portfolio. Consequently, the resulting archetypes are intended to support generalization within the analysed building portfolio and comparable post-war public housing stocks, rather than statistical generalization to the entire Italian residential building stock. The application of this criterion led to the identification of seven representative archetypes, while two typological combinations were excluded due to limited territorial diffusion, which was below the minimum representativeness threshold. From a methodological perspective, the typological matrix represents a key component of the proposed integrated framework, as it constitutes the link between building scale and portfolio scale. It enables retrofit analysis to move beyond building-specific assessments and become an operational tool for the strategic planning of interventions across large public housing stocks.

Table 1. Typological matrix and selection of the seven representative case-study archetypes of the ALER residential building stock. (Authors' original elaboration, 2026).

	Multi-Family Buildings (C) 	**Multi-Storey Buildings (D)** 	**Tower Buildings (E)** 
1945–1960	1C Comasina (1953)	1D Gallaratese G1 (1957)	/
1961–1974	2C Chiesa Rossa (1964)	2D Gratosoglio (1962)	2E Gallaratese G2 (1964)
1975–1990	/	3D Ludovico il Moro (1975)	3E Cascina Anna (1976)

2.3. Retrofit Scenarios

The analysis considered five macro-categories of retrofit interventions: glazing replacement, frame replacement, external façade insulation, roof insulation, and replacement of the heating generation system with a condensing boiler (Table 2). These intervention categories were selected because they represent some of the most widely adopted retrofit measures in existing residential buildings, particularly in post-war housing stock characterized by poor envelope performance and obsolete HVAC systems. For each category, several more specific intervention alternatives were defined, which are reported in Table 2. Each specific intervention was evaluated considering different material configurations and, where applicable, different insulation thicknesses. The inclusion of multiple thickness levels allowed the analysis to capture the trade-off between thermal performance, material use, and overall sustainability, in line with life-cycle-oriented retrofit approaches [30]. Given the large number of specific intervention alternatives, scenario generation followed a two-stage procedure. First, the alternatives belonging to each intervention category (A–E) were comparatively assessed through TOPSIS using the criterion weights reported in Table 3. This preliminary category-level assessment was used to identify the most competitive alternatives and to inform the definition of a predefined set of combined retrofit scenarios. The second-stage scenario set was not generated through exhaustive combinatorial enumeration nor restricted exclusively to the single highest-ranked alternative of each category. Eighteen predefined multi-intervention configurations were retained for the subsequent analysis, primarily combining the category-level reference alternatives while preserving selected additional configurations for comparative purposes. In the scenario notation, Ax, Bx, Cx, and Dx identify the specific alternatives belonging to intervention categories A–D, respectively, while E1 represents replacement of the existing heating generator with a condensing boiler. The resulting scenario library comprised 56 alternatives. Scenarios 1–38 correspond to the individual intervention alternatives initially evaluated within categories A–E, whereas scenarios 39–56 represent the 18 predefined multi-intervention configurations informed by the preliminary category-level assessment. The complete set of combined scenarios is reported in Table 2. The same scenario library was applied to each of the seven representative archetypes, resulting in 392 post-retrofit simulations. This classification reflects the distinction commonly adopted in retrofit literature between shallow/intermediate retrofits, based on limited or phased interventions, and deep retrofits, involving simultaneous upgrades of multiple building subsystems to achieve maximum energy reduction [31]. The objective of the analysis was not to identify the intervention associated with the maximum absolute reduction in energy demand, but rather to determine the retrofit strategy capable of balancing the decision dimensions considered in this study. For this reason, the scenarios were evaluated through a multiple-criteria framework capable of accounting not only for energy performance, but also for economic, operational, and environmental criteria, consistent with recent decision-support approaches in sustainable building retrofit [7].

Table 2. Intervention typologies. (Authors' original elaboration, 2026).

Category A—Glazing Replacement
A1 4 + 12 + 4 argon-filled glazing replacement
A2 4 + 15 + 4 argon-filled glazing replacement
A3 4 + 12 + 4 + 12 + 4 air-filled triple glazing replacement
A4 4 + 12 + 4 + 12 + 4 argon-filled triple glazing replacement
Category B—Frame Replacement
B1 Aluminium frame replacement, 60 mm
B2 Aluminium frame replacement, 70 mm
B3 Aluminium frame replacement, 75 mm
B4 PVC frame replacement, 70 mm
B5 PVC frame replacement, 80 mm
B6 PVC frame replacement, 90 mm
B7 PVC/wood frame replacement, 70 mm
B8 PVC/aluminium frame replacement, 70 mm
B9 Laminated wood frame replacement, 70 mm
Category C—Façade Insulation
C1 External EPS insulation, (1.1) 80 mm (1.2) 100 mm (1.3) 120 mm (1.4) 140 mm
C2 External rock wool insulation, (2.1) 80 mm (2.2) 100 mm (2.3) 120 mm (2.4) 140 mm
C3 External wood fibre insulation, (3.1) 80 mm (3.2) 100 mm (3.3) 120 mm (3.4) 140 mm
C4 External cork insulation, (4.1) 100 mm (4.2) 120 mm (4.3) 140 mm
C5 External polyurethane insulation, (5.1) 60 mm (5.2) 80 mm (5.3) 100 mm (5.4) 120 mm
Category D—Roof Insulation
D1 EPS roof insulation, (1.1) 80 mm (1.2) 100 mm (1.3) 120 mm
D2 Rock wool roof insulation, (2.1) 120 mm (2.2) 140 mm
Category E—Heating System Replacement
E1 Condensing boiler replacement
Combined Scenarios
A2 + E1
A2 + D1
D1 + E1
C4 + E1
C4 + D1
A2 + C4
A2 + D1 + E1
C4 + D1 + E1
A2 + C4 + E1
A2 + C4 + D1
A2 + B3 + E1
A2 + B5 + D1
A2 + B5 + C4
A2 + C4 + D1 + E1
A2 + B5 + D1 + E1
A2 + B5 + C4 + E1
A2 + B5 + C4 + D1
A2 + B5 + C4 + D1 + E1

Table 3. Intervention criteria and criterion weights adopted in the TOPSIS assessment. The arrows reported indicate the conceptual direction of the decision objective. (Authors' original elaboration, 2026).

Criterion	Decision Objective	Weight
Energy Performance Index (EPI)	↓	1.00
Initial Investment Cost	↓	0.50
Net Present Value (NPV)	↑	0.50
Reversibility	↑	0.33
Invasiveness	↓	0.33
Sustainability	↑	0.33

2.4. Building Energy Simulation

Building energy performance was assessed using the EC700 module of Edilclima (v11) software through a monthly semi-steady-state calculation approach. This modelling strategy was selected because the study aimed to consistently compare a large number of baseline and post-retrofit configurations across representative building archetypes, focusing on the relative variation in energy performance between scenarios rather than on the detailed hourly thermal behaviour of individual buildings. Accordingly, the analysis was conceived as a comparative assessment under standardized and consistent calculation conditions. The calculations were performed in accordance with the UNI/TS 11,300 technical specifications. Climatic boundary conditions were defined using the monthly reference climatic data provided by UNI 10349; therefore, no hourly reference climatic year was employed. The simulations enabled the calculation of the energy-performance indicators required for the comparative assessment of baseline and retrofit configurations under standardized conditions. The same calculation assumptions and boundary conditions were maintained for each archetype when comparing baseline and retrofit configurations, allowing differences in energy performance to be attributed to the investigated retrofit measures. The building models incorporated the geometric and thermo-physical characteristics of the representative archetypes. The main geometric parameters, envelope characteristics, thermal transmittances, and baseline heating-system characteristics adopted for each archetype are reported in the original baseline energy characterization sheets provided in Appendix A (Figures A1–A7). Opaque-envelope components were characterized in terms of thermal transmittance according to UNI EN ISO 6946 [32], while heat transfer through ground-contact components was assessed according to UNI EN ISO 13370 [33]. Window thermal transmittance was calculated according to UNI EN ISO 10077 [34]. Thermal bridges were accounted for using the simplified approach based on percentage increases according to UNI EN ISO 14683 [35] and UNI EN ISO 10211 [36]. Shading effects associated with external obstacles, vegetation, and horizontal and vertical projections were considered according to Appendix D of UNI/TS 11300-1 [37]. Since detailed information on the original building systems was not consistently available for all case studies, baseline HVAC configurations were reconstructed according to construction period and building type using the available building documentation and the reference information provided by the TABULA/EPISCOPE framework. The resulting system configurations were used to reproduce the existing heating and domestic hot-water systems in the energy models. Heating-system characteristics and subsystem efficiencies were differentiated according to construction period and system configuration in accordance with UNI/TS 11300-2 [38]. Heating generation performance was calculated using the boiler-directive method based on manufacturer-declared performance data according to Directive 92/42/EEC [39]. No calibration against measured operational energy consumption or utility-bill data was performed. The simulations were not intended to predict the actual energy consumption of individual buildings, which would require detailed information on occupancy, user behaviour, operating schedules, and actual system operation. Instead, the standardized semi-steady-state framework was adopted to provide a consistent basis for comparing the energy-performance variation between baseline and retrofit scenarios across the seven representative archetypes.

2.5. Evaluation Criteria and MCDM Procedure

Each retrofit scenario was evaluated according to six criteria: minimization of the Energy Performance Index (EPI), representing operational energy consumption; minimization of the initial investment cost; maximization of the Net Present Value (NPV); maximization of reversibility; minimization of invasiveness; and maximization of sustainability, operationalized through the minimization of embodied energy (Table 3). The selection of these criteria reflects the multidimensional nature of retrofit decision-making, where energy efficiency alone is insufficient to identify the most suitable intervention strategy. Recent literature on sustainable building retrofit increasingly emphasizes the need to integrate technical, economic, environmental, and operational criteria within a unified decision-support framework. In particular, sustainability assessments based on embodied energy and material lifecycle impact have gained relevance in recent years, as operational energy reductions may be partially offset by the environmental burden associated with construction materials [31,40]. The criterion weights actually adopted in the TOPSIS assessment are reported in Table 3. A weight of 1.00 was assigned to EPI, 0.50 each to initial investment cost and NPV, and 0.33 each to invasiveness, reversibility, and sustainability. The adopted weights represent an author-defined reference decision structure and were not derived from stakeholder elicitation, expert consensus, or an objective weighting algorithm. They should therefore be interpreted as baseline preference assumptions rather than universally applicable criterion priorities. This weighting structure distributes the overall importance across the energy-performance, economic, and technical/environmental dimensions considered in the decision process. The six criteria were operationalized as follows. Energy performance was represented by the Energy Performance Index (EPI, kWh/m^2·year), obtained from the standardized Edilclima simulations described in Section 2.4. Initial investment cost (€) included the building components, materials, plant components, and implementation activities required by each retrofit alternative. Economic profitability was represented by Net Present Value (NPV, €), calculated through discounted cash-flow analysis according to UNI EN 15459:2008 [41]. The analysis considered the initial investment and discounted cash flows associated with operating and periodic costs, component replacement and disposal, energy-cost savings, and residual value where applicable. Calculation periods were differentiated according to the estimated residual service life of the building classes: 15 years for 1945–1959, 30 years for 1960–1974, and 40 years for 1975–1990. Positive NPV values indicate economically advantageous interventions, whereas negative values indicate non-advantageous investments. In the present framework, NPV is used as a comparative economic criterion rather than as an absolute prediction of investment profitability. All retrofit alternatives within each building archetype were assessed using the same original economic calculation framework, allowing their relative economic performance to be incorporated consistently into the MCDM procedure. However, the original calculation records available for the present study do not retain the specific discount-rate and energy-price assumptions adopted in the underlying NPV calculations. Consequently, the reported NPV values cannot be considered fully reproducible as absolute financial estimates and should be interpreted only in comparative terms within the analysed scenario set. This limitation is explicitly acknowledged, and future applications of the framework should document all financial parameters required for complete economic reproducibility. Environmental sustainability was operationalized exclusively through embodied energy as the environmental proxy in the TOPSIS assessment. Material-specific values (MJ/kg), derived from cradle-to-gate literature data and cross-checked against the Inventory of Carbon & Energy (ICE) database [42,43], were multiplied by the corresponding material masses and summed to obtain the total embodied energy (MJ) of each retrofit alternative. As a dimensional cross-check, the corrected embodied-energy value of the 120 mm polyurethane façade-insulation alternative (C5) for Cascina Anna was verified using representative material parameters. Considering an embodied-energy coefficient of 101.5 MJ/kg for rigid polyurethane, a density of 35 kg/m^3, and an insulation thickness of 0.12 m, the reported value of 2,307,274 MJ corresponds to an equivalent intervention area of approximately 5412 m^2. The calculation can be expressed as:

$$EE = A \times t \times \rho \times EE_m \quad (1)$$

For boiler replacement (E1), the original assessment adopted 0 MJ as a modelling convention because component-specific embodied-energy data were unavailable. Since this assumption may artificially favour scenarios including E1, an additional check was performed by assigning E1 a non-zero embodied-energy range of 2100–7500 MJ. The lower and upper bounds were derived from published LCA data for gas condensing boilers, considering a production-stage energy requirement of approximately 53.74 MJ/kg and representative equipment inventories covering approximately 39–139.5 kg [44,45]. The baseline case (E1 = 0 MJ) was therefore compared with two cases, corresponding to E1 = 2100 MJ and E1 = 7500 MJ. The bounds were intentionally rounded to represent plausible lower- and upper-bound conditions rather than product-specific estimates. All other criterion values and TOPSIS weights were kept unchanged, and the resulting rankings were compared to identify possible rank reversals among the highest-ranked scenarios. Invasiveness and reversibility were represented through ordinal, rule-based scores derived from predefined technical and operational characteristics of the retrofit interventions. Invasiveness was assessed on a five-level scale, ranging from 1 (most disruptive) to 5 (least disruptive), considering intervention duration, noise generation, access to occupied dwellings, and the possible need for temporary evacuation. Reversibility was assessed on a three-level scale, where 1 denotes highly reversible interventions, 2 partially reversible interventions, and 3 substantially irreversible interventions; none of the alternatives investigated in this study reached level 3. The arrows reported in Table 3 indicate the conceptual direction of the decision objective rather than the numerical direction of the ordinal coding. Accordingly, reducing invasiveness corresponds operationally to maximizing its score (1 = most invasive; 5 = least invasive), whereas increasing reversibility corresponds to minimizing its score (1 = highly reversible; 3 = substantially irreversible). Similarly, sustainability is conceptually maximized, while its operational proxy, embodied energy, is minimized. These numerical directions were applied in the TOPSIS calculations; therefore, no transformation of the ordinal invasiveness and reversibility scores was required. Since reversibility depends on the intrinsic characteristics of the intervention rather than on the individual building, the same classification was applied across all archetypes. No Delphi process, AHP-based expert elicitation, or multi-expert scoring procedure was used to assign these values; consequently, inter-rater agreement or consistency testing was not applicable. Instead, the scoring rules were defined a priori and consistently applied to all alternatives, thereby limiting case-by-case subjective judgment. Before weighting, both quantitative criteria and ordinal scores were transformed using the vector normalization adopted in the TOPSIS procedure.

The primary objective of this research was to verify the effectiveness of applying multiple-criteria decision-making (MCDM) methods to the selection of highest-ranked retrofit strategies under the baseline weighting structure, leveraging the typological repetition of the building stock. To compare and rank the different retrofit alternatives, the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method was adopted as one of the most widely used MCDM approaches for decision problems characterized by the simultaneous presence of quantitative and qualitative criteria that may be mutually conflicting [9]. The choice of TOPSIS was motivated by its ability to efficiently manage a large number of design alternatives while producing an easily interpretable ranking, making it particularly suitable for decision-making processes in building retrofit. In the present study, each retrofit scenario must be evaluated not only in terms of energy performance, but also considering economic, environmental, and operational aspects, which often involve significant trade-offs. The principle underlying TOPSIS is that the highest-ranked alternative under the baseline weighting structure is the one that is simultaneously closest to the positive ideal solution, i.e., the theoretical solution that maximizes all benefit criteria and minimizes all cost criteria, and farthest from the negative ideal solution, i.e., the theoretically worst-performing solution.

TOPSIS was applied to the intervention alternatives for each representative case study in order to identify the most competitive solution within each intervention category. The category-specific assessment was performed progressively: the selected alternative from a preceding category was incorporated, where applicable, into the assessment of the subsequent intervention category. The resulting category-specific alternatives were then used in the definition and energy assessment of the combined retrofit scenarios described in Section 2.3. The sensitivity analysis presented in Section 2.6 was subsequently used to investigate the influence of alternative weighting structures on the TOPSIS scores. From an operational perspective, the method starts with the construction of a decision matrix:

$$\mathrm{X} = [\mathrm{x_{ij}}], \tag{2}$$

where each row represents an intervention alternative and each column represents one evaluation criterion. Since the criteria are expressed in different units (e.g., kWh/m^2·year, euro, and qualitative scores), the data were first normalized using vector normalization:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}}, \tag{3}$$

The normalized matrix was then weighted by multiplying each criterion by its corresponding weight, thus obtaining the weighted decision matrix. Subsequently, the positive ideal solution S_i^+, corresponding to the best theoretically achievable performance, and the negative ideal solution S_i^-, corresponding to the worst performance, were identified for each criterion. For each alternative, the Euclidean distance from both ideal solutions was calculated. Finally, the closeness coefficient was computed as:

$$CC_i = \frac{S_i^-}{S_i^+ + S_i^-}, \tag{4}$$

The coefficient CC_i ranges between 0 and 1. Higher values indicate more preferable alternatives, as they simultaneously approach the ideal solution while remaining distant from the worst-performing one. Within the context of this research, TOPSIS proved particularly effective because it enabled the translation of a complex multidimensional decision problem into a quantitative ranking of retrofit strategies. This made it possible not only to identify the most energy-efficient scenarios, but above all to determine those offering the best overall balance between energy efficiency, sustainability, cost, and operational feasibility.

2.6. Sensitivity Analysis of Criterion Weighting

A scenario-based sensitivity analysis was performed to explore the influence of criterion weighting on the TOPSIS scores. This analysis was conceived as an exploratory assessment of score sensitivity and not as a rank-stability or rank-reversal analysis. Rather than applying continuous weight perturbations with a predefined step size, four discrete weighting configurations were tested at the level of three meta-criteria: energy performance, cost, and technical compatibility. In Set I, the three meta-criteria were assigned equal weights (1/3, 1/3, 1/3). In Sets II–IV, each meta-criterion was alternatively emphasized by assigning it twice the weight of the other two: Set II = (1/2, 1/4, 1/4), Set III = (1/4, 1/2, 1/4), and Set IV = (1/4, 1/4, 1/2), respectively. Within each meta-criterion, its weight was equally distributed among the individual criteria belonging to that group. Sensitivity was quantified as the absolute divergence between the TOPSIS score obtained under each alternative weighting configuration (Sets II–IV) and the corresponding score obtained under the equal-weight baseline (Set I). Figure 3 shows the distribution of these divergence values for the three alternative weighting configurations. The analysis showed relatively limited score divergence when greater importance was assigned to energy performance (Set II), whereas emphasizing technical compatibility (Set IV) produced the largest variations. The greater dispersion observed for Set IV indicates a higher sensitivity of the TOPSIS scores to changes in the weight assigned to technical compatibility, while the more compact distribution obtained for Set II indicates lower score sensitivity when energy performance is emphasized. Based on the inverse of the observed divergence, a rebalanced relative weighting structure of 2.0 for energy performance, 1.0 for cost, and 0.7 for technical compatibility was identified. This weighting structure represents an exploratory methodological outcome of the sensitivity analysis and a potential basis for subsequent applications of the decision-support framework. All TOPSIS scores and rankings reported in the present study were calculated exclusively using the baseline criterion weights reported in Table 3. The alternative weighting configurations examined in the sensitivity analysis were used to investigate the response of TOPSIS scores to changes in criterion importance and were not used to generate alternative case-study rankings. Accordingly, the present sensitivity analysis does not establish whether rank reversals occur under alternative weighting structures; assessment of rank stability requires recalculation of the complete rankings and is identified as a necessary development of the framework.

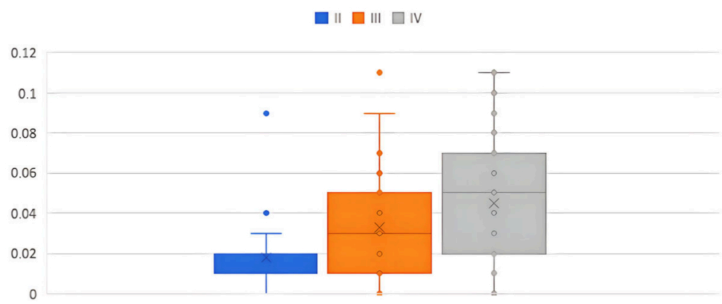

Figure 3. Distribution of TOPSIS-score divergence for weighting Sets II–IV relative to the equal-weight baseline (Set I). The × symbol indicates the arithmetic mean, while the horizontal line within each box represents the median; points beyond the whiskers indicate outlying observations. (Authors' original elaboration, 2022; reproduced from preliminary research conducted within a currently embargoed thesis).

3. Results

3.1. Ranking of Single-Category Retrofit Interventions

The first phase of the multiple-criteria analysis consisted of evaluating the alternatives belonging to each intervention category (A–E) in order to identify, for each category, the best-performing solution according to the six criteria considered: energy performance, cost, Net Present Value (NPV), reversibility, invasiveness, and sustainability. The application of the TOPSIS method using the criterion weights reported in Table 3 revealed recurring patterns across the seven archetypes.

Glazing replacement (Category A)

Glazing replacement proved to be one of the most effective interventions in terms of the balance between energy benefits, cost, and low invasiveness. In particular, the solutions most frequently ranked in the top positions were:

A2—4 + 15 + 4 argon-filled glazing
A4—triple glazing 4 + 12 + 4 + 12 + 4 argon-filled
A1—4 + 12 + 4 argon-filled glazing

Among these, A2 emerged as the most robust solution across the different case studies, ranking highest in several archetypes due to its balanced combination of good thermal performance, moderate cost, and limited invasiveness.

Frame replacement (Category B)

Frame replacement generally showed lower performance compared with glazing and roof-related interventions. Among the available alternatives, B5 PVC frame replacement proved to be the most competitive, owing to its good thermal insulation properties, durability, and favourable balance between sustainability and cost. However, in most case studies, category B interventions do not appear among the top-ranked final scenarios, suggesting that complete frame replacement is a lower-priority strategy when financial resources are limited.

Façade insulation (Category C)

The effectiveness of façade insulation was found to be strongly dependent on building typology. The alternatives most frequently appearing among the higher-ranked solutions were:

C4—100 mm cork insulation
C5—60–80 mm polyurethane insulation
C3—80–100 mm wood fibre insulation

Among these, C4 emerged as the most balanced solution, benefiting from its comparatively low embodied energy together with its overall performance across the remaining TOPSIS criteria. EPS-based solutions often showed lower initial costs but were penalized by the sustainability criterion.

Roof insulation (Category D)

Roof insulation proved to be one of the most effective intervention categories overall. The best-performing solutions were:

D1—80 mm EPS roof insulation
D1—100 mm EPS roof insulation
D2—120 mm rock wool roof insulation

The D1 (80 mm EPS) alternative frequently emerged as the top-performing solution. This suggests that, within the ALER building stock considered, heat losses through the roof represent a critical component of the overall energy balance.

Heating system upgrade (Category E)

The only alternative considered within category E was E1—condensing boiler replacement. Although this was not the most impactful intervention in purely energy terms, E1 achieved high rankings in many combined scenarios due to its relatively low cost, limited invasiveness, and short payback period, while its environmental contribution cannot be robustly compared because the embodied-energy value adopted for E1 is a modelling convention.

3.2. Ranking of Combined Retrofit Scenarios Across the Seven Archetypes

Subsequently, the complete set of 56 retrofit scenarios, comprising the individual intervention alternatives and the 18 predefined combined configurations described in Section 2.3, was compared through TOPSIS using the criterion weights reported in Table 3. Figure 4 summarizes the best-performing scenario for each archetype. The analysis reveals significant variability across the archetypes, confirming that the effectiveness of retrofit strategies is strongly dependent on building typology. Three main patterns emerge from the results: glazing replacement consistently dominates, roof insulation proves highly effective, and deep retrofit is not always the highest-ranked solution within the investigated scenario set. Interventions belonging to Category A (glazing replacement) appear in all seven best-performing scenarios. This indicates that glazing replacement represents the strategy with the most favorable balance between cost, reduction in heat losses, invasiveness, and reversibility. In particular, A2 appears in four out of the seven highest-ranked scenarios under the baseline weighting structure. Interventions belonging to Category D (roof insulation) also appear frequently among the highest-ranked scenarios. This suggests that, in buildings with high roof exposure, reducing vertical heat losses through roof insulation represents a highly effective retrofit strategy. One of the most significant findings of the study is that deep retrofit scenarios, involving the simultaneous implementation of glazing replacement, frame replacement, façade insulation, roof insulation, and heating system upgrade, rarely rank in the top positions. Scenarios involving the highest number of interventions are generally penalized by high initial investment costs, greater invasiveness, lower reversibility, and increased embodied energy. As a result, the highest-ranked retrofit solution under the baseline weighting structure does not necessarily coincide with the most comprehensive retrofit solution. This finding highlights the added value of the multiple-criteria approach compared with evaluations based exclusively on energy performance. While the cross-archetype analysis provides a general overview of recurring retrofit patterns, a more detailed understanding of the multiple-criteria trade-offs requires examining the behaviour of a specific archetype in depth.

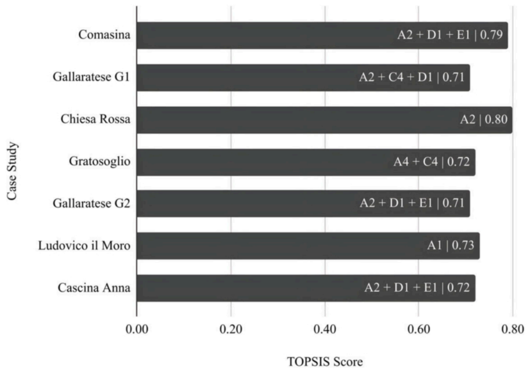

Figure 4. Comparison of the highest-ranked retrofit strategies under the baseline weighting structure identified for the seven building archetypes. Bars represent the final TOPSIS score of the highest-ranked alternative for each case study; labels also report the corresponding retrofit strategy. (Authors' original elaboration, 2026).

3.3. Detailed Case Study: Cascina Anna

Among the seven archetypes included in the comparative analysis, Cascina Anna (3E) was selected to provide an in-depth application of the proposed methodological framework to the tower-building typology, which is characterized by a distinctive high-rise configuration and an extensive vertical envelope. The selection of Cascina Anna does not imply that this archetype is quantitatively the most representative of the ALER building stock or the most critical in terms of energy performance. The detailed analysis should therefore be understood as an illustrative application of the methodology to one of the seven statistically identified archetypes, while the comparative assessment and identification of the highest-ranked retrofit strategies under the baseline weighting structure were performed for all seven archetypes.

The Cascina Anna case study was analysed by evaluating all 56 retrofit scenarios generated through the combination of the abovementioned intervention categories. Each scenario was assessed according to the six criteria adopted in the multiple-criteria framework: energy performance (EPI), intervention cost, Net Present Value (NPV), invasiveness, reversibility, and sustainability (embodied energy). The following subsections present the results obtained for each criterion separately, highlighting the main differences among retrofit scenarios. Descriptive statistics are subsequently provided to summarize the distribution and dispersion of the six evaluation criteria across the complete set of alternatives (Table 4). The section concludes with the final TOPSIS-based multiple-criteria ranking, which identifies the highest-ranked retrofit strategy for the 3E archetype under the adopted modelling assumptions.

Table 4. Descriptive statistics of the evaluation criteria for the 56 retrofit scenarios of Cascina Anna (3E). (Authors' original elaboration, 2026).

Criterion	Unit	Mean	SD	Median	Minimum	Maximum
Energy Performance Index (EPI)	kWh/m^2·year	99.09	17.43	104.71	59.34	129.62
Initial investment cost	€	157,977.89	91,392.47	164,332.29	11,312.00	381,917.01
Net Present Value (NPV)	€	270,558.52	153,956.54	233,911.13	41,276.22	586,312.16
Invasiveness	1–5	2.70	0.98	3.00	1.00	5.00
Reversibility	1–3	1.75	0.45	2.00	1.00	2.00
Embodied energy	MJ	707,657.49	488,941.83	663,580.01	33,150.00	2,307,274.00

Note: Descriptive statistics were calculated for the complete set of 56 retrofit scenarios evaluated for the Cascina Anna archetype. Mean, median, minimum, maximum, and population standard deviation (SD) were calculated using the original, unrounded values; results are reported to two decimal places. Invasiveness and reversibility are ordinal, rule-based scores defined according to the assessment criteria described in Section 2.5. For embodied energy only, E1 was excluded from the descriptive statistics because its baseline value of 0 MJ represents a modelling convention rather than a physically calculated embodied-energy value; therefore, N = 55 for embodied energy and N = 56 for all other variables.

Energy Performance Analysis

A more detailed analysis of the energy performance results for the *Cascina Anna* highlights significant differences among the retrofit scenarios in terms of energy demand reduction. The lowest energy performance index was achieved by the full retrofit scenario: A2 + B5 + C4 + D1 + E1 with EPI = 59.34 kWh/m^2·year. This scenario combines the best-performing alternative from each intervention category and represents the most effective solution from a purely energy-related perspective. The best-performing scenarios in terms of EPI systematically include interventions on glazing, frame replacement and façade insulation. In particular, scenarios combining A2, B5 and C4 consistently occupy the top positions of the energy ranking, indicating the strong impact of envelope-related interventions on overall building performance. Façade insulation, especially the cork-based solution C4, shows a particularly relevant contribution to energy demand reduction, confirming the importance of improving the thermal performance of vertical dispersing surfaces in this building typology. Conversely, roof insulation provides the lowest energy benefit when considered as a stand-alone intervention. The worst-performing scenarios in the ranking correspond to category D interventions only, with EPI values ranging from 129.21 to 129.62 kWh/m^2·year. This result confirms that, in the 3E archetype, heat losses through the roof are relatively limited compared with the total dispersing envelope. The heating system replacement (E1) also yields measurable improvements, reaching an EPI of 118.94 kWh/m^2·year, thus performing slightly better than roof insulation alone.

Intervention Cost Analysis

The analysis of intervention costs for the Cascina Anna shows substantial variability among retrofit scenarios, with investment costs ranging from €11,312 to €381,917.01. The lowest-cost interventions correspond to roof insulation scenarios (category D). In particular, the cheapest solution is D1 (EPS 80 mm), followed by D1 solutions with higher insulation thickness and D2 rock wool alternatives. These results identify roof insulation as the least expensive retrofit category for this building archetype. Glazing replacement interventions (category A) also show relatively limited costs. The double-glazing solutions A1 and A2 require investments of approximately €29,000, while triple-glazing solutions (A3 and A4) increase the investment to approximately €48,000–53,000. A substantial increase in cost is observed for façade insulation scenarios (category C). Depending on material and thickness, these interventions range from €109,633.75 to €241,194.25, placing them in the medium-to-high cost range. The highest costs are associated with frame replacement interventions (category B), particularly when high-performance solutions are adopted. The most expensive scenario is A2 + B9 (laminated wood frame), which represents the highest investment among all evaluated scenarios. This result reflects the high unit cost of the laminated-wood solution combined with the large number of repeated window units in the high-rise Cascina Anna building; consequently, the total investment is not directly proportional to the number of intervention categories included in a scenario. The full retrofit scenario A2 + B5 + C4 + D1 + E1, corresponding to the energetically best-performing configuration, requires an investment of €344,166.7, making it the second-most expensive scenario among the evaluated alternatives.

Net Present Value Analysis (NPV)

The analysis of the Net Present Value (NPV) for the Cascina Anna also reveals substantial variability among retrofit scenarios, with values ranging from €41,276.22 to €586,312.16. The highest NPV is achieved by the scenario A2 + C4 + D1 + E1. This configuration combines glazing replacement, façade insulation, roof insulation and heating system replacement, representing the most economically advantageous scenario in lifecycle terms. The scenarios with the highest NPV values are generally multi-intervention configurations combining three or four retrofit actions. The top-ranked scenarios consistently include interventions on glazing (category A), façade insulation (category C), roof insulation (category D), and heating system upgrade (category E). Glazing replacement alone also provides high NPV values. Façade insulation scenarios (category C) occupy an intermediate position in the ranking, with NPV values ranging from €97,664.14 to €188,132.46, depending on material and insulation thickness. The lowest NPV values are associated with stand-alone roof insulation interventions (category D). These scenarios occupy the last positions in the ranking, with values between €41,276.22 and €47,512, representing the least advantageous solutions in economic terms.

Invasiveness Analysis

Unlike the previous criteria, invasiveness is not case-study-dependent but is determined exclusively by the intrinsic characteristics of each retrofit intervention. Consequently, the same invasiveness scores apply to all seven building archetypes. Invasiveness was assessed using an ordinal scale from 1 to 5, where 1 corresponds to the most invasive interventions and 5 to the least invasive ones. The highest invasiveness level (score = 1) is associated with full retrofit scenarios combining multiple intervention categories. In particular, the most invasive configurations are A2 + B5 + C4 + D1 + E1 and other scenarios combining glazing replacement, frame replacement and façade insulation. These interventions involve simultaneous modifications to several building components and therefore represent the highest operational impact. Façade insulation interventions (category C) generally occupy the medium-high invasiveness range, with scores predominantly equal to 2. All external insulation solutions, regardless of material or thickness, are classified within this group, indicating a relatively high level of intervention complexity. Glazing replacement and frame replacement interventions (categories A and B) are generally associated with intermediate invasiveness, with scores equal to 3. These scenarios occupy the central portion of the ranking. The lowest invasiveness level (score = 5) corresponds to stand-alone heating system replacement (E1) and roof insulation interventions (category D). These scenarios represent the least disruptive retrofit solutions for the case study.

Reversibility Analysis

As for the invasiveness criterion, reversibility is not case-study-dependent but is determined exclusively by the intrinsic characteristics of each retrofit intervention and the same reversibility scores apply to all seven building archetypes. Reversibility was assessed using a three-level ordinal scale, where 1 corresponds to the most reversible interventions and 3 to the least reversible ones. Within the set of retrofit scenarios considered in this study, no intervention was classified with the lowest reversibility level (score = 3). Therefore, all scenarios fall within the range between 1 and 2. The highest reversibility level (score = 1) is associated with glazing replacement (category A), frame replacement (category B), and heating system replacement (category E). All interventions belonging to these categories are classified as highly reversible, as they involve replacement or upgrading of building components without causing permanent modifications to the main building structure. By contrast, façade insulation (category C) and roof insulation (category D) are associated with intermediate reversibility (score = 2). All insulation-based interventions fall into this category, regardless of material or thickness. As a result, combined scenarios including at least one intervention from categories C or D generally assume a reversibility score equal to 2, while scenarios composed exclusively of interventions from categories A, B, and E retain the maximum reversibility score.

Sustainability Analysis (Embodied Energy)

The sustainability criterion was assessed through the embodied energy associated with each retrofit scenario, assuming that lower embodied energy corresponds to higher environmental sustainability within the adopted assessment framework. For Cascina Anna, embodied-energy values show substantial variability across intervention categories. For heating-system replacement (E1), the baseline embodied-energy value follows the 0 MJ modelling convention described in Section 2.5 and should therefore not be interpreted as a physically calculated environmental performance. The potential influence of this assumption was separately evaluated through the lower- and upper-bound sensitivity cases described in Section 2.5, while the descriptive statistics reported below refer to the baseline dataset. Among the interventions with explicitly calculated embodied energy, roof-insulation solutions (category D) show the lowest values. This result is partly attributable to the comparatively limited roof area of the tower relative to the façade and glazing surfaces, since the total embodied-energy indicator is an extensive quantity dependent on both material properties and the amount of material required. Glazing replacement interventions (category A) also show comparatively low embodied-energy values, with A1 and A2 reaching 299,086 MJ and A3 and A4 reaching 481,750 MJ. Façade-insulation scenarios (category C) show substantially greater variability, reflecting the combined influence of material properties, insulation thickness, and the larger surface area involved. The highest embodied-energy values within the adopted dataset are associated with polyurethane-based façade insulation (C5), with the 120 mm C5 alternative reaching 2,307,274 MJ.

Final Multiple-Criteria Ranking

The final TOPSIS ranking for Cascina Anna highlights significant differences among retrofit scenarios, with scores ranging from 0.72 to 0.27. The highest-ranked scenario under the modelling assumptions and baseline weighting structure adopted in this study is A2 + D1 + E1, combining glazing replacement (A2), roof insulation (D1), and heating system replacement (E1). Its first-ranked position should therefore be interpreted within the adopted decision model; the potential influence of the simplifying embodied-energy convention applied to E1 is specifically examined through the sensitivity check reported below. Table 5 reports the highest-ranked alternatives together with their resulting EPI, percentage EPI reduction, initial investment cost, NPV, and TOPSIS score. When two or more alternatives have the same TOPSIS score at the reported two-decimal precision, their relative order in Table 5 is determined using resulting EPI as the first secondary criterion and initial investment cost as the second, with lower values preferred for both criteria. This ordering rule is introduced solely to improve the readability of alternatives with equal rounded TOPSIS scores and does not alter the TOPSIS calculation or the underlying closeness coefficients. Percentage reductions are calculated relative to the baseline EPI of Cascina Anna (134.72 kWh/m^2·year). The comparison highlights that the highest TOPSIS score does not necessarily correspond to the maximum energy reduction or the highest NPV. The first-ranked A2 + D1 + E1 scenario reduces EPI to 89.71 kWh/m^2·year (−33.4%), with an investment cost of €75,116.82 and an NPV of €362,793.38. Conversely, A2 + C4 + D1 + E1 achieves a substantially greater EPI reduction (−50.4%) and higher NPV (€586,312.16), but requires a considerably higher initial investment (€152,266.62). This comparison illustrates the multiple-criteria nature of TOPSIS, in which the final preference results from the simultaneous consideration of energy, economic, environmental, invasiveness, and reversibility criteria rather than from the optimization of a single indicator. The presence of roof insulation (D1) in the highest-ranked scenario further illustrates this trade-off. As a stand-alone intervention, roof insulation provides a relatively limited energy benefit for Cascina Anna because of its tower configuration, where the roof represents a small proportion of the overall heat-dispersing envelope. Nevertheless, its comparatively low investment cost and its combination with glazing and heating-system replacement contribute to a favourable overall multiple-criteria balance. Thus, the inclusion of D1 in the highest-ranked scenario under the adopted assumptions highlights the distinction between the stand-alone energy effectiveness of an intervention and its overall suitability within an integrated retrofit strategy. More generally, the top-ranking scenarios are predominantly characterized by combinations of relatively low-cost interventions and glazing replacement solutions. Interventions belonging to categories A, D, and E are recurrent among the highest-ranked alternatives, while stand-alone glazing replacement scenarios also perform particularly well. Intermediate positions are occupied by façade insulation scenarios (category C), particularly lower-thickness solutions, whereas the lowest-ranking scenarios are mainly associated with frame replacement interventions (category B), especially high-cost solutions. The lowest score corresponds to A2 + B9. Notably, the full retrofit scenario A2 + B5 + C4 + D1 + E1, which achieves the best energy performance (EPI = 59.34 kWh/m^2·year), obtains a TOPSIS score of 0.47 and therefore falls in the lower-middle part of the ranking. This result further confirms that maximizing energy performance alone does not necessarily identify the highest-ranked retrofit strategy under the adopted assumptions when economic, environmental, and intervention-related criteria are considered simultaneously. Overall, the broad distribution of TOPSIS scores indicates that the selected criteria effectively discriminate among retrofit scenarios and generate a structured multiple-criteria hierarchy. Finally, the sensitivity check on the embodied energy assigned to E1 showed that replacing the baseline 0 MJ convention with lower- and upper-bound values of 2100 and 7500 MJ, respectively, did not alter the identity of the highest-ranked scenario or the ordering of the principal alternatives at the reported two-decimal precision. A2 + D1 + E1 remained first-ranked (TOPSIS ≈ 0.72), followed by A2 + E1 (≈ 0.71). The principal ranking can therefore be considered robust within the investigated embodied-energy range for boiler replacement.

Table 5. Highest-ranked retrofit scenarios for case study 3E (Cascina Anna), with final TOPSIS scores and corresponding energy and economic performance. (Authors' original elaboration, 2026).

Rank	Retrofit Scenario	Resulting EPI (kWh/m^2·Year)	EPI Reduction (%)	Investment Cost (€)	NPV (€)	TOPSIS Score
1	A2 + D1 + E1	89.71	33.4	75,116.82	362,793.38	0.72
2	A2 + E1	93.31	30.7	60,976.82	340,856.03	0.71
3	A2 + C4 + D1 + E1	66.82	50.4	152,266.62	586,312.16	0.70
4	A2: 4 + 15 + 4 argon	104.91	22.1	29,476.82	463,582.56	0.70
5	A1: 4 + 12 + 4 argon	106.56	20.9	28,836.00	520,409.00	0.70
6	A4: 4 + 12 + 4 + 12 + 4 argon	106.13	21.2	52,545.63	522,843.22	0.69
7	A2 + D1	100.72	25.2	43,616.82	294,169.22	0.68

4. Discussion

The main contribution of this study lies in reversing the usual analytical direction of UHI-oriented research: rather than modelling urban overheating first and then deriving building implications, the framework starts from technical-architectural retrofit options and evaluates their potential relevance for urban-scale climate adaptation. The findings of this study confirm that the optimization of retrofit strategies for large public housing stocks cannot be reduced to a purely energy-based problem. From a technical architecture perspective, retrofit design emerges as a multi-scalar decision process in which building performance, construction feasibility, material sustainability, and urban climate effects must be simultaneously considered. The multiple-criteria approach adopted in this research highlights that the energetically best-performing solution does not necessarily correspond to the most suitable intervention when economic, operational, and environmental constraints are included. This result is particularly relevant for public housing managers, who must prioritize interventions under limited budgets while maximizing benefits at the portfolio scale. A first major result concerns the systematic relevance of glazing replacement (Category A) across all archetypes. Glazing interventions consistently appear among the highest-ranked scenarios, suggesting that relatively low-invasive envelope upgrades can generate substantial performance improvements while maintaining low embodied energy and high reversibility. This finding aligns with previous studies showing that window retrofits often provide one of the best cost-to-benefit ratios in existing residential buildings, especially when original glazing systems are highly obsolete [8]. From the perspective of technical architecture, this reinforces the importance of component-level interventions that improve thermal resistance without requiring deep alterations to the building system. A second key result is the strong performance of roof insulation (Category D), particularly in several archetypes where it appears among the highest-ranked solutions under the baseline weighting structure. This partially contrasts with part of the Mediterranean retrofit literature, where façade insulation is often considered the primary intervention due to the dominant role of wall transmission losses. However, the present results suggest that, in the ALER stock, roof-related heat exchange remains highly relevant, especially in buildings characterized by exposed horizontal surfaces and limited roof insulation. This behaviour is particularly evident for Cascina Anna. The relatively limited stand-alone energy benefit of roof insulation is primarily related to its tower configuration, in which the roof area is small relative to the extensive vertical envelope and total conditioned volume. Consequently, roof insulation alone produces a comparatively limited reduction in EPI. However, its inclusion in higher-ranked combined TOPSIS scenarios illustrates the multiple-criteria nature of the assessment: an intervention with limited stand-alone energy benefits may still contribute to a preferred overall solution when energy, economic, environmental, invasiveness, and reversibility criteria are considered simultaneously. This result confirms that retrofit priorities remain strongly dependent on building morphology and construction period, supporting the typological approach adopted in this study. Conversely, deep retrofit strategies involving simultaneous interventions on glazing, frames, façades, roofs, and heating systems rarely occupy the highest positions in the final TOPSIS ranking. Although these scenarios achieve the best energy performance, they are penalized by high initial costs, increased invasiveness, lower reversibility, and higher embodied energy. This result is consistent with the growing literature questioning the universal economic convenience of deep retrofits, especially in aging residential stock where marginal energy gains may not justify the additional environmental and financial burden [6]. From an architectural engineering standpoint, this suggests that incremental and phased retrofitting strategies may often be preferable to full-scale renovation, particularly when scalability across thousands of dwellings is required. The results also provide relevant insights regarding material selection, particularly in façade insulation scenarios. Cork-based external insulation (C4) systematically performs better than several synthetic alternatives when environmental criteria are considered. This confirms that material choice in technical architecture cannot be evaluated solely through thermal conductivity. Embodied energy, circularity potential, moisture behaviour, and reversibility increasingly influence sustainable retrofit decisions. This is consistent with life-cycle-based approaches in sustainable architecture, where low-carbon bio-based materials are gaining relevance as climate-responsive design solutions.

From the perspective of urban heat island mitigation, the findings support an important conceptual distinction between direct and indirect mitigation strategies. Classical UHI mitigation literature identifies urban albedo increase, vegetation enhancement, cool roofs, cool pavements, and urban ventilation improvement as the primary direct countermeasures [46]. These strategies act directly on urban microclimate by reducing solar absorption, enhancing evapotranspiration, or improving convective heat dissipation. In contrast, most retrofit interventions analyzed in this study operate at the building scale and therefore do not directly modify urban canyon geometry or city-scale albedo. However, any potential contribution of the retrofit strategies examined in this study to UHI mitigation should be interpreted as indirect rather than as a directly quantified outcome. The simulations demonstrate substantial improvements in building energy performance. For Cascina Anna, for instance, the Energy Performance Index (EPI) decreases from 134.72 kWh/m^2·year in the pre-retrofit condition to 59.34 kWh/m^2·year for the energy-optimal full retrofit scenario, corresponding to a reduction of approximately 56%. Similar reductions were observed across the other representative archetypes. These results provide quantitative evidence of the capacity of the investigated retrofit measures to reduce the overall energy performance index at the building scale. A reduction in building energy requirements may, in turn, potentially contribute to decreasing HVAC-related anthropogenic heat emissions, which have been identified as one of the factors affecting urban overheating [5]. In this sense, retrofit interventions that reduce operational energy demand may potentially support UHI mitigation, not by directly cooling urban surfaces, but through a possible reduction in HVAC-related anthropogenic heat emissions. From this perspective, tower buildings such as Cascina Anna provide a relevant case for investigating the potential building-to-city implications of energy retrofit. High-rise residential buildings possess large vertical dispersing surfaces and significantly interact with solar radiation, long-wave radiation exchange, and urban airflow. The detailed case study shows that façade insulation strongly improves energy performance in this typology, confirming the importance of vertical envelope optimization in high-rise structures. Recent studies on the role of the building envelope in UHI mitigation similarly show that façade properties significantly influence both surface temperatures and cooling demand [17]. From the viewpoint of technical architecture, this reinforces the relevance of considering the building envelope not merely as a thermal barrier, but also as a potential interface between building energy performance and urban microclimatic processes.

At the methodological level, this study contributes to existing literature by integrating typological classification, building simulation, and MCDM analysis into a scalable framework. Most previous MCDM-based retrofit studies focus on individual buildings or small samples, limiting transferability to large public portfolios. The present approach addresses this limitation by leveraging typological repetition within the ALER stock. This represents a meaningful methodological advancement because it bridges the gap between detailed building-scale assessment and strategic asset management at the urban scale. In technical architecture, this shift from object-scale to portfolio-scale decision support is increasingly necessary for climate adaptation planning. Compared with other MCDM methods such as AHP, ELECTRE, and VIKOR, the use of TOPSIS proved particularly effective due to its ability to manage a large number of alternatives while maintaining interpretability of results. AHP offers strong support in deriving subjective weights but becomes cumbersome with many alternatives. ELECTRE provides robust outranking relations but may be less intuitive for stakeholders. VIKOR performs well in compromise solutions but is more sensitive to normalization choices. TOPSIS, by contrast, offers a straightforward geometric interpretation based on distance from ideal and anti-ideal solutions, making it particularly suitable for operational decision-making in public housing management.

Despite these contributions, some limitations should be acknowledged. The baseline weighting structure adopted in TOPSIS reflects methodological assumptions that may vary across stakeholders. Although the sensitivity analysis explored the response of TOPSIS scores to alternative weighting configurations, it did not assess rank stability or rank reversal. This limitation is particularly relevant for closely ranked alternatives. For Cascina Anna, the two highest-ranked scenarios under the baseline weighting structure, A2 + D1 + E1 and A2 + E1, obtained TOPSIS scores of 0.72 and 0.71, respectively. Given this limited score separation, the stability of the first-ranked scenario under alternative weighting configurations cannot be established from the present analysis. Future developments should therefore recalculate the complete TOPSIS ranking under alternative weighting structures and explicitly assess rank stability and rank reversal. Similarly, the ordinal invasiveness and reversibility criteria were based on predefined engineering judgment rules rather than on a multi-expert elicitation process; future applications could validate these classifications through structured expert or stakeholder assessment. The preliminary category-level screening reduces the combinatorial complexity of the analysis but may exclude combinations involving alternatives that are not individually top-ranked. Therefore, the resulting ranking should be interpreted within the predefined scenario set rather than as an exhaustive global optimization of the complete theoretical solution space. The conventional zero embodied-energy value assigned to boiler replacement (E1) remains a simplifying baseline assumption. However, the additional lower–upper bound sensitivity check showed that assigning E1 embodied-energy values between 2100 and 7500 MJ did not alter the principal ranking at the reported two-decimal precision. Nevertheless, future applications should incorporate product- or component-specific embodied-energy data for HVAC equipment to improve the physical representativeness of the sustainability criterion. The energy analysis was based on the overall Energy Performance Index and did not separately quantify cooling demand or HVAC-related anthropogenic heat rejection. Therefore, the causal pathway linking building retrofit, reduced HVAC-related anthropogenic heat emissions, and changes in urban temperature was not quantitatively validated in the present study. Future research should disaggregate the energy balance into heating and cooling components and couple building energy simulations with urban microclimate models to assess whether, and to what extent, reductions in building energy requirements translate into measurable reductions in anthropogenic heat emissions and UHI intensity.

5. Conclusions

5.1. Core Research Contributions

This study developed an integrated decision-support framework for the sustainable retrofitting of post-war public residential buildings by combining building-stock typological classification, energy performance assessment, and multiple-criteria decision-making through the TOPSIS method. Applied to representative archetypes of the ALER public housing stock in Milan, the framework enables retrofit alternatives to be assessed beyond energy performance alone by simultaneously considering energy, economic, environmental, and intervention-related criteria. The main methodological contribution therefore lies in linking archetype-based building-stock analysis with multi-criteria retrofit prioritization, providing a structured approach for translating building-scale assessments into portfolio-scale decision support. Rather than identifying a universally optimal retrofit solution, the framework accounts for the influence of building typology and competing performance criteria in the selection of appropriate intervention strategies.

5.2. Practical Application Value

The proposed framework provides ALER and comparable public housing management agencies with a systematic approach for prioritizing retrofit interventions across large and heterogeneous building portfolios. Representative building archetypes can be used as operational proxies for groups of buildings sharing similar geometric and construction characteristics, thereby reducing the need for independent detailed assessments of every individual building. By integrating energy performance with investment cost, economic return, invasiveness, reversibility, and sustainability, the methodology can support the allocation of limited financial and technical resources while accounting for constraints that are particularly relevant to the renovation of existing public housing. The framework is therefore intended as a decision-support tool for developing differentiated and scalable retrofit strategies rather than prescribing a single intervention solution for the entire building stock.

5.3. Future Research Directions

Future research should extend the framework by quantitatively assessing the relationship between building retrofit and urban thermal conditions. In the present study, the potential contribution of retrofit to urban heat island mitigation is considered only through an indirect pathway associated with reductions in building energy requirements and potentially related HVAC anthropogenic heat emissions. This causal pathway was not quantitatively validated, and changes in cooling demand, anthropogenic heat rejection, urban air temperature, or UHI intensity were not directly quantified. A subsequent research stage should therefore couple building-energy simulations with district-scale microclimate or urban canopy modelling and explicitly quantify changes in cooling demand, anthropogenic heat release, and urban thermal conditions under different retrofit scenarios. Further development could also integrate heat pumps and other low-carbon HVAC solutions, nature-based solutions, cool materials, and passive cooling strategies within the same decision-support framework, allowing building-scale retrofit measures and urban-scale climate adaptation strategies to be evaluated jointly.

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Abbreviations

The following abbreviations are used in this manuscript:

MCDM	Multiple-Criteria Decision Making
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution

Appendix A. Baseline Energy Characterization of the Representative Building Archetypes

The following original case-study sheets provide the baseline energy characterization of the seven representative building archetypes. The documentation is reproduced in its original Italian version and reports, for each case study, building volume, surface-to-volume ratio (S/V), number of conditioned floors and dwellings, thermal transmittance (U-value) of the main envelope components, heating and domestic hot-water system characteristics, and baseline energy-performance results.

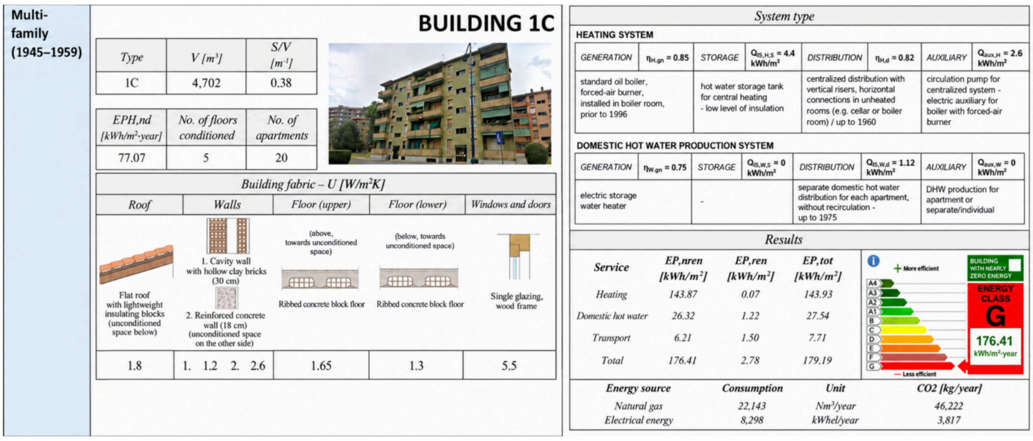

Figure A1. Baseline energy characterization sheet of the representative multi-family building archetype 1C, Comasina case study. Original documentation in Italian (authors' elaboration, 2022; reproduced from preliminary research conducted within a currently embargoed thesis).

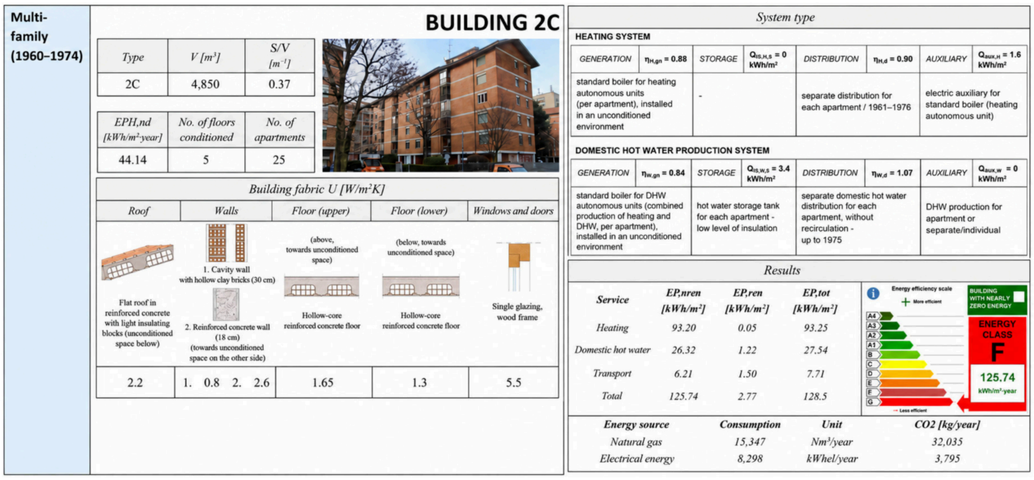

Figure A2. Baseline energy characterization sheet of the representative multi-family building archetype 2C, Chiesa Rossa case study. Original documentation in Italian (authors' elaboration, 2022).

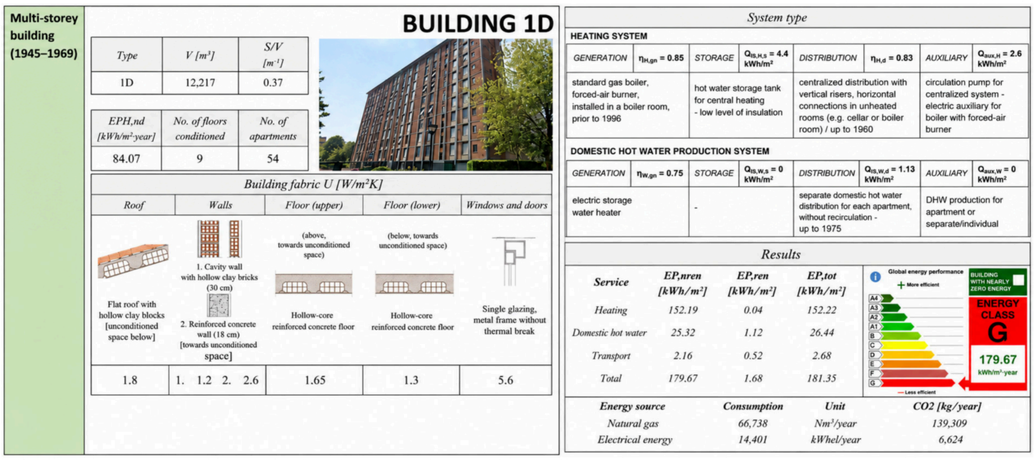

Figure A3. Baseline energy characterization sheet of the representative multi-storey building archetype 1D, Gallaratese G1 case study. Original documentation in Italian (authors' elaboration, 2022; reproduced from preliminary research conducted within a currently embargoed thesis).

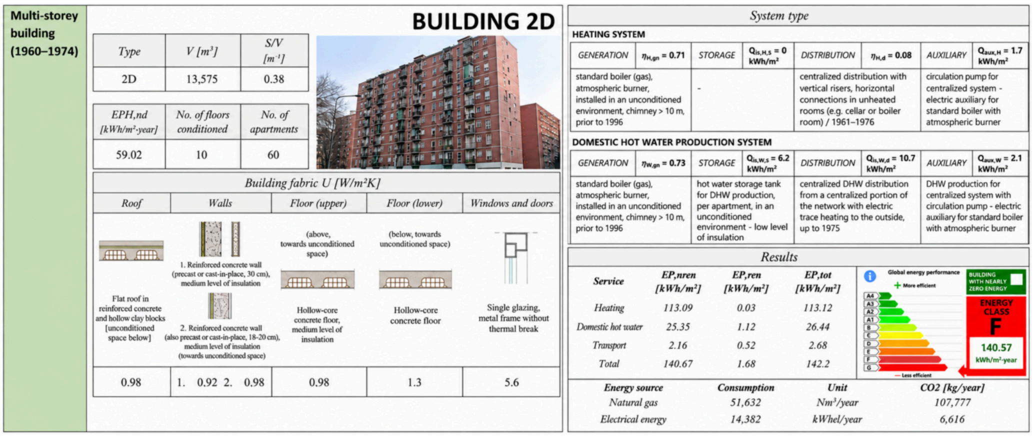

Figure A4. Baseline energy characterization sheet of the representative multi-storey building archetype 2D, Gratosoglio case study. Original documentation in Italian (authors' elaboration, 2022).

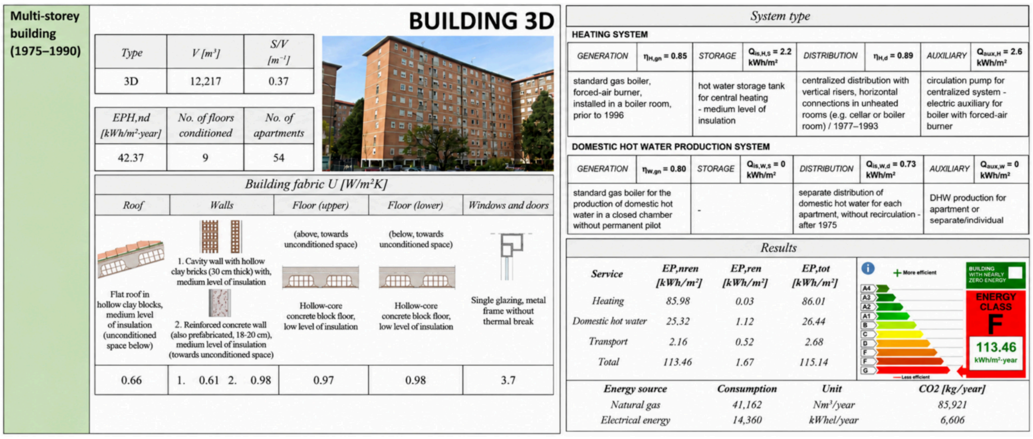

Figure A5. Baseline energy characterization sheet of the representative multi-storey building archetype 3D, Ludovico il Moro case study. Original documentation in Italian (authors' elaboration, 2022; reproduced from preliminary research conducted within a currently embargoed thesis).

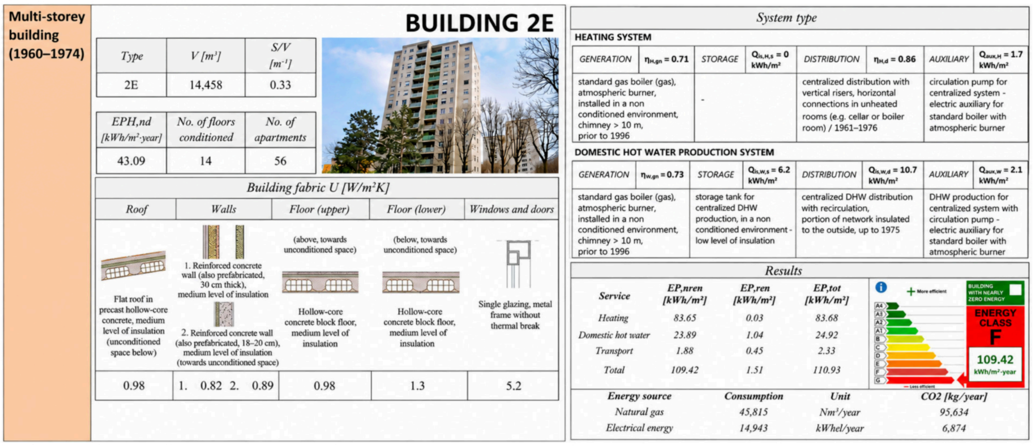

Figure A6. Baseline energy characterization sheet of the representative tower building archetype 2E, Gallaratese G2 case study. Original documentation in Italian (authors' elaboration, 2022).

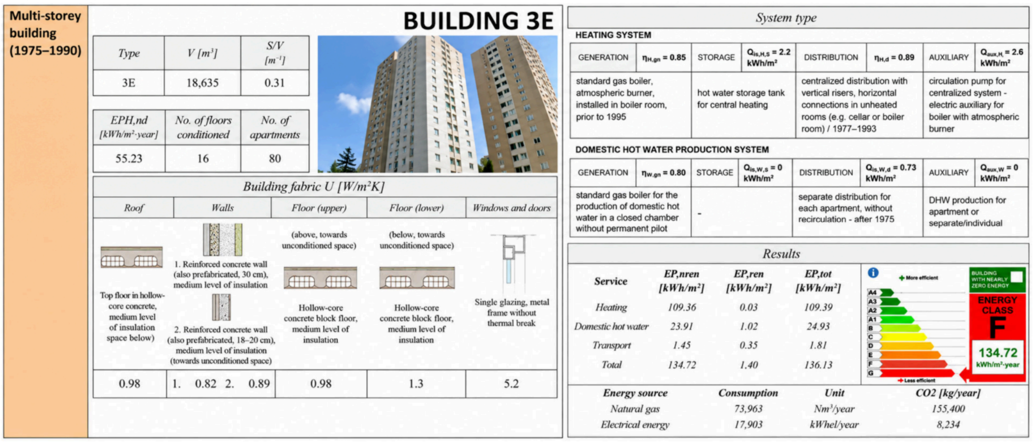

Figure A7. Baseline energy characterization sheet of the representative tower building archetype 3E, Cascina Anna case study. Original documentation in Italian (authors' elaboration, 2022; reproduced from preliminary research conducted within a currently embargoed thesis).

References

1. Santamouris, M. Regulating the damaged thermostat of the cities—Status, impacts and mitigation challenges. *Energy Build.* **2015**, *91*, 43–56. [CrossRef]
2. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2023: Synthesis Report*; IPCC: Geneva, Switzerland, 2023. Available online: https://www.ipcc.ch/report/sixth-assessment-report-cycle/ (accessed on 30 June 2026).
3. European Commission. Energy Efficient Buildings. Available online: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings_en (accessed on 30 June 2026).
4. Kolokotsa, D.; Santamouris, M.; Zerefos, S.C. Green and cool roofs' urban heat island mitigation potential in European climates for office buildings under free floating conditions. *Sol. Energy* **2013**, *95*, 118–130. [CrossRef]
5. Santamouris, M. Recent progress on urban overheating and heat island research: Integrated assessment of the energy, environmental, vulnerability and health impact. *Energy Build.* **2020**, *207*, 109482. [CrossRef]
6. Arroyo, P.; Tommelein, I.D.; Ballard, G. Comparing AHP and CBA as decision methods to resolve the choosing problem in detailed design. *J. Constr. Eng. Manag.* **2014**, *141*, 268–276. [CrossRef]
7. Nesticò, A.; Somma, P. Comparative analysis of multiple-criteria methods for the enhancement of historical buildings. *Sustainability* **2019**, *11*, 4526. [CrossRef]
8. Moghtadernejad, S.; Chouinard, L.E.; Mirza, M.S. Multi-criteria decision-making methods for preliminary design of sustainable facades. *J. Build. Eng.* **2018**, *19*, 181–190. [CrossRef]
9. Hwang, C.L.; Yoon, K. *Multiple Attribute Decision Making: Methods and Applications*; Springer: Berlin, Germany, 1981.
10. Amorocho, J.A.P.; Hartmann, T. A multi-criteria decision-making framework for residential building renovation using pairwise comparison and TOPSIS methods. *J. Build. Eng.* **2022**, *53*, 104596. [CrossRef]
11. Gade, A.N.; Larsen, T.S.; Nissen, S.B.; Jensen, R.L. REDIS: A value-based decision support tool for renovation of building portfolios. *Build. Environ.* **2018**, *142*, 107–118. [CrossRef]
12. Österbring, M.; Camarasa, C.; Nägeli, C.; Thuvander, L.; Wallbaum, H. Prioritizing deep renovation for housing portfolios. *Energy Build.* **2019**, *202*, 109361. [CrossRef]
13. Pannier, M.-L.; Recht, T.; Robillart, M.; Schalbart, P.; Peuportier, B.; Mora, L. Identifying optimal renovation schedules for building portfolios: Application in a social housing context under multi-year funding constraints. *Energy Build.* **2021**, *250*, 111290. [CrossRef]
14. Loga, T.; Stein, B.; Diefenbach, N. *TABULA Building Typologies in 20 European Countries-Making Energy-Related Features of Residential Building Stocks Comparable*; IWU: Darmstadt, Germany, 2016.
15. Ballarini, I.; Corgnati, S.P.; Corrado, V. Use of reference buildings to assess the energy saving potentials of the residential building stock: The experience of TABULA project. *Energy Policy* **2014**, *68*, 273–284. [CrossRef]
16. TABULA Project. Typology Approach for Building Stock Energy Assessment. Available online: https://episcope.eu/building-typology/ (accessed on 22 June 2026).
17. Martinelli, A.; Carlucci, F.; Fiorito, F. On the Role of the Building Envelope on the Urban Heat Island Mitigation and Building Energy Performance in Mediterranean Cities: A Case Study in Southern Italy. *Climate* **2024**, *12*, 113. [CrossRef]
18. Yang, J.; Tham, K.W.; Lee, S.E.; Santamouris, M.; Sekhar, C.; Cheong, D.K.W. Anthropogenic heat reduction through retrofitting strategies of campus buildings. *Energy Build.* **2017**, *152*, 813–822. [CrossRef]
19. ALER Milano. Official Website. Available online: https://aler.mi.it/home/ (accessed on 22 June 2026).

20. Croci, E. *A Comparative Analysis of Global City Policies in Climate Change*; Bocconi University: Milan, Italy, 2010.
21. Ballerini, V.; Rossi di Schio, E.; Valdiserri, P. On the impact of climate change on the thermal energy demand for a building: An analysis based on 50 years of meteorological data. *Energy Ecol. Environ.* **2026**, *11*, 177–195. [CrossRef]
22. ISPRA. Heating Degree Days Indicator. Available online: https://climadat.isprambiente.it/ (accessed on 22 June 2026).
23. ARPA Lombardia. Meteo e Clima. Available online: https://www.arpalombardia.it/dati-e-indicatori/dati-suddivisi-per-tematica/meteo-e-clima/ (accessed on 22 June 2026).
24. Regione Lombardia. Programma per la Valorizzazione del Patrimonio Abitativo ALER. Available online: https://www.regione.lombardia.it/ (accessed on 22 June 2026).
25. Ciulla, G.; Galatioto, A.; Ricciu, R. Energy and economic analysis and feasibility of retrofit actions in Italian residential historical buildings. *Energy Build.* **2016**, *128*, 649–659. [CrossRef]
26. Palladino, D.; Di Turi, S. Energy and Economic Savings Assessment of Energy Refurbishment Actions in Italian Residential Buildings: Comparison between Asset and Tailored Calculation. *Sustainability* **2023**, *15*, 3647. [CrossRef]
27. European Environment Agency (EEA). Heating and Cooling Degree Days. Available online: https://climate-adapt.eea.europa.eu/en/metadata/indicators/heating-degree-days (accessed on 22 June 2026).
28. International Energy Agency (IEA). Heating Degree Days in Italy, 2000–2020. Available online: https://www.iea.org/ (accessed on 22 June 2026).
29. Oke, T.R. *Boundary Layer Climates*, 2nd ed.; Routledge: London, UK, 1987.
30. Pomponi, F.; Moncaster, A. Embodied carbon mitigation and reduction in the built environment—What does the evidence say? *J. Environ. Manag.* **2016**, *181*, 687–700. [CrossRef]
31. Buildings Performance Institute Europe (BPIE). *Europe's Buildings Under the Microscope*; BPIE: Brussels, Belgium, 2011.
32. *UNI EN ISO 6946:2018*; Building Components and Building Elements—Thermal Resistance and Thermal Transmittance—Calculation Methods. UNI: Milan, Italy, 2018.
33. *UNI EN ISO 13370:2018*; Thermal Performance of Buildings—Heat Transfer via the Ground—Calculation Methods. UNI: Milan, Italy, 2018.
34. *UNI EN ISO 10077-1:2018*; Thermal Performance of Windows, Doors and Shutters—Calculation of Thermal Transmittance—Part 1: General. UNI: Milan, Italy, 2018.
35. *UNI EN ISO 14683:2018*; Thermal Bridges in Building Construction—Linear Thermal Transmittance—Simplified Methods and Default Values. UNI: Milan, Italy, 2018.
36. *UNI EN ISO 10211:2018*; Thermal Bridges in Building Construction—Heat Flows and Surface Temperatures—Detailed Calculations. UNI: Milan, Italy, 2018.
37. *UNI/TS 11300-1:2014*; Energy Performance of Buildings—Part 1: Evaluation of Energy Need for Space Heating and Cooling. UNI: Milan, Italy, 2014.
38. *UNI/TS 11300-2:2019*; Energy Performance of Buildings—Part 2: Evaluation of Primary Energy Need and of System Efficiencies for Space Heating, Domestic Hot Water Production, Ventilation and Lighting for Non-Residential Buildings. UNI: Milan, Italy, 2019.
39. Council of the European Communities. Efficiency requirements for new hot-water boilers fired with liquid or gaseous fuels. In *Official Journal of the European Communities*; Council Directive 92/42/EEC of 21 May 1992; Council of the European Communities: Brussels, Belgium, 1992; Volume 167, pp. 17–28.
40. Röck, M.; Saade, M.R.M.; Balouktsi, M.; Rasmussen, F.N.; Birgisdottir, H.; Frischknecht, R.; Habert, G.; Lützkendorf, T.; Passer, A. Embodied GHG emissions of buildings-The hidden challenge for effective climate change mitigation. *Nat. Sustain.* **2020**, *3*, 515–521.
41. *UNI EN 15459:2008*; Energy Performance of Buildings—Economic Evaluation Procedure for Energy Systems in Buildings. UNI: Milan, Italy, 2008.
42. Hammond, G.P.; Jones, C.I. *Inventory of Carbon & Energy (ICE)*, Version 2.0; Sustainable Energy Research Team, Department of Mechanical Engineering, University of Bath: Bath, UK, 2011.
43. Hammond, G.P.; Jones, C.I. Embodied energy and carbon in construction materials. *Proc. Inst. Civ. Eng. Energy* **2008**, *161*, 87–98. [CrossRef]
44. Naumann, G.; Schropp, E.; Gaderer, M. Life Cycle Assessment of an Air-Source Heat Pump and a Condensing Gas Boiler Using an Attributional and a Consequential Approach. *Procedia CIRP* **2022**, *105*, 351–356. [CrossRef]
45. Reza, A.M.M.; Rogoža, A. Life cycle assessment of a condensing gas boiler and compare with an air source heat pump in a residential building. *Moksl.—Liet. Ateitis/Sci.—Future Lith.* **2024**, *16*, 1–8. [CrossRef]
46. Akbari, H. Potentials of urban heat island mitigation. In Proceedings of the 2005 International Conference on Passive and Low Energy Cooling for the Built Environment, Santorini, Greece, 19–21 May 2005.