

Intervention Trajectories for Deep Energy Retrofit: a Comparative Assessment Across Climatic Contexts

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Abstract: - Deep renovation of existing buildings is commonly planned according to the Fabric-First principle, with envelope improvements preceding heating-system upgrades. This study assesses whether a different ordering of the same retrofit measures can provide better intermediate energy and economic outcomes. Two cumulative trajectories are compared: a conventional Fabric-First sequence and a Low-Invasiveness-First sequence, in which system upgrades precede extensive insulation works. The analysis uses a coupled 0D–1D dynamic building–plant model, combining lumped energy balances for indoor zones and heating emitters with one-dimensional transient heat conduction through envelope components, driven by hourly Typical Meteorological Year data. The method is applied to a representative 1970s Italian apartment building in Salerno and Tolmezzo, representing mild Mediterranean and cold Alpine climates. Seasonal heating demand, operating expenditure, capital cost, and marginal cost-effectiveness are evaluated for each cumulative package. Both trajectories reach the same final configuration, but their intermediate performance differs. The Low-Invasiveness-First sequence generally yields lower operating costs at low and medium investment levels, especially in Salerno. Once the complete package is implemented, operating costs decrease by more than 70% in both locations. The results show that retrofit sequencing can materially affect the timing and cost-effectiveness of renovation benefits.

Key-Words: - Heat decarbonisation, Weather Uncertainty Analysis, Typical Meteorological Year, Dynamic thermal model, Building Energy Simulation, Energy retrofit, Fabric first

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1 Introduction

De carbonising the existing building stock requires substantial reductions in heating demand together with a transition towards more efficient and increasingly electrified energy systems. Retrofit programmes have traditionally followed the Fabric-First principle, under which improvements to walls, roofs and windows are completed before the heating plant is replaced or upgraded. Envelope measures can provide large reductions in transmission losses, particularly in poorly insulated buildings. Their marginal benefit, however, does not remain constant as the renovation becomes deeper. Once the most effective components have been treated, further insulation may require extensive construction work and high capital expenditure while acting on an already reduced heat demand. At the same time, advances in heat pumps, low-temperature emitters and weather-compensated control have increased the potential

value of system upgrades introduced at an earlier stage of the renovation process [1]. The choice of intervention order is therefore relevant when renovation measures are implemented progressively rather than as a single project. Budget constraints, access to occupied spaces, construction time and disruption to residents frequently prevent all measures from being carried out simultaneously. More importantly, the effect of an individual action depends on the configuration in which it is introduced. Replacing a heat generator before insulating the envelope, for example, does not produce the same operating conditions as installing the same generator after a large reduction in the building load. For this reason, the present study describes retrofit pathways as ordered sequences of cumulative packages. Starting from the

baseline building, one measure is added at each stage and remains in all subsequent configurations. This representation makes it possible to examine both the combined effect of the measures already implemented and the marginal contribution of the most recent addition. It also captures the interaction between envelope performance, heating-system efficiency and control behaviour along the renovation trajectory. Two alternative intervention logics are considered. The first follows the conventional Fabric-First sequence and prioritises windows and opaque-envelope insulation. The second, termed Low-Invasiveness-First, introduces selected system-level upgrades before the more extensive insulation works. Both sequences contain the same measures and reach the same final configuration; only their order differs. This construction allows differences in intermediate energy performance and cumulative investment to be attributed directly to the retrofit sequence. The comparison is carried out for a representative Italian multi-family residential building dating from the 1970s. The same archetype is analysed in Salerno and Tolmezzo, which provide markedly different heating conditions: a mild Mediterranean climate and a cold Alpine climate, respectively. The use of two locations makes it possible to assess how the value of envelope and system interventions changes with the magnitude and duration of the heating load. A dynamic building-plant model is used because the response of a renovated building cannot be described solely through steady or monthly averaged quantities. Thermal storage in the envelope, hourly outdoor conditions, solar and internal gains, emitter inertia, part-load generator behaviour and control actions all influence the energy exchanged between the building fabric and the heating system. In the adopted formulation, indoor environments and heating emitters are represented by lumped energy balances, while multilayer envelope components are treated as one-dimensional transient heat-conduction domains. The coupled equations provide indoor-air and surface temperatures together with the heating energy required under each retrofit configuration. The analysis focuses on seasonal heating demand, operating expenditure, cumulative capital expenditure and marginal cost-effectiveness. The main question is not simply which set of measures gives the lowest final demand, since both trajectories share the same end state. Instead, the study examines how quickly operating costs fall along each sequence, how much investment is required to obtain those reductions, and whether the relative advantage of the two retrofit logics changes with climate.

2 Problem Formulation: Proposed Dynamic Framework

Standardised calculation procedures for building energy performance, such as UNI/TS 11300, [2], are widely adopted for regulatory compliance and energy certification. However, these approaches are typically

based on quasi-steady-state assumptions, which are known to contribute significantly to the gap between predicted and actual energy consumption [3].

To overcome these limitations, the proposed methodology adopts a dynamic modelling framework that integrates building-plant simulation with hourly climatic data based on Typical Meteorological Years (TMY) [4]. This allows the model to account for the climatic variability of boundary conditions while preserving physical consistency in the representation of thermal processes.

The adoption of a dynamic approach is essential to properly capture key physical phenomena that are neglected in simplified methods, including thermal inertia effects, transient heat transfer, and the non-linear performance of systems operating under part-load conditions.

Within this context, the proposed framework is intended not only as a predictive tool, but as a decision-support methodology for the evaluation of alternative retrofit strategies in terms of both capital and operational expenditures.

The modelling approach is structured around five main dimensions:

- *Temporal Resolution*: the model operates at an hourly time step, enabling the representation of transient effects and peak load conditions.
- *Thermal Inertia*: the thermal storage capacity of the building envelope is explicitly modelled as a physical property rather than an empirical correction factor.
- *Gain Modelling*: solar and internal gains are treated as time-dependent boundary conditions.
- *System Behaviour*: non-linear part-load operation of generators is explicitly considered, allowing accurate representation of performance variations (e.g., COP degradation in heat pumps).
- *Control and Comfort*: control strategies are included as active model variables, ensuring that thermal comfort is treated as a constraint in the overall techno-economic assessment.

3 Tools and methods

The adopted methodological framework is structured into two main components: a dynamic numerical model to simulate the building-plant system, and the definition of climatic scenarios based on Typical Meteorological Years. The former establishes the physical and operational representation of the system, while the latter provides statistically representative boundary conditions for the evaluation of the energy demand and operational costs associated with the proposed intervention trajectories.

3.1. Coupled lumped- and distributed-parameter dynamic model

The thermal behaviour of the building–plant system is represented through a physics-based dynamic model combining lumped-parameter and distributed-parameter subsystems. The overall scheme comprises three zero-dimensional (0D) thermal subsystems—the conditioned indoor environment, the adjacent unconditioned space, and the heating emitter—and three one-dimensional (1D) multilayer envelope components. The latter represent the external wall separating the conditioned space from the outdoor environment, the partition separating the conditioned and unconditioned zones, and the external wall separating the unconditioned zone from outdoors.

The 0D subsystems are characterised by spatially uniform temperatures and are described through transient energy-balance equations. Conversely, the opaque envelope components are represented as distributed domains in which the temperature varies across the wall thickness and evolves over time. The outdoor environment provides the climatic boundary conditions, while transparent components, ventilation, solar gains, internal gains, and the heating system are included through the corresponding heat-flow terms.

The plant control logic is incorporated as an active part of the coupled model. Depending on the considered configuration, it determines the operating state and thermal output of the heating system from the relevant indoor, outdoor, and water-temperature signals. The formulation can therefore reproduce different control strategies, including on/off operation, modulation, and weather-compensated supply-temperature control.

Figure 1 (Appendix) illustrates the complete building–plant representation, including the thermal zones, the multilayer envelope components, the heating emitter, the heat generator, and the associated control logic. The resulting system is solved through the finite element method in COMSOL Multiphysics [5].

Lumped-parameter energy balances for the 0D subsystems For the conditioned indoor environment, characterised by a spatially uniform air temperature (T_i) and an equivalent thermal capacitance (C_i), the energy balance includes the heating input ($\dot{Q}_{HS}$), solar gains through transparent components ($\dot{Q}_{sol,w}$), internal gains ($\dot{Q}_{int}$), transmission heat flows through the opaque and transparent envelope components ($\dot{Q}_{tr,i,1}$, $\dot{Q}_{tr,i,2}$, $\dot{Q}_{tr,w}$), and ventilation heat exchange ($\dot{Q}_{ven}$). It can be written as

$$C_i \frac{\partial T_i}{\partial t} = \dot{Q}_{HS} + \dot{Q}_{sol,w} + \dot{Q}_{int} - \dot{Q}_{tr,i,1} - \dot{Q}_{tr,i,2} - \dot{Q}_{tr,w} + \dot{Q}_{ven} \quad (1)$$

The heating-input term represents the power delivered by the emitter to the indoor environment. The transmission terms in eqs. (2) and (3) describe convective heat exchange between the indoor environment and the internal surfaces

of the adjacent 1D envelope components:

$$\dot{Q}_{tr,i,1} = h_i A_i [T_i(t) - T_1(0, t)] \quad (2)$$

$$\dot{Q}_{tr,i,2} = h_i A_{s,i} [T_i(t) - T_2(0, t)] \quad (3)$$

Here, the wall temperatures evaluated at the surfaces facing the indoor environment are supplied by the corresponding one-dimensional models. These terms therefore provide the direct coupling between the lumped indoor environment and the distributed envelope components. The adjacent unconditioned space, represented in the present case by the stairwell, is also modelled as a lumped thermal subsystem. Using the adopted heat-flow sign convention, its energy balance is

$$C_s \frac{\partial T_s}{\partial t} = \dot{Q}_{sol,w} + \dot{Q}_{tr,2,s} + \dot{Q}_{tr,s,3} + \dot{Q}_{ven} \quad (4)$$

where the left-hand side represents thermal storage within the unconditioned zone. The transmission terms couple this subsystem with the partition facing the conditioned space and with the envelope component facing outdoors. The heating emitter is provided with its own thermal inertia and is dynamically coupled with both the hydronic circuit and the indoor environment. For a radiator, the corresponding balance is written as

$$C_{rad} \frac{\partial \bar{T}_{rad}}{\partial t} = 2 \dot{m}_{H_2O} c_{p,H_2O} (\bar{T}_{rad} - T_{w,o}) + \quad (5)$$

$$- h_{rad} A_{rad} (\bar{T}_{rad} - T_i(t))$$

In this expression, the radiator is represented through a mean temperature $\bar{T}_{rad}$, the water outlet temperature $T_{w,o}$, and the water mass flow rate $\dot{m}_{H_2O}$. The product of the emitter heat-transfer coefficient and exchange area determines its heat-transfer capability and depends on its type, size, and number of emitting elements [6]. The second term on the right-hand side corresponds to the heating power transferred to the indoor environment.

One-dimensional transient model of the multilayer envelope components Unlike the thermal zones and the heating emitter, each opaque envelope component is represented as a one-dimensional distributed-parameter domain. The spatial coordinate x is defined across the component thickness, and each material layer is assigned its own density, specific heat capacity, and thermal conductivity. For the j -th homogeneous layer, occupying the interval between two consecutive interfaces, the transient heat-conduction equation is

$$\rho_j c_j \frac{\partial T_j(x, t)}{\partial t} = \frac{\partial}{\partial x} \left(k_j \frac{\partial T_j(x, t)}{\partial x} \right) \quad (6)$$

where density ρ , specific heat capacity c , and thermal conductivity k are defined separately for each layer. At the interfaces between adjacent layers, continuity of both temperature and conductive heat flux is imposed. At the surface facing an indoor or unconditioned zone, heat

exchange is described through a convective boundary condition. The surface temperature obtained from the one-dimensional model is consequently coupled directly with the energy balance of the adjacent 0D thermal environment. At an external surface, the boundary condition accounts for convective heat exchange with the outdoor air, absorbed short-wave solar radiation, and long-wave radiative exchange with the sky.

The incident short-wave solar radiation is introduced as an hourly forcing term derived from PVGIS for the orientation of the considered façade, thereby accounting for the azimuth-dependent solar exposure of each vertical surface. The long-wave radiative contribution is evaluated through the nonlinear Stefan–Boltzmann term

$$\dot{q}_w = \varepsilon \sigma (T_w^4 - T_{sky}^4) \quad (7)$$

where T_w denotes the external surface temperature, T_{sky} the effective sky temperature, ε the surface emissivity, and σ the Stefan–Boltzmann constant. In the present implementation, the effective sky temperature is estimated by adopting representative mean-cloudiness conditions, providing an effective description of the radiative exchange between the external surface and the sky. The distributed formulation provides the complete transient temperature field across each multilayer component, together with its internal and external surface temperatures. In combination with the indoor-air temperature, the internal surface temperatures provide the physical quantities required for assessing indoor thermal comfort, including radiant and operative-temperature effects. At the same time, the coupled dynamic response of the envelope, thermal zones, heating emitter, and generator enables the operation and performance of different HVAC control strategies to be evaluated.

Numerical solution and model verification The complete set of coupled ordinary and partial differential equations is solved through the finite element method in COMSOL Multiphysics. Hourly climatic and operational inputs are applied as time-dependent forcing functions, while the numerical solver resolves the transient interaction among the envelope, thermal zones, emission system, heat generator, and control logic.

Model verification is performed through a case-study-based benchmarking procedure using the certified building-energy simulation software TerMus Plus, which provides hourly dynamic calculations. The comparison refers to the baseline building configuration located in Salerno and subjected to TMY climatic conditions. The primary energy demand for space heating predicted by the proposed model differs from the reference simulation by approximately 6%, indicating satisfactory agreement for the purposes of the present comparative assessment.

Model verification was also performed through comparison with analytical solution for limiting case and reference calculation method based on the UNI/TS 11300 standard for quasi-steady-state thermal conditions. The

relative deviations between the energy demand calculated by the proposed model and the values obtained from the TerMus BIM software are reported in Table 1, showing the level of agreement between the two approaches. The objective is not to reproduce the full functionality of a commercial simulation package, but to provide a transparent, fully controllable, physics-based model suitable for detailed investigation of building energy performance, indoor thermal conditions, and building–plant control interactions.

Month	TerMus BIM
NOV	1.78
DEC	1.30
JAN	1.72
FEB	0.48

TABLE 1: RELATIVE DEVIATION [%].
SOURCE: CREATED BY THE AUTHORS.

3.2. TMY Selection

To ensure that the driving forces applied to the dynamic model are physically consistent and representative of real conditions, the methodology involves the construction of a TMY; it is defined as a synthetic climatic year composed of 12 real months, each independently selected as the most representative of long-term climate in a given location [4]. The primary objective of this procedure is to minimise statistical discrepancies between the typical year and the multi-year historical dataset, thereby ensuring the consistent preservation of temporal correlations among meteorological variables.

The selection procedure is based on the Finkelstein–Schafer (F–S) statistic, an internationally recognised method whose application follows established methodological protocols [7]. The analysis comprises the following steps:

- *Cumulative Distribution Analysis:* for each meteorological variable, the empirical cumulative distribution function (ECDF) is computed. A reference distribution (F_{ref}) is defined, derived from the aggregation of the entire historical time series, and a specific distribution is calculated for each candidate month (F_{cand}).
- *Statistical Deviation Calculation:* the F–S statistic is defined as the integral of the absolute difference between F_{ref} and F_{cand} and quantifies the statistical distance between the variability of the candidate month and that of the ten-year reference dataset.
- *Selection and Composition:* each month of the TMY is selected from the set of corresponding months within a ten-year record to minimise the F–S deviation. This approach overcomes the limitations associated with simple monthly averaging by

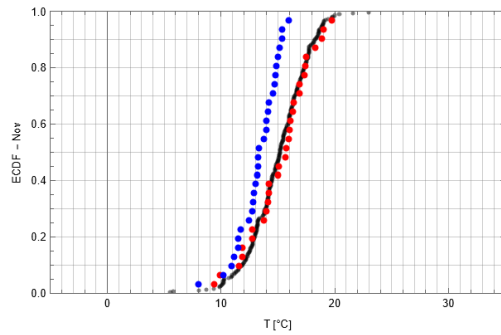


Fig. 1: Candidate month considered for the selection of the TMY (NOV 2016, SA) and the corresponding month used in the generation of the XMY (NOV 2017, SA).

Source: created by the authors.

providing hourly forcing data consistent with the dynamic behaviour of the building system, while preserving site-specific meteorological variability, Figure 1.

Beyond the standard TMY, the adopted methodology enables the generation of additional synthetic climate years, which constitute essential tools for assessing system resilience under non-typical thermal conditions. In particular, the *XMY* (*Extreme Meteorological Year*) represents the scenario associated with the maximum statistical deviation from average climatic conditions, and is used as a climatic stress test to evaluate the robustness and performance limits of the building-plant system. The use of this set of meteorological forcing variables allows the evaluation of retrofit strategies not only under standard operating conditions, but also under peak loads and extreme thermal variations that can occur within the same geographical location.

For the purposes of the case study, the analysis is based on a ten-year dataset (2014–2023) collected from meteorological stations located at the investigated sites, namely the Salerno METEO station, managed by the Centro Funzionale Multirischi Campania, and the Tolmezzo station, operated by ARPA Friuli Venezia Giulia. The datasets provide the main meteorological variables required for the analysis, including air temperature, wind speed, relative humidity, solar radiation, and precipitation.

The Tolmezzo station provides data with an hourly acquisition time step, whereas the Salerno station records measurements every 10 minutes. Therefore, the Salerno dataset was resampled at an hourly resolution to ensure temporal consistency between the two datasets.

A 15% threshold of missing data was adopted as the acceptability limit [4]. The isolated missing values were corrected by linear interpolation, while more extensive gaps were filled using data from nearby meteorological stations located within a maximum radius of 30 km. Finally, the datasets were validated by assessing their consistency with the historical time series.

The Figures 2a, 2b (Appendix) illustrate the time evolution of the four synthetic years generated for the two

locations analysed. The heating season is also highlighted, evidencing a marked difference between Salerno and Tolmezzo, which are classified as climate zones C and F¹, respectively.

4 Cumulative Modelling of Building Retrofit Trajectories

Energy efficiency improvements in buildings are achieved through targeted interventions in the envelope and/or building systems. In this context, efficiency measures are defined as elementary actions that can be implemented either individually or in combination, and are classified into two main categories: (i) envelope-related interventions and (ii) system and control upgrades.

Envelope interventions include: (a) replacement of existing windows with high-performance units featuring low-emissivity double glazing and thermally broken frames, thereby reducing transmission losses and air infiltration; (b) partial insulation targeting the most heat-loss-prone elements (north-facing walls and roof) and (c) full insulation of the opaque envelope. System interventions comprise: (a) condensing boilers with modulating operation and climatic control; (b) fan coil units, characterised by low thermal inertia and rapid control response; and (c) air-to-water heat pumps, whose performance is strongly dependent on operating conditions and climatic context.

Although the analysis of individual interventions enables the assessment of their isolated impact on building energy performance, it does not adequately reflect real-world retrofit processes. In practice, measures are rarely implemented in isolation; rather, they are combined and sequenced according to technical, economic, regulatory, and construction-related constraints.

Each intervention alters the system configuration and, consequently, influences the effectiveness of subsequent measures. As a result, the overall performance cannot be interpreted as the linear sum of individual effects, but must be understood as the outcome of their interaction.

To address this aspect, a cumulative modelling framework is adopted. Retrofit trajectories are represented as ordered sequences of cumulative intervention packages. Each package is obtained by adding one intervention to the previous configuration, without replacing the measures already included. The index (i) therefore identifies the aggregation level of the retrofit package. The retrofit process is formalised as follows:

$$P[i] = P[i - 1] \cup \Delta[i] \quad i = 1, \dots, 6 \quad (8)$$

where $\Delta[i]$ denotes the incremental intervention added to the package $P[i - 1]$.

The initial state $P[0]$ represents the baseline configuration. It is characterised by the absence of

¹climate zone F, no regulatory upper limit is defined for the duration of the heating period; however, for simulation purposes, a conventional time horizon of 200 days has been adopted, corresponding to the upper bound prescribed for climate zone E.

thermal insulation and the presence of high-transmittance windows. The heating system consists of a traditional boiler operating at a fixed set-point with radiators.

For each individual measure and intervention package, both capital (CapEx) and Operational expenditure (OpEx) are evaluated. Capital costs are treated as cumulative costs associated with the corresponding package, while operating costs are evaluated for the resulting retrofit configuration under the selected climatic boundary conditions. Cost data are derived from current regional price lists (2025), with reference to the regions of Friuli Venezia Giulia, and Campania. Where cost items are consistent across regions, a unified value is adopted; otherwise, regional differences are explicitly accounted for.

Within this framework, two alternative retrofit trajectories, Table 2, are developed, each reflecting a different strategic approach. The Fabric First trajectory (FF) prioritises envelope improvements before system replacement. The Low-Invasiveness-First trajectory (LIF) initially favours system-level interventions and subsequently introduces envelope-related measures. Both trajectories are applied to the two locations analysed, in order to assess the interaction between retrofit logic, technological choices and climatic context.

TABLE 2: BASELINE CONFIGURATION AND ORDERED SEQUENCES OF INCREMENTAL RETROFIT MEASURES DEFINING THE FF AND LIF TRAJECTORIES.

i	Fabric First	Low Invasiveness
0	Baseline configuration	Baseline configuration
1	Window replacement	Window replacement
2	Roof + N-wall insulation	Replacement of the existing boiler with an EHP ^(a)
3	NE/NW-wall insulation	FC units
4	S-wall insulation	Roof + N-wall insulation
5	Replacement of the existing boiler with an EHP ^(a)	NE/NW-wall insulation
6	FC units	S-wall insulation

SOURCE: CREATED BY THE AUTHORS.

^(a) Air-to-water electric heat pump equipped with weather-compensated control (EHP).

5 Case study

The case study refers to a representative archetype of Italian residential buildings from the post-war period, designed to capture the typical construction and energy characteristics of the existing building stock, Figure 3 (Appendix). The selected model is a six-story multi-family building dating to the 1970s, defined to

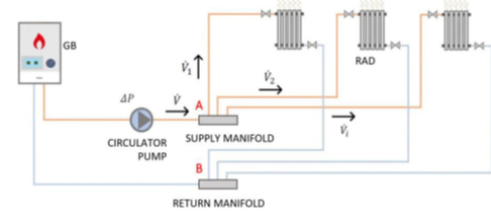


Fig. 2: Functional diagram of the heating system.

Source: created by the authors.

provide a realistic yet generalisable framework for analysing the thermal behaviour and system performance of pre-2000 constructions. From an envelope perspective, the building reflects the technological transition from massive to lightweight construction systems, Table 3 and Table 4. The external walls consist of a double-leaf masonry infill within a reinforced concrete frame, a solution widely adopted during the period. Specifically, the wall is composed of two beams of horizontally perforated clay blocks, separated by an air cavity and finished with plaster layers on the exposed faces [5]. The building envelope is uninsulated and features single-glazed windows with a high thermal transmittance of $5.0 \text{ W m}^{-2} \text{ K}^{-1}$, resulting in significant heat losses through the glazed surfaces. Furthermore, the roof exhibits a thermal transmittance of $U = 1.1632 \text{ W m}^{-2} \text{ K}^{-1}$.

The heating system consists of a traditional boiler operating at a fixed supply-water temperature and feeding cast-iron radiators. The boiler is regulated by its built-in water-temperature thermostat, without room-level temperature control, Figure 2.

This configuration is assumed as the baseline scenario $P[0]$ for the application of retrofit intervention packages and is used as the reference case for the evaluation and comparison of all energy efficiency improvement strategies.

TABLE 4: STATIC AND DYNAMIC WALL PROPERTIES ACCORDING TO [8] AND [9] RESPECTIVELY.

Layer	L [mm]	ρ [kg m ⁻³]	c [J kg ⁻¹ K ⁻¹]	k [W m ⁻¹ K ⁻¹]	T.R. [m ² K W ⁻¹]
Plaster	10	1400	1000	0.700	0.014
Brick	120	667	840	0.304	0.395
Air layer	50	—	—	—	0.180
Brick	120	667	840	0.304	0.395
Plaster	10	1400	1000	0.700	0.014

TABLE 3: THERMAL PROPERTIES OF THE EXTERNAL WALL LAYERS.

SOURCE: CREATED BY THE AUTHORS.

Static transm.	Dynamic transm.	Decrement factor	Time lag
U [W m ⁻² K ⁻¹]	Y_{IE} [W m ⁻² K ⁻¹]	f [-]	t_{IE} [h]
0.8562	0.5220	0.57	6.80

SOURCE: CREATED BY THE AUTHORS.

5.1. Fabric First Approach

The FF strategy is based on the widely recognised envelope-first principle established in the European building energy literature and regulatory frameworks. The initial phase prioritises interventions on the building fabric which are primarily responsible for transmission heat losses and demand for space heating.

In particular, envelope insulation is improved by adding an expanded polystyrene (EPS) layer, as previously described, with a thickness of 10 cm and a base thermal conductivity of $\lambda = 0.03 \text{ Wm}^{-1}\text{K}^{-1}$, to reduce conductive heat losses and improve overall thermal performance. This intervention results in a reduction in overall thermal transmittance (U-value) from $0.8562 \text{ Wm}^{-2}\text{K}^{-1}$ to $0.2222 \text{ Wm}^{-2}\text{K}^{-1}$, corresponding to a decrease of 74.05%, thus significantly increasing the thermal resistance of the envelope. Insulation is implemented in a stepwise manner, starting with the north-facing walls, followed by the East and West orientations, and finally the South-facing walls, to reflect a staged retrofit of the building envelope. For the roof, a high-performance retrofit solution was implemented, upgrading the original uninsulated reinforced concrete and hollow brick assembly to a thermally insulated configuration. This intervention reduced overall thermal transmittance to $0.2010 \text{ Wm}^{-2}\text{K}^{-1}$, thus significantly reducing heat losses through the upper envelope of the building by 82.70%. The envelope retrofit was further complemented by the replacement of existing windows with low-emissivity double-glazed units, characterised by a thermal transmittance of $2.4 \text{ Wm}^{-2}\text{K}^{-1}$. These measures are characterised by long service life and limited maintenance requirements, while also contributing to improved indoor temperature stability and thermal comfort. Although external thermal insulation systems (ETICS) are subject to degradation mechanisms driven by environmental exposure (e.g. solar radiation and moisture), these effects develop over long timescales (approximately 35 years), ensuring that the benefits of reduced energy demand and improved envelope performance prevail over the operational life of the building [10]. Therefore, their effect is mainly associated with a permanent reduction in the heating load [11] and with a lower sensitivity of the building to outdoor climatic fluctuations.

The subsequent phase focuses on the upgrade of the building service system. The reduction in heating demand enables a transition towards lower-temperature operation and the adoption of more efficient heat-generation and emission technologies [12]. In this context, replacement of the existing radiator system with exposed fan coil units, combined with the installation of a new two-pipe hydronic distribution network with apartment-level manifolds, allows the system to operate with reduced thermal inertia, faster response, and improved room-level control. The heat-generation system was upgraded by installing an air-to-water heat pump using R290 as the refrigerant and equipped with weather-compensated supply temperature

regulation. This control strategy continuously adjusts the temperature of the water supply according to outdoor conditions, reducing the increase in temperature for most of the heating season and consequently improving the seasonal coefficient of performance (SCOP). Despite its advantages, this strategy is associated with some drawbacks. These include higher investment costs, longer implementation times, and greater invasiveness compared to system-orientated interventions. Moreover, after substantial envelope improvements, heat generators may operate for longer periods close to their minimum modulation capacity. This can lead to suboptimal part-load operation and increased cycling effects, with possible impacts on seasonal system efficiency.

5.2. Low-Invasiveness-First Approach

The LIF strategy prioritises interventions that minimise disruption to building operation, followed by measures that require progressively more substantial modifications to the existing building system.

The same retrofit measures previously defined for the Fabric-First approach are retained, while their implementation sequence is rearranged according to the level of invasiveness and operational disruption associated with each intervention. This criterion is consistent with the approach adopted in the retrofit literature, where invasiveness and disruptiveness are recognised as relevant parameters for the evaluation of renovation strategies, considering both the impact of interventions on the characteristics of the existing building and the degree of interference with the use of the building and the activities of the inhabitants [13].

The order was established through a qualitative assessment of each measure in terms of physical invasiveness, interference with occupied spaces, need for internal construction works, execution time, and disruption of normal building operation. System-level measures were generally placed before extensive envelope interventions because they involve more localised works and less alteration of the existing building fabric, while façade and roof insulation require broader construction activities and more substantial modifications to the envelope. Although fan-coil installation requires work within occupied spaces, it was ranked before extensive envelope insulation because, under the implementation assumptions adopted in this study, the intervention is spatially localised, can be carried out incrementally at apartment level, requires a shorter execution time, and does not alter the external building fabric.

Consequently, envelope-related measures, particularly extensive insulation upgrades, are positioned in the later stages of the LIF sequence because they involve longer execution times, broader construction activities, greater modification of the existing envelope, and higher implementation complexity during building operation.

This makes the approach particularly suitable for incremental retrofit strategies, enabling a more adaptable

and staged energy-upgrade pathway. It should be emphasised that only the ordering of the retrofit measures is modified according to the Low-Invasiveness-First logic. All technical specifications and performance parameters of the individual interventions remain unchanged.

6 Results and discussion

Based on the methodologies described above, dynamic numerical simulations were carried out for each cumulative retrofit package and for the climatic scenarios previously defined. The same occupancy schedules and internal heat-gain profiles were adopted for all configurations, as shown in Figure 3, in order to ensure a consistent comparison among retrofit packages and climatic boundary conditions. In the present analysis, the package index does not represent an implementation time. It identifies the position of each cumulative configuration within the ordered retrofit sequence. Therefore, each package is evaluated as an independent building-plant configuration: CapEx represents the cumulative investment associated with the package, while OpEx is calculated for the corresponding operating configuration under the selected climatic forcing.

The simulation outputs include seasonal heating energy demand, operating expenditure, indoor air temperatures, and internal surface temperatures of the building envelope components. In this study, the discussion focuses on seasonal heating demand, OpEx, cumulative CapEx and marginal cost-effectiveness. Indoor air and surface temperature results are used to verify the consistency of the thermal response, but they are not discussed in detail here and will be addressed in future developments.

Fabric First - Salerno As the analysed configuration consists of a cumulative package of retrofit measures, the total CapEx — and, consequently, the economic trajectory — increases monotonically as the cumulative package index increases, Figure 4.

The trajectory is characterised by discrete cost increases of varying magnitude, reflecting the different economic weight associated with each retrofit action.

In particular, window replacement and the first envelope insulation intervention (North wall and roof insulation) represent the most capital-intensive measures. Similarly, the installation of fan coil units and the heat pump leads to substantial increases in the total investment cost, consistent with the typical economic structure of HVAC retrofit interventions. By contrast, subsequent envelope insulation measures (NE+NW and South walls) generate intermediate cost increases.

Figure 4a (Appendix) also illustrates the energy trajectory of the system, highlighting the monotonic reduction in both operating costs and energy demand as additional measures of energy-efficiency are progressively included in the cumulative package.

The differences among the climatic scenarios are more pronounced in the initial configurations, which are

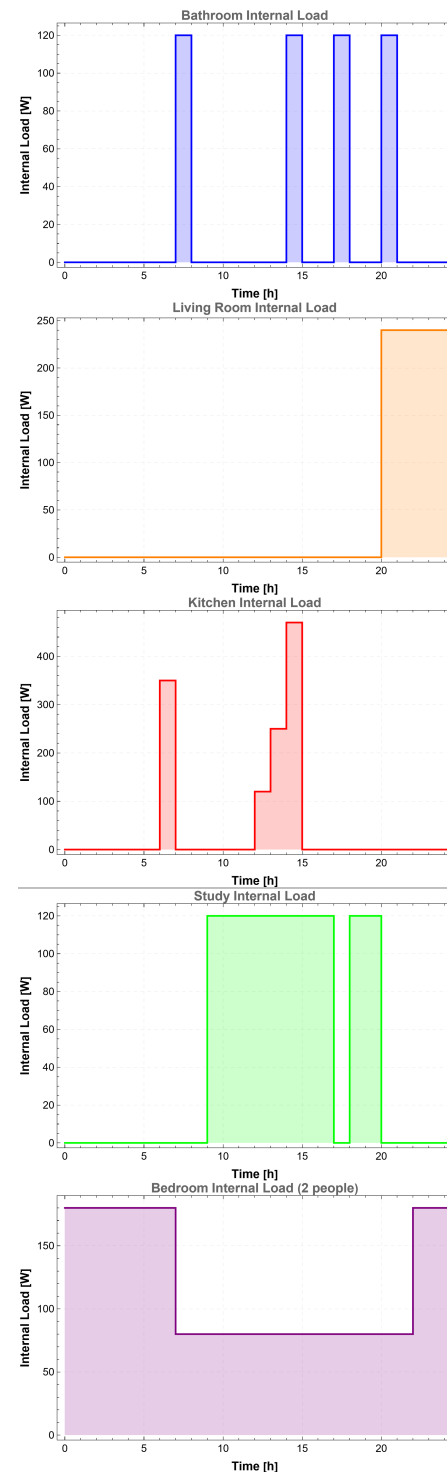


Fig. 3: Hourly daily internal load profiles for different rooms.
Source: created by the authors.

characterised by a high energy demand and a stronger dependence on external climatic conditions. As additional measures are included in the cumulative package, these differences gradually decrease as the residual energy demand becomes increasingly less sensitive to climatic variability.

Overall, the trajectory demonstrates that highly efficient configurations not only achieve substantial reductions in energy-related operating costs, but also ensure more stable energy performance under different climatic conditions.

The slope of the cost–performance curve, Figure 5, is expressed through the marginal effectiveness indicator $R[i]$, associated with the addition of the retrofit measure $\Delta[i]$, namely with the transition from package $P[i - 1]$ to package $P[i]$:

$$R[i] = \frac{\text{OpEx}[i - 1] - \text{OpEx}[i]}{\text{CapEx}[i] - \text{CapEx}[i - 1]} \quad i = 1, \dots, 6 \quad (9)$$

OpEx denotes the energy cost associated with space-heating consumption during the single heating season considered for each climatic scenario, whereas CapEx denotes the cumulative capital investment associated with the retrofit package. Accordingly, $R[i]$ is dimensionless and expresses the seasonal operating-cost reduction obtained per unit of additional capital investment. Higher values of $R[i]$ therefore identify retrofit additions with greater marginal cost-effectiveness within the adopted package sequence.

Overall, the curve exhibits a pronounced OpEx reduction in the first package additions, indicating that the initial configurations provide the highest marginal returns in terms of operating-cost reduction. As further measures are included, each additional intervention acts on an increasingly reduced residual energy demand, resulting in diminishing marginal effectiveness along the cumulative retrofit trajectory.

A further significant reduction in OpEx is observed in correspondence with the final HVAC-related package additions, particularly after the replacement of the heat generator, which produces a step-change in overall system efficiency.

From a marginal performance perspective, the most effective interventions along the *Fabric First* pathway are:

- (i) window replacement, which, despite its relatively high investment cost, delivers substantial operational savings;
- (ii) heat generator replacement, characterised by a relatively limited incremental CapEx and a strong impact on OpEx reduction; and
- (iii) the installation of fan coil units contributes significantly to the improvement of overall system efficiency.

In contrast, subsequent envelope insulation measures exhibit progressively lower marginal effectiveness. In

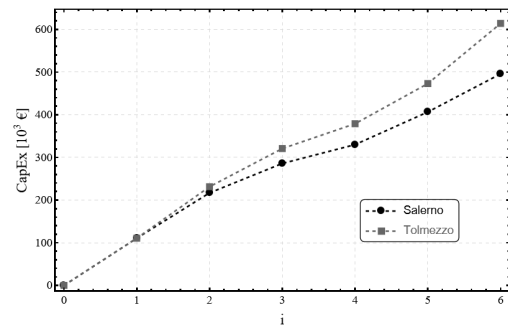


Fig. 4: Economic trajectory: cumulative CapEx evolution as the cumulative package index increases, based on the Fabric-First approach, for Salerno and Tolmezzo.

Source: created by the authors.

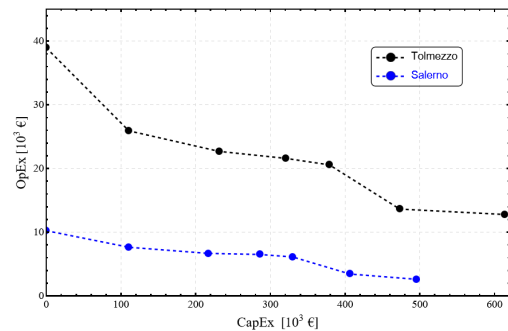


Fig. 5: Cost/performance curve- Fabric First Approach.

Source: created by the authors.

particular, the NE+NW wall insulation intervention shows the weakest performance, providing only limited additional energy savings relative to the associated investment cost, Table 5.

In general, the results indicate that the highest economic efficiency is concentrated in the initial envelope improvement measures and in the final HVAC system interventions, while the intermediate insulation actions are characterised by progressively decreasing marginal returns.

TABLE 5: MARGINAL EFFECT R ASSOCIATED WITH EACH RETROFIT MEASURE, FABRIC FIRST SALERNO.

Measure	R
1	0.024
2	0.009
3	0.002
4	0.009
5	0.035
6	0.009

SOURCE: CREATED BY THE AUTHORS.

Fabric First - Tolmezzo The total CapEx increases progressively throughout the intervention sequence, Figure 4. The most significant cost increases are associated with measures related to HVAC, particularly the installation of fan coil units and the heat pump, which represent a substantial share of the overall investment.

A sharp reduction in OpEx is observed during the first package additions, Table 6, reflecting the strong impact of the initial improvements to the envelope on the high heating demand of the reference building, Figure 4b (Appendix). Subsequent interventions continue to reduce operating costs, although with progressively smaller benefits as residual energy demand decreases.

The energy trajectory also highlights a marked sensitivity to climatic variability. Although all configurations exhibit operating costs lower than in the baseline case, a noticeable gap between TMY and XMY conditions persists throughout most of the retrofit sequence, indicating that winter severity remains a major driver of energy performance. This behaviour is particularly evident during the envelope-retrofit phase, where the reduction in energy demand is not accompanied by a comparable reduction in climatic sensitivity. A more significant convergence between the climatic scenarios is observed after the inclusion of HVAC-related measures. In addition to further reducing operating costs, these interventions contribute to stabilising the overall energy behaviour of the building, making its performance less dependent on year-to-year climatic fluctuations.

Overall, the results show that the retrofit pathway progressively improves both energy efficiency and performance robustness, with the largest energy benefits achieved during the initial stages and the greatest reduction in climatic sensitivity occurring after HVAC upgrades.

TABLE 6: MARGINAL EFFECT R ASSOCIATED WITH EACH RETROFIT MEASURE, FABRIC FIRST TOLMEZZO.

Measure	R
1	0.118
2	0.317
3	0.035
4	0.033
5	0.193
6	0.018

SOURCE: CREATED BY THE AUTHORS.

Low-Invasiveness First - Salerno The second intervention strategy in Salerno, cumulative capital expenditure increases progressively across the sequence of retrofit measures, while the cost–performance curve maintains a consistently decreasing trend. Within this framework, the most relevant insight concerns the evolution of marginal effects rather than the absolute reduction in energy demand, Table 7.

Interventions involving replacement of the generation system emerge as particularly effective, delivering a pronounced reduction in energy demand relative to their investment cost. Their marginal performance is therefore highly favourable and broadly comparable to that achieved through roof insulation and insulation of the north-facing wall, indicating a similar level of cost-efficiency in terms of energy savings per unit of capital invested.

By contrast, full-envelope insulation strategies exhibit diminishing marginal returns. Although they contribute to the reduction of overall demand, their incremental effectiveness decreases as cumulative investment increases, resulting in a less advantageous cost-to-benefit ratio compared to earlier measures in the sequence.

The intervention on the south-facing wall shows a marginal effect that is slightly higher than that of the north-western wall, despite the unexpected nature of this result given its orientation. However, this difference is not indicative of superior thermal performance; rather, it can be explained by the significantly larger surface area involved.

TABLE 7: MARGINAL EFFECT R ASSOCIATED WITH EACH RETROFIT MEASURE, LOW-INVASIVENESS FIRST SALERNO.

Measure	R
1	0.024
2	0.080
3	0.034
4	0.089
5	0.002
6	0.005

SOURCE: CREATED BY THE AUTHORS.

Low-Invasiveness First - Tolmezzo For the intervention strategy applied in Tolmezzo, cumulative capital expenditure increases progressively across the sequence of retrofit measures, while the cost–performance curve maintains an overall decreasing trend. Within this framework, attention can be directed to the distribution of marginal effects associated with each intervention, suggesting a notable heterogeneity in their relative effectiveness, Table 8.

The replacement of windows, together with the transition to a heat pump system, is associated with relatively higher initial marginal effects, indicating a meaningful improvement in performance in relation to the corresponding investment. This is followed by the replacement of emission terminals and the insulation of the north-facing wall and roof, which appear to provide more moderate marginal contributions, suggesting a less pronounced but still relevant impact on overall energy demand.

A more pronounced marginal effect can be observed for the insulation of the north-east and north-west walls, pointing towards a potentially stronger role of envelope-related measures in enhancing system performance. This outcome may reflect the influence of building fabric interventions when applied to surfaces characterised by more significant thermal exchange or larger exposed areas.

In contrast, the insulation of the south-facing wall is associated with a comparatively lower marginal contribution within the sequence, which may indicate a reduced relative effectiveness under the specific boundary conditions of the intervention set.

Overall, the results appear to suggest that envelope-related measures tend to play a central role in shaping performance improvements in this case study, with fabric interventions—particularly those involving larger or more exposed surfaces—potentially contributing more significantly than system-level upgrades alone.

TABLE 8: MARGINAL EFFECT R ASSOCIATED WITH EACH RETROFIT MEASURE, LOW-INVASIVENESS FIRST TOLMEZZO.

Measure	R
1	0.120
2	0.101
3	0.023
4	0.389
5	0.009
6	0.079

SOURCE: CREATED BY THE AUTHORS.

Comparison between intervention strategies In Salerno, the comparison between the Low-Invasiveness-First and Fabric First strategies indicates that, with the exception of the initial common package, the Low-Invasiveness-First ordering generally achieves lower OpEx values across most intermediate cumulative configurations. The Fabric First approach, by contrast, maintains higher OpEx values over a large part of the package sequence, with convergence between the two trajectories occurring only in the final cumulative configuration.

These results suggest that, under mild climatic conditions, placing system-oriented measures in the first part of the ordered package sequence produces a more favourable cost–performance balance at lower and intermediate cumulative investment levels. The Fabric First strategy distributes the benefits more gradually along the package sequence and reaches comparable final outcomes only when the full set of measures is included.

In Tolmezzo, both strategies result in substantial reductions in operational expenditure, consistently with the higher heating demand associated with colder climatic conditions. The Low-Invasiveness-First trajectory generally shows a steeper OpEx reduction over the first cumulative configurations, whereas the Fabric First approach follows a more gradual reduction pattern. Across most of the package sequence, the Low-Invasiveness-First trajectory remains associated with lower operating costs, although the magnitude of the difference between the two strategies is not uniform.

At the final cumulative configuration, both approaches converge towards similar OpEx levels, indicating broadly comparable overall effectiveness in terms of achievable energy savings. The main differences therefore concern the position along the ordered package sequence at which operational savings are obtained, rather than the final performance outcome. Overall, in a severe climate such as Tolmezzo, the ordering of retrofit packages affects the evolution of the cost–performance curve, while the final

energy performance appears less sensitive to the adopted strategy.

7 Conclusion

This study examined how the ordering of retrofit measures affects the performance of a deep-renovation pathway. Two sequences were applied to the same residential building archetype: a conventional Fabric-First strategy and a Low-Invasiveness-First strategy, in which system upgrades precede the more extensive envelope interventions. The comparison was carried out for Salerno and Tolmezzo, representing mild Mediterranean and cold Alpine conditions.

The two trajectories contain the same set of measures and therefore lead to the same final building configuration. Their intermediate behaviour is nevertheless different. After the common window-replacement step, the Low-Invasiveness-First sequence generally produces a faster reduction in operating expenditure, while the Fabric-First pathway requires a larger cumulative investment before reaching comparable performance.

This difference is particularly evident in Salerno. Under mild climatic conditions, early replacement of the heat generator and emission terminals makes better use of the remaining heating load and provides substantial operating-cost savings before the complete envelope retrofit is undertaken. The Fabric-First sequence reduces demand progressively, but several of its intermediate insulation measures offer comparatively limited additional savings relative to their cost.

The results for Tolmezzo follow the same general pattern, although the higher heating demand increases the effectiveness of both envelope and system interventions. The Low-Invasiveness-First trajectory still achieves lower operating costs across most intermediate packages, but the difference between the two strategies is less uniform than in Salerno. In the final configuration, the trajectories converge because all the selected measures have been implemented.

The main implication is that retrofit performance cannot be assessed only from the final configuration. The route followed to reach that configuration also matters, especially when renovation is carried out in stages. Measure ordering determines when energy and operating-cost reductions become available and how much cumulative investment is required to obtain them. In the cases analysed here, introducing system-level measures early provides a more favourable balance at low and intermediate investment levels, whereas the envelope-first sequence delivers its full benefit later in the renovation process.

The proposed cumulative-package method provides a transparent way to compare these alternative pathways while accounting for the interaction among measures, transient building behaviour, HVAC operation, and climatic conditions. Future work will extend the analysis by introducing explicit implementation schedules,

component service lives, discounted cash flows, energy-price scenarios, and optimisation criteria for selecting renovation trajectories over a defined planning horizon.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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APPENDIX

This appendix provides additional material supporting the modelling framework and results presented in the main text, including additional details on the numerical model, meteorological data, building envelope representation, and economic performance.

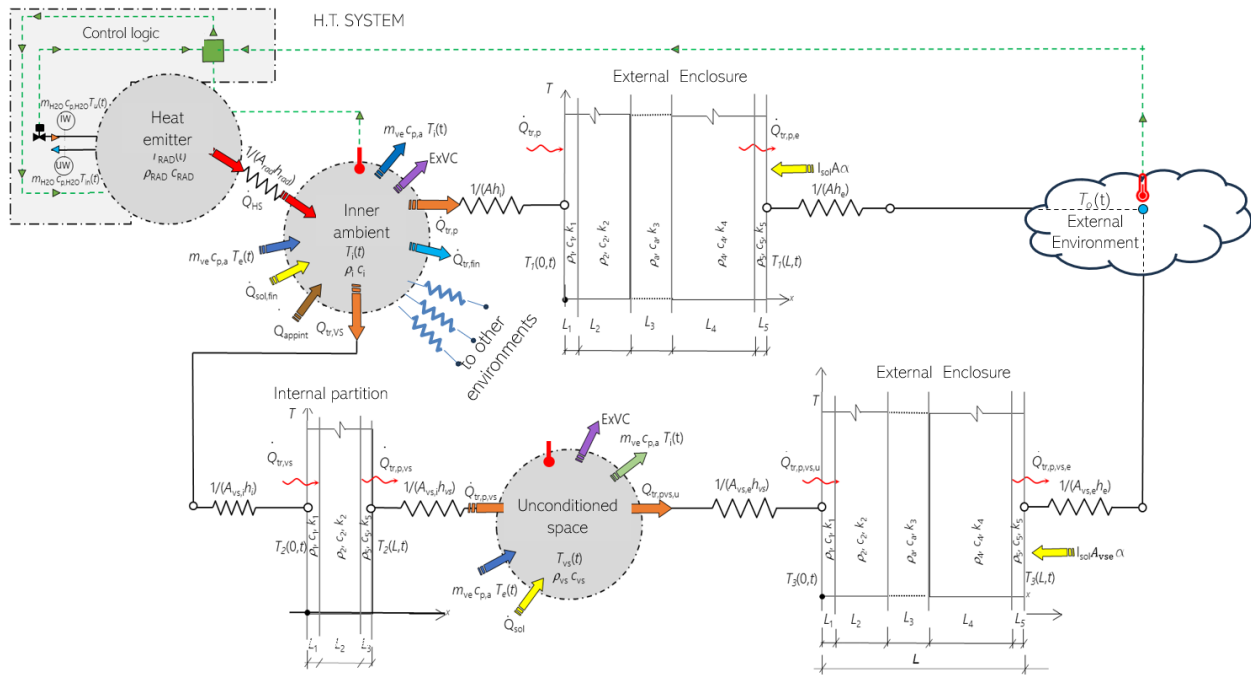
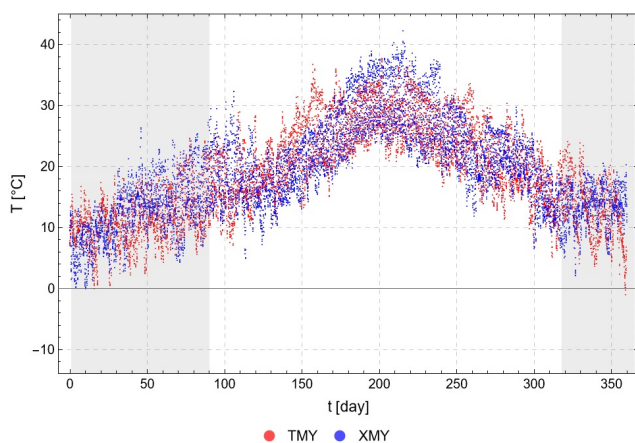
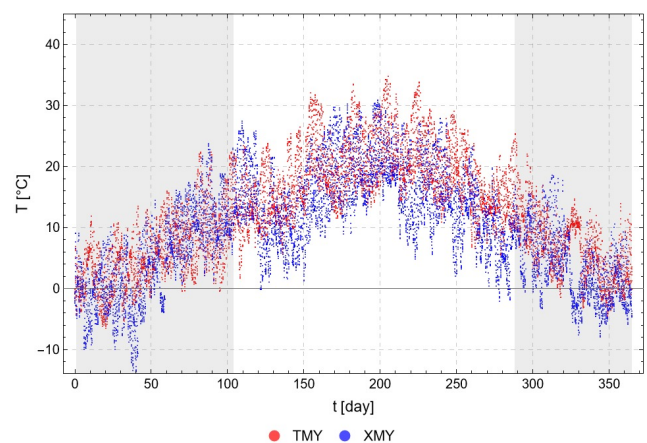


Fig. 1: FEM model for dynamic thermal response of the building envelope and plant.
Source: created by the authors.



(a) Salerno (GG 994, zone C)



(b) Tolmezzo (GG 3036, zone F)

Fig. 2: Statistically reconstructed synthetic meteorological years derived from long-term climatic time series for the analysed locations.
Source: created by the authors.

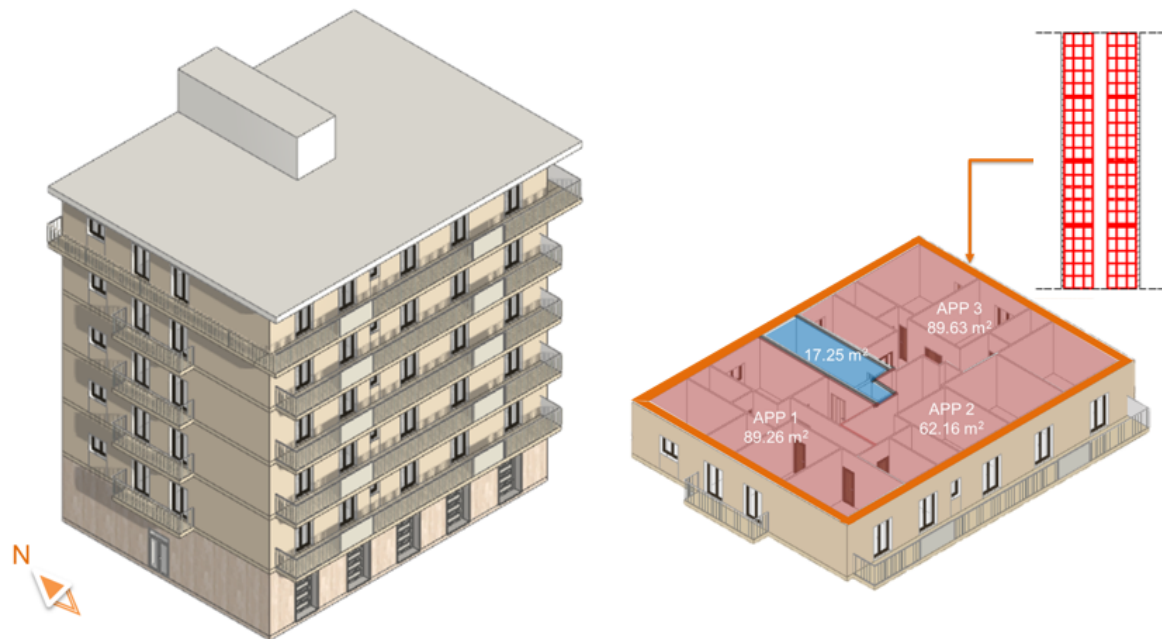


Fig. 3: Building envelope geometry definition.
Source: created by the authors.

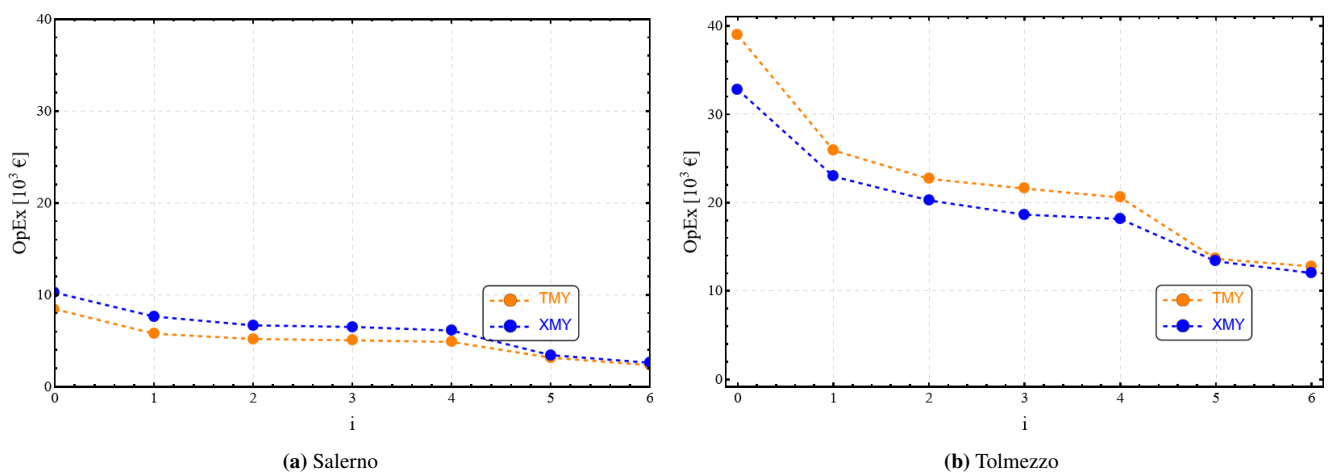


Fig. 4: Operating-cost trajectories as a function of the cumulative package index for Salerno and Tolmezzo.
Source: created by the authors.