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Master of Building Engineering



**Energy modeling of buildings at urban
scale to evaluate the effectiveness of
climate-resilient strategies**

By

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Declaration

I hereby declare that the contents and organization of this dissertation constitute my own original work and do not compromise in any way the rights of third parties, including those relating to the security of personal data.

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June 2026

* This dissertation is presented in partial fulfilment of the requirements for **Master degree** in the Building Engineering of Politecnico di Torino

I would like to dedicate this thesis to my loving family for their great support
and my kind supervisors for their patient instruction.

Acknowledgment

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AI declaration statement

I acknowledge the use of ChatGPT-4 to generate initial ideas and suggest a structural outline for the literature review section. None of the AI-generated text was directly copied or used in the final submission. I reviewed all structural suggestions, conducted independent research to support the claims, and took full responsibility for the final content. I used DeepL in the preparation of this assignment specifically for translating source material from Chinese to English, and for improving the grammatical structure of my writing. The core arguments, analysis, and references are entirely my own original work.

Abstract

Climate change is increasingly reshaping the energy performance of urban building stocks by reducing heating requirements while intensifying cooling demand, overheating risks, and urban heat island effects. As buildings account for a substantial share of global energy consumption and carbon emissions, improving their long-term climate resilience has become a critical challenge for urban energy planning. UBEM has emerged as an effective approach for assessing building stock performance at large scales; however, several limitations remain. Existing studies often lack representative archetype databases for the Italian context, insufficiently integrate future climate projections into building stock assessments, and frequently evaluate building-scale and urban-scale adaptation measures separately, despite their strong interactions.

To address these gaps, this study develops an archetype-based UBEM framework for evaluating climate-resilient strategies in an existing urban district in Turin, Italy. First, a representative building archetype library was constructed following the Italian UBEM framework through the collection, harmonization, and clustering of multi-source datasets, including energy audits, Energy Performance Certificates (EPCs), and cadastral records. The resulting archetypes were subsequently implemented within the CitySim simulation platform to establish a district-scale UBEM. Three Typical Meteorological Year (TMY) weather files representing historical (2010s), mid-term (2050s), and long-term (2090s) climate conditions were employed to quantify future changes in building performance. A set of climate-resilient strategies (CRSs), including cool pavements, enhanced vegetated surfaces, envelope insulation, cool roofs and facades, solar-control glazing, and internal shading systems, was then evaluated using a combination of urban-scale and building-scale performance indicators, aligned with the objectives of the revised EPBD (EU/2024/1275).

The results demonstrate a clear climate-driven transition in building energy demand. As climate conditions evolve from the 2010s to the 2090s, annual heating demand decreases consistently across all archetypes, while cooling demand and overheating risks increase substantially. Vulnerability assessment identified nineteen thermally vulnerable buildings exhibiting particularly strong sensitivity to future warming. The analysis further revealed considerable variability among buildings belonging to the same archetype, indicating that geometric characteristics, orientation, glazing ratio, and urban exposure significantly influence climate vulnerability. Regarding adaptation performance, reflective urban surfaces reduced summer ground temperatures by up to 8.1 °C, while cool roof measures lowered roof surface temperatures by approximately 7–8 °C under all climate scenarios. The integrated CRS package achieved the greatest benefits, reducing heating demand by approximately 21–63% and cooling demand by 40–75% across the identified vulnerable buildings. Although future climate change substantially increases cooling requirements, the effectiveness of the proposed adaptation measures remained largely preserved, demonstrating strong long-term resilience.

Overall, this study provides a transferable framework that integrates archetype development, urban-scale simulation, climate vulnerability assessment, and climate-resilient retrofit evaluation within a single workflow. The proposed methodology offers a practical decision-support tool for identifying vulnerable buildings, prioritizing adaptation measures, and supporting climate-resilient urban renovation strategies in existing European building stocks.

Keywords: Urban building energy modelling (UBEM); CitySim; Climate resilience; Building archetype; Heating and cooling demand; Climate vulnerability

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Chapter 1 Introduction

1.1 Research background and problem statement

It is widely acknowledged that, with the steady advance of modernization, the level of infrastructure development has markedly improved across nations worldwide. Consequently, the utilization of concrete structures in building engineering, highway bridges, tunnels, and protective infrastructures has increased substantially (Van Damme, 2018; Wang et al., 2024). However, alongside the rapid expansion of human construction activities and industrialization, the excessive consumption of energy resources has rendered global climate change one of the most formidable challenges confronting humanities in the twenty-first century.

Within this framework, the built environment exhibits a distinctly dual and inherently paradoxical role. It is not only a significant contributor to greenhouse gas emissions but also serves as a key arena for implementing both mitigation and adaptation measures in response to climate change. Broadly speaking, the phenomenon of global warming results from the combined effects of natural variability and human-induced activities. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) highlighted that the rise in atmospheric carbon emissions since 1750 has been largely attributable to anthropogenic drivers (Collins et al., 2006). More recent findings presented in the Sixth Assessment Report (AR6) further confirm that the global mean surface temperature has already increased by approximately 1.1 °C compared with pre-industrial conditions, and projections indicate that the 1.5 °C threshold could be surpassed as early as 2030 (Lee et al., 2023). Empirical analyses also emphasize the central role of the building sector within the global energy system. Buildings located in urban areas account for over two-thirds of worldwide energy consumption and contribute more than 70% of total carbon dioxide emissions (Hong et al., 2002; Nejat et al., 2015). These emissions predominantly originate from fossil fuel combustion associated with heating, cooling, and lighting demands, as well as electricity generation required for building operations. The

escalation of such carbon outputs is closely linked to the growing occurrence and intensity of extreme weather events, including heatwaves and heavy precipitation. These climatic changes, in turn, significantly influence building energy requirements and indoor thermal comfort conditions. Figure 1. 1 provides a comparative overview of energy consumption patterns across various countries and construction-related sectors.

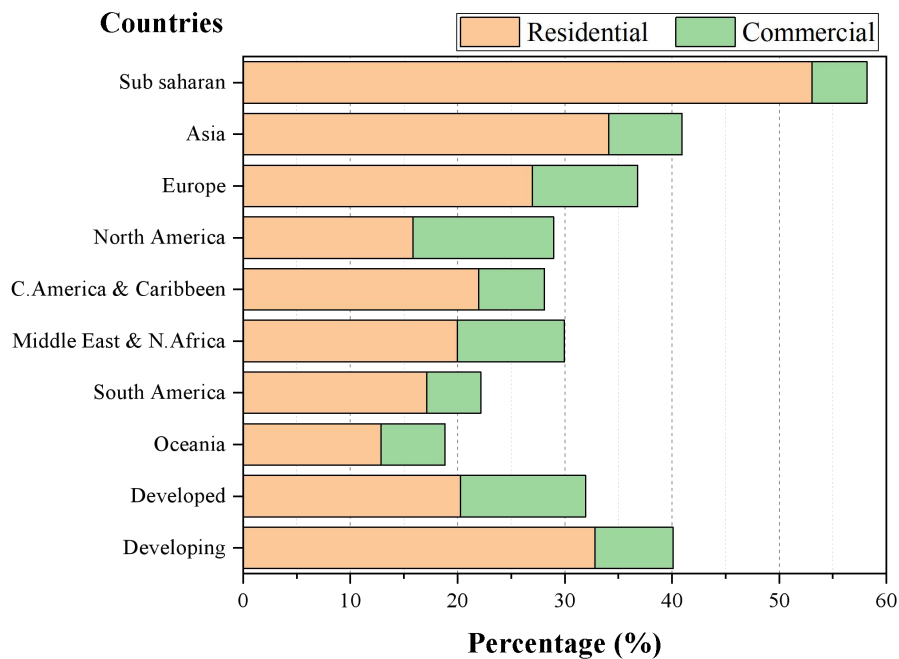


Figure 1. 1 Building energy consumption in different countries and construction sectors.

The European Union has consistently demonstrated a proactive stance in addressing global climate change through the formulation and implementation of comprehensive policy frameworks. Notably, the European Green Deal, introduced in 2019, established a binding commitment to achieve climate neutrality by 2050. In conjunction with this long-term vision, the Fit for 55 initiative established an interim emissions reduction target of 55% by 2030 (CEC, 2019). This ambition has since been codified within the European Climate Law, thereby granting it binding legal status and generating significant regulatory consequences for the building sector.

Against this backdrop of progressively tightening governance, a pivotal advancement is represented by the introduction of the Emissions Trading System (ETS2) for buildings and road transport, which is planned to come into force in

2027. This expanded carbon pricing mechanism broadens the scope of the original emissions trading framework by incorporating buildings, road transport, and additional sectors previously excluded.

In parallel, the revised Energy Performance of Buildings Directive (EPBD) establishes more rigorous and clearly defined decarbonization obligations for Member States. The EPBD is the key legislative framework governing the energy performance of buildings within the European Union. It was originally introduced in 2002 (EU/2002/91, 2002) and recast in 2010 (EU/2010/31, 2010), amended in 2018 (EU/2018/844, 2018), and comprehensively revised in 2024 (EU/2024/1275, 2024) as part of the European Green Deal. The latest revision entered into force in May 2024 and placed greater emphasis on accelerating the renovation of existing buildings, reducing operational greenhouse gas emissions, improving building energy performance, and achieving a zero-emission building stock by 2050. These policy developments underscore the growing importance of developing scalable methodologies capable of assessing the energy performance of existing building stocks and supporting evidence-based renovation strategies under future climate conditions.

Several provisions of the revised EPBD are directly relevant to the scope of this thesis. The Directive requires Member States to develop National Building Renovation Plans based on evidence-driven prioritization of renovation actions and encourages the use of digital building data and analytical tools to support strategic decision-making. It also promotes the progressive renovation of the worst-performing buildings, the reduction of operational greenhouse gas emissions, and the achievement of zero-emission buildings, while emphasizing the need to improve indoor environmental quality and enhance the resilience of buildings to future climate conditions. Furthermore, the EPBD highlights the importance of adopting integrated renovation approaches that simultaneously address energy efficiency, decarbonization, and climate adaptation rather than focusing solely on reducing heating demand.

These policy developments create an increasing demand for reliable urban-scale assessment methodologies capable of identifying vulnerable buildings, evaluating the effectiveness of renovation measures, and supporting long-term planning under changing climatic conditions. However, existing UBEM studies often remain limited by fragmented building data, simplified representations of existing building stocks, and insufficient consideration of future climate impacts when assessing retrofit strategies. Consequently, there is still a lack of practical

frameworks capable of supporting evidence-based implementation of the revised EPBD at the district and city scales. This research addresses these challenges by integrating archetype-based building characterization, district-scale energy simulation, future climate assessment, and climate-resilient retrofit evaluation within a unified UBE framework.

At the scale of the European Union, the alignment of increasingly stringent policy objectives with the expansion of carbon pricing instruments has created a pressing need for robust analytical frameworks capable of informing decision-making at the urban level. Traditional building energy simulation tools, such as EnergyPlus, TRNSYS, and IDA ICE, are widely recognized for their ability to provide highly detailed and physically accurate performance evaluations for individual buildings (Ferrando et al., 2020; Kamel, 2022; Kong et al., 2023). Nevertheless, their application to city-scale analyses remains inherently limited. This limitation arises from several interrelated challenges, including the considerable computational burden associated with conducting large numbers of simulations, the extensive input data requirements needed to characterize building geometry and material attributes, and the necessity of capturing complex inter-building interactions, such as mutual shading and localized microclimatic effects. Collectively, these factors represent substantial barriers to their effective deployment at urban or regional scales. Globally, there has been a significant increase in attention focused on the energy efficiency analysis of existing large building complexes. In fact, the most effective way to achieve a significant reduction in energy consumption in the building sector is to improve the energy efficiency of existing buildings. To this end, it is essential to assess the actual energy performance of buildings as accurately as possible and then implement appropriate retrofit measures based on both technical and economic considerations. Extensive research has been conducted on this topic, ranging from understanding the current status of existing building stock (Ravetz, 2008) to applying statistical data analysis (Theodoridou et al., 2011), collecting and organizing data (Dascalaki et al., 2010), and establishing methods for assessing the energy efficiency of the building stock (Corgnati et al., 2008; Fracastoro and Serraino, 2011).

In response to these constraints, UBE framework has developed into a distinct and rapidly advancing field of research. This domain focuses on designing methods and computational tools specifically suited for large-scale urban energy assessments, with the aim of reconciling modeling accuracy with computational efficiency (Ballarini et al., 2014; Ferrando and Causone, 2020). Core

methodological approaches within UBEM include typology-driven parameterization, simplification of geometric representations, and the utilization of reduced-order modeling techniques, all of which facilitate the analysis of extensive building stocks. A number of dedicated UBEM platforms have consequently been established and applied in practice, including CitySim, Urban Modeling Interface (UMI), and SimStadt.

More generally, urban energy modeling endeavors to capitalize on the expanding availability of high-resolution urban datasets, in combination with advanced simulation techniques, to explore and assess potential pathways toward sustainable urban development. These modeling frameworks integrate capabilities in urban sensing, data processing, and system-level analysis, thereby enabling comprehensive evaluations of energy consumption and environmental performance at the city scale. In this context, urban modeling is intrinsically interdisciplinary, positioned at the intersection of computational science and urban research, and encompassing a wide range of domains, including transport systems, civil engineering, energy analysis, environmental studies, economics, ecology, and sociology (Hong et al., 2002).

Despite these methodological advancements, several critical gaps persist in the existing body of research. One key shortcoming is that the majority of UBEM studies focus on present climatic conditions, with limited consideration of how future climate change may influence the long-term effectiveness of proposed strategies. Moreover, the application of UBEM within the Italy context remains relatively underexplored, particularly in terms of region-specific calibration and validation processes that reflect local construction techniques and regulatory requirements. Additionally, there is still a lack of systematic and comprehensive investigations into the comparative performance of various climate adaptation measures across different building typologies and under a range of projected climate scenarios. Consequently, developing reliable urban-scale energy modelling frameworks capable of identifying vulnerable buildings and evaluating climate-resilient renovation strategies is becoming increasingly important for supporting the implementation of the revised EPBD and achieving Europe's long-term decarbonization targets.

1.2 Research status

1.2.1 UBEM

As shown in Figure 1. 2, Urban Building Energy Modeling (UBEM) has progressively matured into a well-defined research field focused on evaluating building energy performance at urban and regional scales. Fundamentally, this discipline seeks to overcome the inherent difficulty of extending detailed building-level simulation techniques, known for their high precision but significant computational demands, to large building stocks that may include thousands or even millions of units. In general, UBEM methodologies can be broadly divided into two dominant categories: top-down approaches relying on statistical inference and bottom-up approaches based on physics-driven simulation (Esen and Yakut, 2023; Hong et al., 2002; Reinhart and Davila, 2016; Sherif et al., 2025).

Top-down methods typically utilize aggregated datasets, such as utility billing information or national energy statistics, combined with regression-based modeling techniques to approximate energy consumption across extensive building portfolios (Akalp and Ateş, 2025; Lim and Zhai, 2017). Although these approaches are computationally efficient and require relatively limited input data, they exhibit clear limitations in evaluating specific retrofit measures and in capturing variability at the individual building level. Consequently, their primary applicability lies in benchmarking exercises and macro-scale scenario assessments at regional or national levels, rather than in supporting detailed, building-oriented retrofit decision-making (Abbasabadi and Ashayeri, 2019).

In contrast, bottom-up approaches are grounded in the explicit representation of the physical processes governing building energy behavior, including heat transfer mechanisms, solar radiation exchange, and system operation dynamics (Ang et al., 2020; Dogan et al., 2026). These methods provide enhanced accuracy in assessing targeted energy efficiency interventions and allow for a more detailed characterization of heterogeneity among different building types (Sherif et al., 2025). Within this framework, two principal modeling strategies are commonly identified: detailed building-by-building simulation, in which each structure is represented individually, and archetype-based modeling, where buildings are grouped into representative categories according to attributes such as construction period, functional typology, and geometric features (Davila et al., 2016).

Among the available methodological options, archetype-based modeling has become the dominant strategy for large-scale UBE_M applications, primarily due to its capacity to balance computational efficiency with an acceptable level of physical realism. This approach is predicated on the assumption that, although individual buildings exhibit unique characteristics, those developed within comparable construction periods and typological classifications tend to share similar thermal responses and operational patterns. By allocating representative parameter sets to each archetype, such as thermal transmittance values, air infiltration rates, occupancy profiles, and system specifications, it becomes feasible to simulate extensive building stocks while reducing computational demand by several orders of magnitude compared to fully disaggregated simulations. outlines the four-step modeling framework for evaluating building performance across urban neighborhoods.

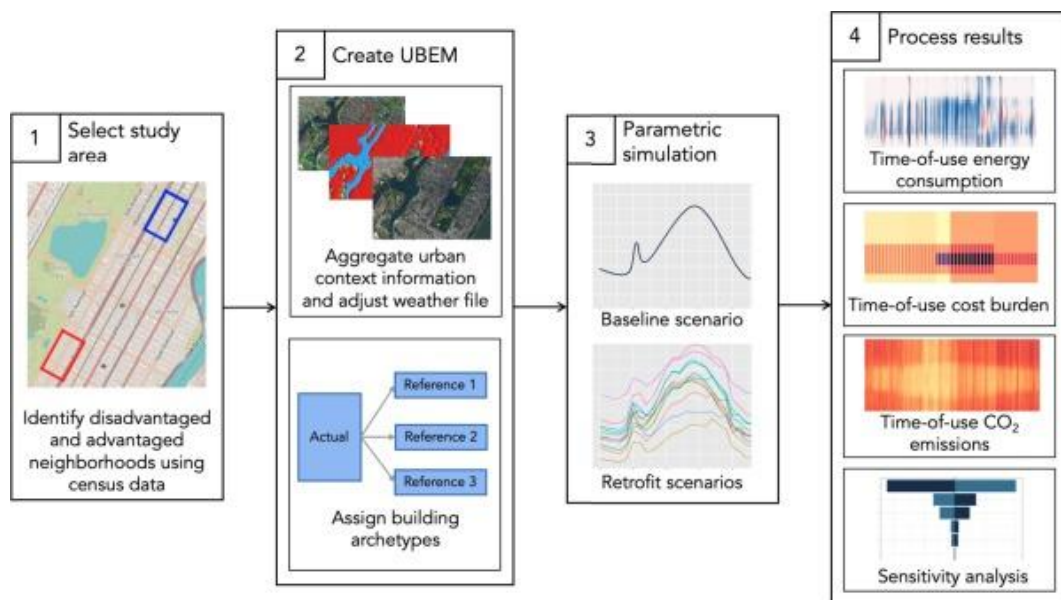


Figure 1. 2 Graphical representation of four-step modeling methodology (Excell et al., 2024).

Notwithstanding these methodological advances, a number of persistent challenges continue to constrain the robustness and applicability of UBE_M studies. A primary concern relates to limitations in data availability and quality, as well as the treatment of uncertainty and the reliability of model calibration. In many cases, access to high-resolution geometric data remains restricted, particularly at a Level of Detail (LOD) sufficient to accurately capture solar radiation interactions. In addition, essential attribute information, including construction properties,

occupant behavior, and system configurations, is frequently incomplete or unavailable, requiring the use of assumptions derived from limited empirical evidence. To address these issues, recent research has increasingly adopted probabilistic modeling frameworks to systematically quantify and propagate uncertainties throughout the simulation process (Geske and Voelker, 2026; Kong et al., 2023).

Calibration against measured energy consumption data, when such datasets are obtainable, is essential for enhancing the credibility and predictive reliability of UBEM outputs. However, comprehensive calibration data at the urban scale are seldom accessible, thereby constraining rigorous validation efforts. Nonetheless, existing studies suggest that UBEM models are capable of achieving reasonable accuracy at aggregate levels, with discrepancies in total energy consumption for building stocks typically ranging between 10% and 20% when compared with observed data (Caputo et al., 2013; Cerezo et al., 2015; Reinhart and Davila, 2016). It should be noted, however, that performance varies across building categories and end-use types; in particular, heating demand is generally predicted with greater reliability than cooling demand, largely due to the more standardized and predictable nature of heating operation patterns.

Finally, the successful deployment of UBEM frameworks in specific geographic contexts necessitates the implementation of regionally adapted calibration procedures that explicitly incorporate local construction practices, climatic conditions, and occupancy characteristics. Such contextualization is critical to ensuring both the validity and the practical applicability of simulation results, particularly in supporting evidence-based urban energy planning and policy development.

1.2.2 CitySim

CitySim is a specialized simulation environment designed for urban-scale building energy analysis, developed through collaborative research efforts between École Polytechnique Fédérale de Lausanne and University of Nottingham. Unlike general-purpose building performance tools such as EnergyPlus or TRNSYS, which are primarily tailored for high-resolution analysis at the level of individual buildings, CitySim employs a simplified dynamic thermal network approach (Doma and Ouf, 2023). This formulation enables a more effective compromise between computational efficiency and modeling

fidelity, making it particularly suitable for district- and city-scale applications (Walter and Kämpf, 2015).

At the core of CitySim lies a resistor–capacitor (RC) network representation, in which building thermal behavior is approximated through lumped parameters. By adopting this reduced-order modeling strategy, the platform significantly alleviates the computational demands associated with solving detailed heat balance equations across large building stocks comprising hundreds or thousands of structures (Coccolo et al., 2018; Mauree et al., 2017). The modeling framework incorporates the principal physical processes governing building energy performance, including heat transfer through the envelope, internal heat gains from occupants and equipment, solar radiation absorption and transmission, and the operational dynamics of heating, ventilation, and air-conditioning (HVAC) systems. Simulations are generally performed at an hourly time step, which corresponds to the temporal resolution of standard meteorological datasets while preserving sufficient detail for annual energy performance evaluation.

The notable strength of CitySim lies in its sophisticated radiation modeling scheme, which explicitly accounts for inter-building shading interactions, surface reflectivity, and long-wave radiative exchange processes. This functionality is particularly important in high-density urban settings, where the geometric arrangement of surrounding structures plays a decisive role in determining solar heat gains and cooling energy requirements. The underlying algorithm is based on a view-factor formulation, allowing radiative exchange between surfaces to be quantified with a high degree of accuracy, while avoiding the substantial computational expense typically associated with ray-tracing methods (Robinson et al., 2009).

From the perspective of data integration, CitySim demonstrates a high level of interoperability by supporting a range of input formats, most notably CityGML for three-dimensional geometric representation. This capability is particularly advantageous given the growing availability of urban-scale datasets in standardized formats. In addition, the platform can be coupled with parametric design tools such as Grasshopper, thereby enabling advanced sensitivity analyses and optimization workflows within flexible computational environments. The simulation outputs generated by CitySim include hourly heating and cooling demands, indoor air temperature profiles, and disaggregated end-use energy consumption, with results that can be systematically aggregated at both individual building and district scales.

Validation studies have confirmed that CitySim is capable of reproducing observed energy consumption patterns at the neighbourhood scale with a satisfactory level of accuracy. Systematic verification using the Building Energy Simulation Test (BESTEST) framework indicates that simulation outputs generally fall within acceptable tolerance bands when compared with benchmark tools, although certain discrepancies have been reported in cooling-dominated cases (Walter and Kämpf, 2015). Furthermore, comparative evaluations based on monitored datasets from urban districts in Switzerland and France reveal mean bias errors typically ranging from 5~15% for heating demand and 10~25% for cooling demand (Mauree et al., 2017).

Despite these demonstrated capabilities, several limitations warrant consideration. In particular, the representation of HVAC systems within CitySim is relatively simplified, which may constrain its ability to accurately reflect the operational complexity of advanced system configurations and control logics. In addition, the modeling framework assumes uniform temperature conditions within individual zones, thereby overlooking potential intra-building thermal variability. As a result, applications that require detailed system-level optimization or high-resolution thermal comfort analysis at the room scale may need to be complemented by more sophisticated simulation platforms. Nevertheless, for urban-scale investigations focusing on building envelope performance and retrofit strategy assessment, CitySim remains a reliable and computationally efficient modeling tool.

1.2.3 Climate-resilience strategy

Climate-resilient strategies encompass a broad range of interventions designed to reduce building energy demand, maintain indoor thermal comfort, and enhance adaptive capacity under future climate change. Existing studies generally classify these strategies into building-level and urban-level measures, both of which play important roles in improving the resilience of the built environment. While building-level interventions focus on individual buildings and their energy systems, urban-level strategies address neighbourhood and city-scale factors that influence energy consumption and thermal conditions (Tootkaboni et al., 2025).

1.2.3.1 Building-level strategies

Building-level climate-resilience strategies focus on improving the energy performance and adaptive capacity of individual buildings through passive, active, and integrated measures (Tootkaboni et al., 2025). Passive strategies primarily enhance the thermal performance of the building envelope and reduce energy demand without relying on additional mechanical systems. One of the most effective measures is envelope insulation, whereby thermal insulating materials are incorporated into walls, roofs, and floors to reduce conductive heat transfer and lower both heating and cooling loads (Ferdyn-Grygierek and Grygierek, 2025). The greatest benefits are generally observed in older buildings with poor thermal performance, particularly those constructed before the implementation of modern energy-efficiency standards.

Window retrofitting is another widely adopted intervention. The replacement of single-pane glazing with double- or triple-glazed systems incorporating low-emissivity coatings can substantially reduce heat losses while improving the control of solar heat gains (Mancini, 2025). The effectiveness of such measures depends on the selection of suitable thermal transmittance (U-value) and solar heat gain coefficients according to local climatic conditions and façade orientation.

Additional passive measures include external shading devices and cool roof technologies. Shading systems reduce excessive solar gains during warm periods while preserving beneficial winter solar radiation. Cool roofs employ highly reflective materials to reduce solar heat absorption and cooling demand, particularly in cooling-dominated climates and buildings with large roof areas (Cuce et al., 2025; Tootkaboni et al., 2025). Active strategies focus on improving the efficiency of building energy systems. Heat pumps represent one of the most significant interventions, replacing conventional fossil-fuel heating systems with air-source or ground-source technologies capable of reducing primary energy consumption by approximately 25–40%. In addition to heating, these systems can provide cooling services, increasing resilience to future climate warming.

The integration of photovoltaic (PV) systems enables on-site renewable electricity generation and reduces dependence on grid-supplied energy (Bagheri et al., 2019). When combined with advanced energy management systems, PV installations can improve load matching and demand-side flexibility. Additional savings can be achieved through high-efficiency lighting, appliances, and

ventilation systems, whose cumulative impact can significantly reduce overall energy consumption (Zheng et al., 2025).

Integrated strategies aim to maximize the synergies between passive and active measures. For example, improved insulation reduces heating demand and enables the installation of smaller, more efficient heat pumps. Similarly, shading systems and cool roofs can substantially reduce cooling loads, thereby lowering the operational requirements of air-conditioning systems. Consequently, retrofit packages that combine multiple interventions generally achieve greater energy savings than individual measures implemented in isolation.

1.2.3.2 Urban-level strategies

While building-level interventions are essential, growing evidence suggests that urban-scale characteristics significantly influence building energy demand and climate resilience. Consequently, urban-level strategies have become an important component of climate adaptation frameworks and UBEM. One of the most widely adopted urban-scale approaches is urban greening. The incorporation of street trees, urban parks, green roofs, and green walls can reduce ambient temperatures through shading and evapotranspiration, thereby mitigating the Urban Heat Island (UHI) effect and reducing building cooling demand (Santamouris et al., 2011). These measures also contribute to improved outdoor thermal comfort and enhanced ecosystem services.

Another important strategy involves the use of high-albedo urban surfaces, including cool pavements and reflective roofing materials. By increasing solar reflectance, these interventions reduce heat storage within the urban fabric and help moderate local air temperatures, particularly during heat-wave events (Santamouris et al., 2011). At the district scale, the deployment of district heating and cooling systems can improve overall energy efficiency through centralized generation and optimized distribution. The integration of renewable energy sources, thermal storage technologies, and smart energy management systems further enhances system flexibility and resilience under future climate conditions. Recent developments in renewable energy communities and distributed energy systems have also demonstrated considerable potential for reducing carbon emissions while increasing local energy self-sufficiency.

Urban morphology and planning decisions also play a critical role in shaping energy demand. Parameters such as building density, street-canyon geometry, orientation, and land-use configuration influence solar exposure, wind flow, and outdoor thermal conditions. Optimizing these characteristics can improve natural ventilation, reduce overheating risks, and enhance neighbourhood-scale resilience. For this reason, urban morphology has become a key consideration in recent UBE M studies examining the interactions between buildings and their surrounding environment.

1.2.3.3 Research gaps

Existing studies have identified several consistent trends regarding the effectiveness of climate-resilient strategies. Buildings constructed before 1960 generally exhibit the highest absolute energy-saving potential, with comprehensive retrofit packages capable of reducing primary energy consumption by approximately 50~70% (Schibuola et al., 2025). However, the effectiveness of individual measures evolves under future climate conditions. Heating-oriented strategies, such as insulation upgrades, tend to provide diminishing marginal benefits as temperatures rise, whereas cooling-oriented measures, including shading systems, cool roofs, and UHI mitigation strategies, become increasingly important. Passive interventions are generally considered more robust across a wide range of climate scenarios because their effectiveness often increases under warmer conditions (Santamouris et al., 2011).

Despite these advances, several research gaps remain. Future climate projections are still insufficiently integrated into building stock assessments, systematic comparisons across residential archetypes remain limited, and relatively few studies have been specifically calibrated for the Italian context. Furthermore, building-level retrofit measures and urban-scale adaptation strategies are often assessed independently, despite their strong interactions within urban energy systems. Addressing these gaps requires a multi-scale perspective capable of evaluating climate resilience across both building and urban dimensions. Therefore, the present study adopts a UBE M framework to assess the effectiveness of climate-resilient strategies for an existing building stock of Piemonte under both current and future climate scenarios.

1.3 Research objectives

This study aims to develop and apply an urban-scale building energy modeling (UBEM) framework to evaluate the effectiveness of climate-resilient strategies for the residential building stock in the Piemonte region, using the CitySim simulation platform. Based on the research gaps identified in the literature review and the methodological requirements of the Italian building context, the following specific objectives are defined:

Objective 1: To develop a representative building archetype library for the Piemonte region based on the URBEM framework. This involves the collection, harmonization, and validation of multi-source building data, including energy audits, Energy Performance Certificates (EPCs), and cadastral records. Through hierarchical clustering, a set of archetypes is constructed to represent the dominant construction periods, building typologies, and HVAC configurations, thereby establishing a robust input database for UBEM.

Objective 2: To implement a district-scale UBEM in CitySim using the derived archetypes. A representative urban block in Turin is selected and modeled in CitySim, integrating geometric, thermophysical, and operational parameters. This objective includes the visualization and spatial analysis of baseline energy performance under current climatic conditions.

Objective 3: To assess the baseline energy performance and climate vulnerability of the existing building stock. Annual heating and cooling energy demands, peak loads, indoor thermal comfort (WHDw), and a building climate vulnerability index (VI) are quantified under baseline (2010s), mid-term (2050s), and long-term (2090s) climate scenarios. This identifies the most thermally vulnerable buildings and establishes reference performance levels for strategy evaluation.

Objective 4: To evaluate the effectiveness of an integrated climate-resilient strategy (CRS) under both current and future climate conditions. A combined set of urban-scale (cool pavements, high-evaporative green areas) and building-scale (insulation, cool roofs/façades, solar-control glazing, internal shading) measures are defined and simulated under the three climate scenarios. The CRS is assessed in terms of surface temperature reduction, heating/cooling energy savings, and robustness under future warming.

Chapter 2 Archetype construction for UBE_M in Italy based on the URBEM framework

2.1 URBEM framework: concept, principle and outputs

This chapter establishes the methodological foundation for the urban-scale energy modelling work undertaken in this thesis. This chapter introduces the URBEM (Urban Reference Building for Energy Modelling) framework as the core methodology for prototype definition, parameterization and validation. The framework is specifically designed to address the unique characteristics of Italian residential building stock. This chapter elaborates in detail on the hierarchical classification structure, reference standards, sequential construction process and validation scheme, and concludes with a critical discussion of the key assumptions and inherent limitations of the prototype-based research methodology.

2.1.1 Definition and strategic positioning of URBEM

As mentioned in the introduction, UBE_M has become a key method for quantifying energy demand, assessing renovation potential and developing decarbonization pathways at the urban and regional levels. However, conducting detailed, building-by-building simulations across an entire city faces two fundamental constraints in practical application. Specifically, on the one hand,

the high computational cost required to simulate thousands or even millions of individual buildings. On the other hand, the widespread fragmentation of data, particularly for older buildings, where construction documents, system specifications and operational records are often incomplete or entirely missing. Consequently, to overcome these limitations, prototype-based modelling approaches, which involve classifying buildings with shared characteristics into representative reference models, have become the mainstream strategy for large-scale URBEM applications. In Italy, this method has been systematically standardized through the URBEM framework.

URBEM is not a single software tool, but rather a comprehensive reference system and set of unified technical specifications developed to meet national-level building energy consumption modeling needs (URBEM, accessed on 7 January 2025). Its core mission is to transform heterogeneous, multi-source, and dispersed urban data, including national census statistics, cadastral records, and EPCs, into standardized, fully parameterized reference building models that are directly compatible with the URBEM simulation platform. As a national initiative funded by the Italian Ministry of Universities and Research (MUR) and coordinated by the Politecnico di Milano, URBEM aims to overcome long-standing obstacles such as data fragmentation, inconsistent statistical standards, and poor interoperability between regional databases.

In fact, The URBEM framework is a structured, data-driven research methodology developed specifically to facilitate the implementation of URBEM on a national scale. The core objective of this framework is to transform fragmented, heterogeneous and frequently incomplete building stock data into standardized datasets that can be directly utilized for simulation and analysis, thereby supporting large-scale research into building energy consumption (Ferrando et al., 2025). The methodology developed within the URBEM project is structured as a multi-stage framework designed to generate a national reference library for URBEM. The methodology integrates data collection, harmonization, statistical analysis, and the generation of standardized outputs, with a focus on transparency, reproducibility, and applicability across different regions of Italy and other contexts with similar data inputs.

From a theoretical perspective, URBEM bridges the two major fields of statistical data processing and physics-based energy consumption modelling. Whilst traditional building energy consumption modelling focuses on detailed simulations of individual buildings, URBEM adopts a bottom-up, aggregated research approach. It utilizes statistical methods to derive a finite number of representative building models, thereby achieving a comprehensive

characterization of urban building stock (Kavgic et al., 2010). This approach effectively balances the two conflicting demands of urban building energy consumption modelling: it meets the requirements for large-scale application whilst retaining building characteristic parameters that possess physical significance (Wong et al., 2021).

URBEM's strategic role within the urban building energy modeling framework is that of a foundational support platform. While simulation engines such as EnergyPlus and CitySim are responsible for performing dynamic energy consumption calculations, URBEM provides structured input data, establishing a robust data foundation for various models at the urban scale. This functional division is crucial because the reliability of urban building energy model outputs fundamentally depends on the quality, consistency, and representativeness of the input data (Swan and Ugursal, 2009). One of the core challenges in urban energy consumption modeling is the fragmentation of building-related data. Relevant information is typically scattered across various data sources, including national statistical databases, cadastral records, building energy certification documents, and field survey data. Different datasets vary significantly in spatial accuracy, temporal coverage, and data completeness, often making them impossible to integrate and use directly. URBEM addresses this issue through a systematic data standardization and integration process, uniformly adapting multi-source, heterogeneous data to a common classification framework, thereby ensuring that all types of data can be applied consistently and reliably in modeling work.

From a methodological perspective, URBEM is characterized by a hybrid approach that combines deterministic classification with statistical clustering. First, buildings are classified based on key descriptors known to have a dominant influence on energy performance, such as construction period and use type. Subsequently, additional parameters, such as geometric features and system configurations, are used to refine the classification and generate clusters of similar buildings. Each cluster is then represented by a reference building (or prototype), defined as the centroid of the relevant dataset. This hierarchical abstraction process enables URBEM to significantly reduce the dimensionality of the building stock while retaining the most relevant factors influencing energy consumption. Consequently, the framework strikes a balance between computational efficiency and modeling accuracy, making it particularly suitable for large-scale urban applications.

From a critical perspective, the URBEM framework offers several methodological advantages, yet it also has inherent limitations that cannot be overlooked. One of the framework's core strengths lies in its ability to balance the need for large-scale implementation while preserving physically meaningful architectural features. By employing an abstraction approach based on architectural prototypes, URBEM significantly reduces computational complexity and provides an accurate, statistically representative description of the building stock. Furthermore, its standardized data integration process enables the unified processing of multi-source, heterogeneous datasets, which is particularly critical in scenarios where architectural details are scattered or missing. Another core strength of this framework is the high transparency and reproducibility of its research methodology. Standardized classification criteria and parameter-setting processes facilitate cross-comparisons between different studies while enhancing the reliability of scenario-based analyses, a feature that is particularly prominent in policy-oriented research and practical applications. At the same time, the hierarchical clustering strategy employed by URBEM explicitly prioritizes core influencing variables, such as construction era and building use, thereby effectively enhancing the rigor and stability of architectural prototype definitions.

However, these advantages are accompanied by certain limitations. The reliance on statistical aggregation inevitably introduces simplifications, particularly in the assumption of homogeneity within clusters. Consequently, variations in the performance of individual buildings may not be fully captured, which could lead to discrepancies between simulation results and actual energy consumption. Furthermore, the use of standardized operating modes may not fully reflect real-world occupant behavior, which is well known to be a significant source of uncertainty in building energy simulation. Another limitation relates to data dependency. Although URBEM is designed to integrate heterogeneous datasets, the accuracy of the resulting building archetypes remains heavily dependent on the quality and completeness of the underlying data. If the data is sparse or outdated, the representativeness of the archetypes is significantly compromised. Finally, while the framework effectively supports large-scale analyses, it is less suitable for detailed single-building studies, as the latter may require high-resolution modeling approaches.

Overall, URBEM can be viewed as a robust and scalable modeling framework that strikes a pragmatic balance between accuracy and computational feasibility. Its strengths make it particularly well-suited for city-scale energy consumption analysis and policy evaluation, while its limitations serve as a reminder to

exercise caution when interpreting results and to utilize measured data for calibration whenever possible.

2.1.2 Characteristics of Italian building stock and requirements for archetype-based modeling

The operational logic of the URBEM framework revolves around the definition and construction of reference buildings (i.e., prototypes). A prototype is defined as a statistically representative model that aggregates buildings sharing similar characteristics across key dimensions, including construction period, geometric form, functional type, thermophysical properties of the building envelope, HVAC system configuration, and operating patterns. URBEM prototypes are derived from large-scale statistical data and field surveys, combined with cluster analysis techniques. Unlike traditional building-by-building modeling methods that capture individual differences, the prototype approach extracts common attributes from a population of buildings. This abstraction simplifies the complex and diverse urban building stock into a manageable number of representative and computationally efficient units, thereby achieving a balance between simulation accuracy, data availability, and computational efficiency.

The adoption of the URBEM framework is strongly justified by the specific characteristics of the Italian building stock, which pose significant challenges for conventional modelling approaches. Italy exhibits one of the most heterogeneous building stocks in Europe, reflecting a long and stratified construction history influenced by regional, economic, and regulatory factors. A defining feature of the Italian building stock is its strong dependence on construction period. A large proportion of residential buildings were constructed before the introduction of thermal regulations, particularly prior to Law 373/1976. These buildings are typically characterized by poor thermal insulation, high envelope transmittance, and inefficient heating systems. Subsequent regulatory developments, including Law 10/1991 and the transposition of European energy directives, have progressively improved building performance, leading to a highly diverse range of thermal characteristics across the stock (Ballarini et al., 2014; Ballarini et al., 2017). In addition to temporal heterogeneity, Italy is characterized by significant climatic diversity, spanning from alpine regions in the north to Mediterranean climates in the south. These variations result in substantial differences in heating and cooling demand, even among buildings with similar typologies (Mastrucci et

al., 2014). Consequently, energy modelling in Italy requires a framework capable of accounting for both physical and climatic variability.

Another important aspect is the predominance of existing buildings and the high share of multi-family residential structures in urban areas (Okoye and Ngwu, 2021; Stoiljković and Jovanović, 2010). These buildings often exhibit complex geometries, shared envelopes, and diverse occupancy patterns, further complicating detailed modelling efforts. Moreover, comprehensive and high-resolution data on building characteristics are often unavailable, particularly for older constructions. Under these conditions, the direct modelling of individual buildings becomes both computationally prohibitive and highly uncertain. As highlighted in the literature, the application of bottom-up modelling approaches at the urban scale requires simplifications that preserve the dominant characteristics of the building stock while reducing model complexity (Starzyk et al., 2023). Archetype-based modelling provides an effective solution to these challenges. By grouping buildings into homogeneous clusters and representing each cluster with a reference building, it becomes possible to significantly reduce the number of simulation units while maintaining statistical representativeness. This approach is consistent with established European methodologies, such as the TABULA and EPISCOPE projects, which have demonstrated the effectiveness of archetype-based frameworks for analyzing national building stocks (Ballarini et al., 2014; Loga et al., 2016).

2.1.3 The archetype concept within URBEM

Within the URBEM framework, the archetype, also referred to as a reference building, serves as the fundamental modelling unit for URBEM applications. An archetype is defined as a statistically representative model that encapsulates the dominant physical and operational characteristics of a group of buildings. The conceptual basis of archetypes lies in the assumption that buildings sharing similar attributes—such as construction period, typology, geometry, and system configurations—will exhibit comparable energy behaviour. By aggregating such buildings into clusters, it becomes possible to represent the entire building stock through a limited number of archetypes, thereby reducing computational complexity without significantly compromising accuracy.

In URBEM, archetypes are generated through a structured process that integrates classification and clustering. Construction period and building use are typically treated as primary classification variables, reflecting their strong

influence on envelope performance and occupancy patterns. Secondary variables, including geometric indicators and HVAC system characteristics, are used to refine the clustering and improve representativeness. Each archetype is defined by a comprehensive set of parameters, including geometry, envelope properties, system configurations, and operational profiles. These parameters are derived from a combination of statistical data, regulatory standards, and empirical observations. As such, archetypes represent a synthesis of data-driven and knowledge-based modelling approaches.

However, the use of archetypes introduces inherent assumptions, particularly regarding intra-cluster homogeneity and standardized occupant behaviour. These assumptions, while necessary for scalability, may lead to discrepancies between simulated and actual energy consumption. Therefore, the definition and calibration of archetypes must carefully balance representativeness and simplicity.

2.1.4 Key outputs of the URBEM framework

The URBEM framework produces a set of structured outputs that enable the practical implementation of URBEM at the urban scale. The primary output is a library of building archetypes, each representing a specific segment of the building stock defined by use type, construction period, and climatic zone.

Each archetype is associated with a detailed parameter set, including geometric properties, thermophysical characteristics of the envelope, HVAC system configurations, and operational schedules. These parameters allow archetypes to be directly implemented in building energy simulation tools.

In addition to individual archetypes, URBEM provides statistical information describing the distribution of buildings across different categories. This includes weighting factors that indicate the prevalence of each archetype within the building stock, enabling the scaling of simulation results to the urban level.

Another key output is the harmonized dataset that integrates multiple data sources into a consistent format. This standardized structure enhances reproducibility and facilitates the comparison of results across different studies and regions.

2.2 Parameterization and reference standards

The parameterization of archetypes within the URBEM framework relies on a combination of empirical datasets, regulatory standards, and reference building typologies. This process ensures that each archetype is both physically consistent and representative of real building conditions. Envelope properties are defined based on construction period and regulatory benchmarks, reflecting the evolution of Italian and European energy performance standards. Operational parameters, including occupancy schedules and internal gains, are derived from national standards such as UNI/TS 11300, UNI/TR 11552:2014, and established modelling practices.

System configurations are assigned based on typical technologies observed in the Italian context, with particular emphasis on heating and cooling systems. In cases where detailed data is unavailable, representative values are adopted based on statistical distributions. The parameterization process is further supported by European reference frameworks such as TABULA and EPISCOPE, which provide validated building typologies and construction assemblies. The integration of these sources ensures methodological consistency and enhances the robustness of archetype definitions.

2.3 Archetype construction workflow

The construction of representative building archetypes constitutes one of the most critical phases within the URBEM framework, as it enables the transformation of heterogeneous building datasets into standardized and simulation-ready reference buildings. Within the URBEM methodology, archetypes are not intended to represent individual buildings in a deterministic manner; rather, they are conceived as statistically representative models capable of capturing the dominant physical, thermophysical, operational, and system-related characteristics of groups of buildings sharing similar attributes. Compared with conventional single-building modelling approaches, the archetype-based methodology substantially reduces computational complexity while preserving the principal variables governing building energy performance. This characteristic is particularly important for urban-scale analyses, where the simulation of thousands of individual buildings would otherwise require excessive computational resources and highly detailed datasets that are rarely available on the city scale.

2.3.1 Case study definition and data acquisition

The development of representative archetypes within the URBEM framework requires the availability of sufficiently diverse and statistically representative datasets. In this study, a total of 74 buildings were collected from three case studies provided by ATC Piemonte Centrale and the Agenzia del Demanio. The datasets include residential, office, educational, commercial, industrial, and sports facilities distributed across the Piemonte and Valle d'Aosta regions. Those selected datasets encompass residential and public buildings distributed across different construction periods and climatic conditions, reflecting the diversity and reliability of data. The conditions of three case studies are listed below:

Case Study 1 concerns multi-family residential buildings located along Corso Vercelli in Turin. The dataset includes 16 residential buildings constructed between 1931 and 1940, corresponding to pre-war building typologies within the URBEM classification framework. Available information includes annual energy consumption data for the period 2020–2023, district heating network schemes, technical renovation reports, and detailed information regarding building envelope configurations and thermal systems.

Case Study 2 includes four residential building blocks located at Via Mercadante and Corso Taranto in Turin (Climate Zone E). These buildings were constructed during the post-war period and are classified within the 1951–1960 construction category according to URBEM scorecards. The dataset incorporates technical documentation related to energy retrofit measures, including the implementation of centralized district heating systems and solar thermal collectors.

Case Study 3 comprises a larger and more heterogeneous dataset containing 54 public buildings distributed across Piemonte and Valle d'Aosta. Available documentation includes EPCs, energy audits, retrofit scenarios, system reports, and energy consumption records. Compared with the previous case studies, this dataset provides broader variability in building typology and climatic context, and system configuration.

Table 2. 1 summarizes the distribution of the analyzed buildings according to building use categories. Residential buildings constitute the largest proportion of the dataset, accounting for 50% of the total sample, followed by office buildings with 42%. The remaining categories, including educational, commercial,

industrial, and sports facilities, collectively represent a smaller proportion of the analyzed stock.

Table 2. 1 Summary of datasets adopted for archetype construction.

Building category	Building use	Number of buildings	Percentage
E.2	Offices	31	42%
E.1.(1)	Residential (permanent)	37	50%
E.1.(2)	Residential (Holiday)	1	1%
E.4.(3)	Educational building	2	3%
E.6.(2)	Commercial building	1	1%
E.7	Sports facilities	1	1%
E.8	Industrial and artisan building	1	1%
	Total	74	100%

As indicated in Table 2. 1, the datasets differ substantially in scale, typology, and data availability. While Case Studies 1 and 2 provide high-resolution information suitable for detailed parameterization, Case Study 3 offers broader representativeness on a regional scale. The integration of these datasets enables the development of archetypes that balance physical accuracy and urban-scale applicability. In addition, it can be seen that the predominance of residential and office buildings is consistent with the structure of the Italian urban building stock, where these categories account for a substantial share of operational energy consumption. Consequently, the selected datasets provide a robust basis for the development of archetypes suitable for urban-scale energy analyses. The regional distribution of the analyzed buildings according to geographical region is presented in Table 2. 2. It is clear that most building structures are located within

the Piemonte region, representing 99% of the total dataset, while a smaller proportion originates from Valle d'Aosta.

Table 2. 2 Distribution of entire buildings according to geographical region.

Region	Number of buildings	Percentage
Piemonte	73	99%
Valle d'Aosta	1	1%
Total	74	100%

The predominance of buildings located in Piemonte reflects the availability of detailed datasets provided by regional agencies and public authorities. Although the geographical distribution is not fully representative of the entire Italian territory, the analyzed stock remains highly relevant for the characterization of northern Italian urban environments, particularly within climatic zones E and F. As shown in Figure 2. 2, a substantial proportion of the analyzed buildings were constructed before the implementation of modern thermal regulations, particularly during the periods 1931–1940 and 1951–1960. This distribution reflects the predominance of ageing building typologies within the Italian urban context and highlights the considerable retrofit potential associated with older constructions.

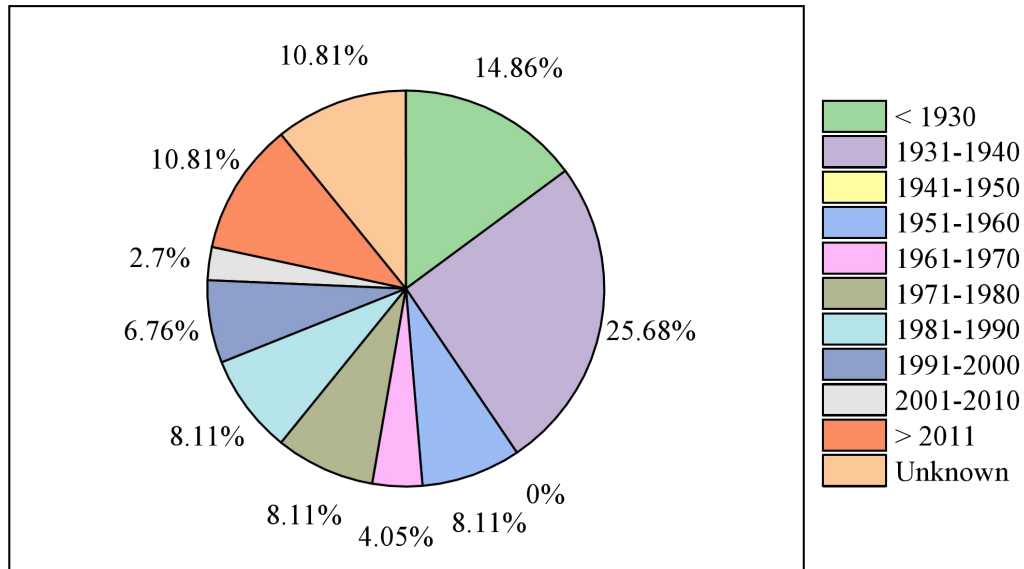


Figure 2. 2 Distribution of entire buildings according to construction period.

Buildings constructed after 2000 represent a comparatively smaller share of the dataset, indicating that the analyzed stock is primarily composed of existing buildings characterized by relatively poor thermal performance. This characteristic is consistent with the broader structure of the Italian building stock, where a significant proportion of buildings were erected prior to the introduction of energy efficiency standards.

The temporal diversity of the dataset is particularly relevant within the URBEM framework, as construction period constitutes one of the principal variables adopted during the clustering and archetype generation procedures. Variations in construction age are closely associated with differences in envelope technologies, HVAC system configurations, construction materials, and regulatory requirements, thereby exerting a strong influence on building energy behaviour. Figure 2. 3 presents the distribution of the analyzed building stock according to Italian climatic zones. The dataset is predominantly composed of buildings located within climatic zone E, while a smaller proportion belongs to climatic zone F.

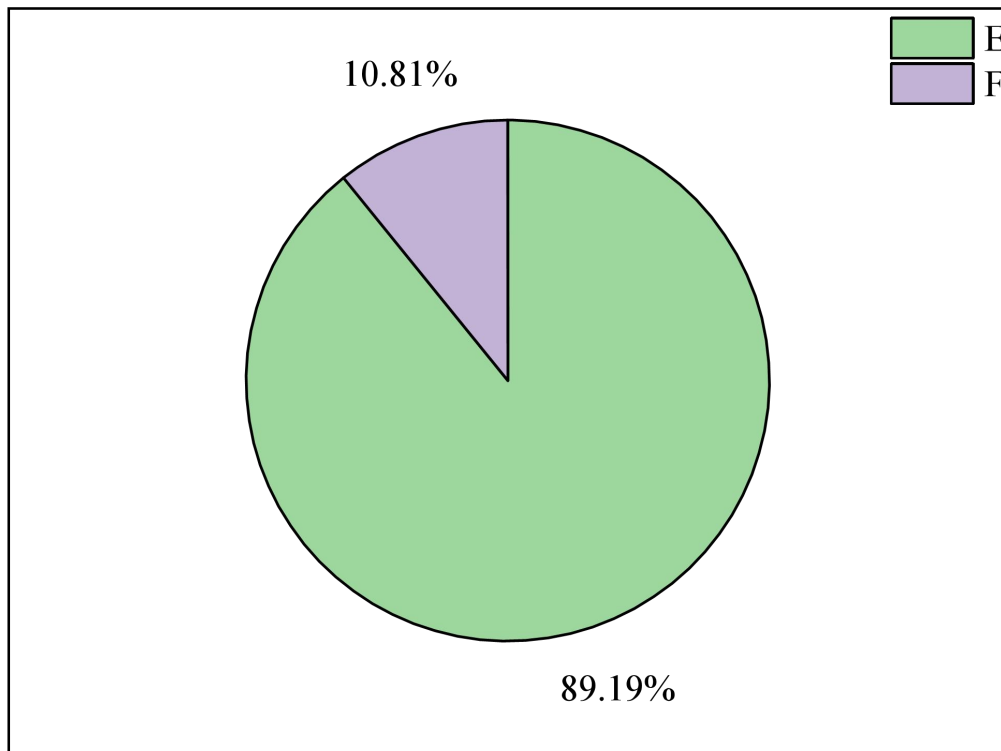


Figure 2. 3 Distribution of entire buildings according to climatic zone.

As illustrated in Figure 2. 3, the strong predominance of climatic zone E reflects the geographical concentration of the datasets analyzed within the Piemonte region. Buildings located in climatic zone E are typically characterized by high heating demand due to relatively cold winter conditions, making them particularly relevant for urban-scale retrofit analyses and heating-oriented energy assessments.

A smaller proportion of buildings belong to climatic zone F, corresponding to colder mountainous regions characterized by higher heating degree days and more severe climatic conditions. The inclusion of buildings from both climatic zones enhances the representativeness of the generated archetypes and enables the consideration of climatic variability within the URBEM framework. Within the archetype construction process, climatic classification represents a particularly important parameter, as climatic conditions directly influence heating and cooling demand, HVAC system sizing, operational schedules, and thermal performance. Consequently, climatic zone constitutes one of the primary descriptors adopted during the hierarchical clustering procedure.

Collectively, the distribution data presented in Table 2. 1 and Table 2. 2 and Figure 2. 2 and Figure 2. 3 indicate that the analyzed dataset accurately reflects the primary typological, temporal, geographical, and climatic characteristics of building complexes in northern Italy. This representativeness provides a solid foundation for subsequent clustering and prototype generation processes within the URBEM framework.

2.3.2 Data processing and harmonization

Once data collection is complete, all datasets undergo a comprehensive standardization and validation process designed to ensure the consistency, completeness, and physical reliability of the data prior to clustering. Since the collected information originates from multiple heterogeneous sources, including energy audit reports, energy performance certificates, municipal cadastral databases, technical reports, and renovation documentation, a systematic preprocessing phase is essential to ensure methodological consistency within the URBEM framework. The primary objective of the harmonization process is to transform heterogeneous and partially inconsistent datasets into a unified parameter structure suitable for prototype generation. Specifically, this involves harmonizing the geometric parameters, thermophysical parameters, and system-related variables for all buildings: geometric parameters such as floor area, number of floors, net heated area, and total heated volume are cross-validated using cadastral databases and technical documentation to ensure the internal consistency of spatial descriptors; subsequently, envelope parameters are standardized based on available stratigraphic information and the Italian regulatory framework (UNI/TS 11300 and related technical standards). When multiple sources report differing values for the same building envelope parameter, a hierarchical reliability standard is applied, prioritizing official technical reports and verified energy audit documents over secondary database records. This process ensures that the typological characteristics of building envelopes and thermal transmittance values across different datasets remain physically consistent and comparable.

For transparent envelope components, the U-value is calculated using an area-weighted average to account for differences in window types, frame materials, and glazing systems. This step is particularly important in older buildings, as multiple renovations and different construction phases often result in inconsistent facade characteristics. Similarly, the classification of HVAC systems, including heating systems, distribution systems, discharge terminals, and domestic hot water

production systems, is uniformly integrated into a standardized classification system defined by the URBEM scorecard.

A key aspect of the harmonization phase involves the handling of missing or incomplete information. In many cases, datasets lack complete records regarding the building envelope's stratigraphy or system configurations. When only partial information is available, missing parameters are reconstructed through cross-referencing across multiple datasets. However, when inconsistencies cannot be resolved or critical variables are missing, the corresponding buildings are excluded from subsequent analyses to prevent errors from propagating to the clustering phase. The specific cases are as follows:

Case Study 1. A total of 16 buildings were selected and aggregated using a bottom-up approach consistent with the URBEM methodology. The selected sample exhibits a high degree of homogeneity in terms of construction period (pre-World War II), envelope typology, and building service systems, including space heating, cooling, and domestic hot water (DHW), thereby supporting the definition of a representative archetype. Input data were derived from renovation documentation provided by ATC Piemonte Centrale, including technical reports compliant with Italian regulatory frameworks (Legge 10), regional project documentation, and winter energy performance assessments based on UNI/TS 11300-2:2019 (UNI, 2019b) and ISO 13790 (BS, 2008). Additional information on envelope stratigraphy and thermophysical properties was obtained from simulations conducted using HVACCAD 2009, which provided thermal transmittance (U-values), hygrothermal verification of building components, and detailed geometric representations. These multiple data sources were cross validated to enhance reliability and reduce uncertainty in model inputs. Particular attention was devoted to the processing of thermal transmittance values. For transparent elements, variability associated with different window sizes and configurations was addressed through an area-weighted averaging approach:

$$U_w = \frac{\sum A_i U_i}{\sum A_i} \quad (1)$$

For opaque envelope components, representative U-values were derived by aggregating all available stratigraphic variations and calculating mean values. This dual approach ensures both statistical robustness and consistency in defining envelope performance parameters, which are critical for energy simulation accuracy. Energy characterization was carried out a bottom-up procedure based

on technical audit data. Monthly energy needs extracted from HVACCAD outputs identified two dominant end uses: space heating (616,501.40 MJ) and DHW (56,263.80 MJ). These values were processed using the quasi-steady-state method defined in UNI/TS 11300 (UNI, 2019b) and ISO 13790 (BS, 2008). Conversion factors specified in the Italian Ministerial Decree of 26 June 2015 were applied to derive primary energy demand and associated CO₂ emissions, ensuring full compliance with national regulatory standards. Geometric parameters, including building height, number of floors, and typological classification, were retrieved from the Geoportale Piemonte and integrated with technical documentation. These parameters were essential for accurately defining the geometric configuration of the archetype and ensuring its representativeness within the residential building stock of Turin.

Case Study 2. The archetype definition is based on an integrated and multi-source dataset including: (i) technical reports on building–plant energy performance calculations, (ii) general building characteristics (e.g., number of dwellings and heated volumes), (iii) monitored energy consumption for space heating and DHW over the period 2018/2019–2022/2023, and (iv) detailed architectural and engineering drawings associated with planned retrofit measures, specifically the transition to a centralized district heating system and the integration of solar thermal collectors. Most geometric parameters were derived directly from technical documentation; however, missing indicators such as footprint area and gross building height were supplemented by Geoportale Torino and cadastral data. Envelope-related parameters and modeling assumptions were aligned with those adopted in Case Study 1 to ensure methodological consistency and comparability across case studies.

At the dwelling scale, data availability is limited. Only the heated net volume of individual units is available; therefore, a simplified representation was adopted by using the average heated net volume as a proxy, complemented by dispersion metrics such as standard deviation and quartile values to account for variability. Similarly, detailed information on thermal systems at apartment level is not available. Consequently, system efficiencies, generation performance, and nominal capacities were derived from technical datasheets and standard assumptions. This includes both generation efficiency at unit level and global system efficiency at building scale, accounting for distribution, emission, and control losses. Energy performance assessment was conducted in accordance with UNI/TS 11300 (UNI, 2019b) and the Ministerial Decree of 26 June 2015. Simulated results were converted into primary energy indicators and CO₂

emissions and normalized over a heated floor area of 3706.3 m² to allow comparability.

The analysis indicates that space heating dominates the building energy balance, representing the main contributor to non-renewable primary energy consumption and associated emissions due to the reliance on fossil fuels. In contrast, the DHW system demonstrates improved performance due to the integration of solar thermal collectors, which cover 50.7% of total demand. This contribution significantly reduces the non-renewable primary energy indicator for DHW and promotes a more balanced renewable/non-renewable energy mix. Nevertheless, the overall energy profile remains strongly influenced by space heating demand. Therefore, further improvements should prioritize interventions targeting the heating system, such as the adoption of high-efficiency heat pumps or the transition to renewable-based district heating systems, in order to achieve substantial decarbonization and improved system resilience.

Case Study 3. This case study extends the analysis to a heterogeneous dataset of 54 buildings located in Piemonte and Valle d'Aosta, representing diverse typologies, construction periods, and system configurations. The dataset includes Energy Performance Certificates, system diagnostic reports, energy audits, retrofit scenarios, and operational energy consumption data (2021–2023). Data processing began with APE classification to identify building typology, climatic zone, geometric characteristics, and energy system configuration. Given the UBE requirement for building-level modelling, unit-scale data were aggregated into building-scale representations through a consistent set of assumptions ensuring physical and energetic coherence. The following criteria were applied during the aggregation process:

(1) Building category and system type: In mixed-use buildings, classification was assigned based on the predominant use (in terms of floor area) and prevailing system configuration (e.g., centralized vs. autonomous systems).

(2) Compactness ratio: Computed as the ratio of total envelope surface area to gross heated volume at building scale, rather than averaging unit-level values, to maintain physical consistency.

(3) Footprint area: In case of discrepancies, values from energy audit reports were preferred over cadastral data, as cadastral surfaces represent administrative

values, whereas audit data reflect the actual physical envelope relevant for energy modeling.

(4) Primary energy demand and emissions: Primary energy demand and CO₂ emissions were aggregated using area-weighted averaging to ensure correct scaling across heterogeneous building types.

$$EP_{building} = \frac{\sum_{i=1}^n (EP_i \cdot A_i)}{\sum_{i=1}^n A_i} \quad (2)$$

Envelope and system parameters were primarily extracted from energy audit documentation, which provides higher reliability than certification-based datasets. The resulting harmonized database enables robust UBEM simulation, supporting large-scale evaluation of energy performance, retrofit strategies, and climate resilience pathways. Based on the above case study description, the validation results for the three case studies are summarized in Table 2. 3.

Table 2. 3 Summary of dataset validation and clustering outcomes.

Case study number	Validation	Number of buildings	Percentage
Case study 1	Clustered	16	22%
	Not clustered	0	0%
Case study 2	Clustered	4	5%
	Not clustered	0	0%
Case study 3	Clustered	41	55%
	Not clustered	13	18%
	Total	74	100%

As shown in Table 2. 3, all buildings included in Case Studies 1 and 2 successfully passed the validation process and were retained for prototype generation. In contrast, 13 buildings in Case Study 3 were excluded due to

incomplete or inconsistent information, particularly regarding the building envelope hierarchy, HVAC system configuration, and geometric reliability. Overall, a total of 61 buildings (82% of the dataset) were retained and successfully converted into prototype scorecards. The higher exclusion rate in Case Study 3 reflects the inherent heterogeneity of datasets compiled from multiple institutional sources. Unlike controlled audit datasets, public databases and energy performance certificate repositories often exhibit variations in data resolution, measurement methods, and documentation completeness. These further underscores the necessity of establishing a rigorous validation framework when integrating multi-source urban building datasets.

From a methodological perspective, the validation phase is critical to ensuring the robustness of the URBEM workflow. Since prototype construction relies on the aggregation of buildings with similar characteristics, inconsistencies in the input data can significantly distort clustering results and reduce the physical representativeness of the final prototype. Therefore, the adopted filtering strategy prioritizes data reliability and physical consistency over dataset size. There is a significant methodological trade-off between dataset completeness and statistical representativeness. While removing incomplete records inevitably reduces the sample size, retaining unreliable data significantly increases the uncertainty of the clustering process and subsequent URBEM simulations. Consequently, the adopted approach embodies a conservative and physically sound strategy, ensuring that only high-quality and consistent records are used to generate the prototype.

Overall, the validation results confirm that the majority of the analyzed is suitable for URBEM-based prototyping, while also highlighting the challenges of integrating heterogeneous urban building information. Consequently, the adopted coordination and validation process is a critical component in ensuring the methodological reliability of the entire workflow.

2.3.3 Clustering outcomes and archetype generation

After completing the data harmonization and validation process, the cleaned dataset was processed using the URBEM clustering method to generate representative building prototypes suitable for city-scale energy consumption simulation. This clustering process aims to group buildings with similar physical, thermophysical, operational, and system-related characteristics into homogeneous clusters, with each cluster represented by a reference prototype. To ensure the

physical reliability of the clustering process, the dataset first underwent a rigorous cleaning and consistency validation process.

Based on engineering principles and Italian technical standards, acceptable ranges were established for key geometric and thermophysical parameters. Specifically, the ratio of total heated volume to total heated floor area must correspond to the building's total height, with a permissible deviation of ± 0.10 meters. Similarly, to ensure the authenticity of volumetric relationships, the ratio of net heated volume to total heated volume was restricted to between 0.55 and 0.85. An additional consistency check was performed on the compactness ratio, defined as the ratio of the envelope area to the total volume after heating, with values restricted to a range of 0.2 to 1.2. The window-to-wall ratio for each orientation was also verified and limited to a range of 0 to 1 to avoid physically unrealistic facade configurations.

Subsequently, the thermal performance was verified using a predefined acceptable range of thermal transmittance values (U-values). The U-value range for exterior walls was limited to $0.15\text{--}2.8 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, for roofs and floors to $0.15\text{--}3.0 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$, and for windows to $0.7\text{--}6.5 \text{ W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$. Where data was available, the air exchange rate was also required to exceed 0.25 h^{-1} to ensure the validity of the ventilation assumptions. In addition to parameter range validation, logical consistency checks were performed on HVAC system configurations. For example, when the heating system is classified as “not present,” all related variables, including generator type, exhaust system, and installed heating capacity, must be null or equal to zero. The same validation criteria were applied to cooling systems and domestic hot water (DHW) configurations to ensure internal consistency across the entire dataset.

A hierarchical filtering strategy was then employed to address inconsistencies identified during the validation phase. For buildings that violated a single validation criterion, corrections were made wherever possible through parameter adjustments or data supplementation; records with multiple inconsistencies or missing critical information were excluded from the clustering phase due to insufficient reliability. This strategy struck a balance between data retention and dataset quality while minimizing the carryover of uncertainty into subsequent prototype generation processes.

Following validation, hierarchical clustering analysis was conducted in accordance with the URBEM methodology. This clustering strategy utilized

construction period, building use, and climate zone as primary classification variables, as these factors have a decisive influence on building energy consumption behavior, building envelope technologies, usage patterns, and HVAC system configurations.

Subsequently, the researchers incorporated several secondary variables, including density ratio, heated volume, thermal transmittance values of the building envelope, ventilation strategies, and HVAC system types, to optimize the clustering process and enhance the consistency of the physical characteristics of the final prototype models. The outcomes of the clustering procedure are summarized in Table 2. 4, which presents the final set of archetypes generated from the analyzed datasets.

Table 2. 4 Summary of archetypes generated from the analyzed case studies.

Number	Archetype code	building category	Construction years	Climatic zone	Region	Number of records
1	OFF_BLDGS_-1933_E_PIE	Offices	before 1933	E	Piemonte	10
2	OFF_BLDGS_1973-1990_E_PIE	Offices	1973-1990	E	Piemonte	5
3	OFF_BLDGS_2000-_E_PIE	Offices	After 2000	E	Piemonte	6
4	OFF_BLDGS_Unknown-_E_PIE	Offices	Unknown	E	Piemonte	5
5	RES_APPBLOCK_1931-1940_E_PIE	Residential building	1931-1940	E	Piemonte	16
6	RES_APPBLOCK_1951-1960_E_PIE	Residential building	1951-1960	E	Piemonte	4
7	RES_APPBLOCK_1995-_E_PIE	Residential building	After 1995	E	Piemonte	4
8	RES_APPBLOCK_1960-1988_E_PIE	Residential building	1960-1988	E	Piemonte	7
9	RES_BLDGS_1960-1991_F_PIE	Residential building	1960-1991	F	Piemonte	4

As shown in Table 2. 4, a total of nine prototypes were generated, covering two building types, i.e., residential and office buildings, located in climate zones E and F. These prototypes span multiple construction periods, ranging from buildings constructed before 1933 to those built after 2000, thereby reflecting the historical evolution of the building stock in northern Italy. Among the identified building prototypes, residential buildings constitute the bulk of the concentrated stock, reflecting the dominance of multi-family housing in the analyzed urban context. Office buildings also exhibit significant differences across construction periods, particularly between pre-regulation buildings and recently constructed office buildings, the latter of which feature superior thermal performance and modern HVAC systems.

The seven identified prototypes are derived from a dataset provided by the Italian State Property Agency (Agenzia del Demanio). Of the 54 buildings initially included, 40 were successfully incorporated into the cluster analysis; the remaining records were excluded due to excessive heterogeneity in construction period, climate zone, or building type. This result highlights the importance of dataset homogeneity within the URBEM framework, as excessive variability may compromise the representativeness and physical consistency of the generated prototypes.

For each building complex, the final prototypes were systematized into standardized scorecards comprising numerical and categorical variables. Numerical variables were used to describe quantitative parameters such as geometric dimensions, thermal transmittance values, airtightness ratios, and energy-related indicators; categorical variables, meanwhile, reflected qualitative information such as building use, building type, HVAC system configuration, and operational characteristics. Table 2. 5 presents an excerpt from the scorecard corresponding to the OFF_BLDGS_-1933_E_PIE prototype, which represents office buildings constructed before 1933 in climate zone E of the Piemonte region.

Table 2. 5 Excerpt of the archetype scorecard: OFF_BLDGS_-1933_E_PIE.

Category	Variables	Values/Distribution
Identification	Archetype code	OFF_BLDGS_-1933_E_PIE
	Region/Zone/Period	Piemonte/Zone E/ before 1933
	Number of records	10
	Data sources	Energy audits: 46%; APECENED

		database (APE): 44%; Municipal database: 10%
Building geometry	Number of floors	3 (Median value)
	Footprint area	969.48 m ² (Median value)
	Heated net floor area	1667.94 m ² (Median value)
	Heated gross volume	9562.27 m ³ (Median value)
	Compactness ratio	0.37 (Median value)
Envelope	Roof type ***	Brick-concrete slab: 50%; Unknown: 40%; Wood structure and planking with tiles: 10%
	U-value of the roof **	1.29 W/m ² K (Median value)
	External walls type	Solid brick masonry: 54%; Hollow brick masonry: 15%; Hollow brick masonry, medium insulation: 8%; Unknown: 23%
	U-value of the wall	1.02 W/m ² K (Median value)
	Slab on the ground floor type	Vault floor with bricks and steel beams: 40%; Concrete floor: 20%; Reinforced concrete slab: 10%; Unknown: 30%
	U-value of the floor **	1.32 W/m ² K (Median value)
	Windows type	Single glazing, wooden frame: 20%; Double glazing, wooden frame: 20%; Double glazing, aluminium frame with thermal break: 23%; Other: 37%
	U-value of the windows	2.95 W/ m ² K (Median value)
	Shading system type	Shutter: 33%; Curtain: 15%; Unknown: 23%; Other: 29%
	Occupancy density *	UNI EN 16798-1 - Table A.19
Gains and ventilation	Lighting power density *	UNI EN 16798-1 - A.8.3
	Equipment power density *	UNI EN 16798-1 - A.8.3
	Type of ventilation	Natural: 80%; Mechanical: 20%
Systems	Heating system type	Centralized: 46%; Autonomous: 27%; Unknown: 27%
	Heating generator	Traditional boiler: 62%; Condensing boiler: 23%; Unknown: 15%
	Energy carrier	Natural gas: 91%; Gas oil: 9%
	Heating emission sub-system	Radiators: 40%; Fan coil: 33%; Unknown: 20%; Other: 7%

Cooling system type	Air-cooled chiller: 50%; Absent: 50%
Cooling emission sub-system	Multisplit:30%; Fan coil: 10%; Unknown:10%; Absent: 50%
DHW system type	Autonomous, detached from heating: 40%; Centralized, coupled with heating: 30%; Absent: 20%; Unknown: 10%
DHW generator	Natural gas boiler:54%; Electric boiler:31%; Absent: 15%

* These values are derived from UNI EN ISO standards; ** U-values of the upper and lower slabs face unconditioned spaces (i.e., attic, basement, etc.); *** Roof type in the envelopes refers to the slab towards unconditioned space (i.e., attic)

As shown in Table 2. 5, the scoring card structure integrates information from multiple data sources, including energy audit reports, the APE database, and municipal records. The prototype description is divided into several thematic categories, covering identification parameters, building geometry, envelope characteristics, energy-saving and ventilation assumptions, and HVAC system configurations. The geometric parameters section lists representative median values such as the number of floors, building footprint, heated floor area, total heated volume, and density ratio. Envelope-related data covers wall types, roof structures, glazing systems, shading devices, and their corresponding thermal conductivity coefficients. The HVAC-related section details heating technologies, cooling systems, energy carriers, emission terminals, and domestic hot water supply strategies.

A key feature of the URBEM scorecard structure is its representation of variability within building clusters. Rather than relying solely on deterministic values, the method expresses multiple parameters as percentage distributions, reflecting the prevalence of specific building technologies or system configurations within the cluster. This design preserves diversity within the cluster while meeting the simplification requirements necessary for city-scale URBEM simulations.

Overall, the scorecards generated constitute standardized, simulation-ready prototype descriptions that can be directly implemented within the URBEM platform. Consequently, these prototypes provide a robust and physically representative foundation for city-scale energy modeling applications in the Italian context.

Chapter 3 Archetype-based urban building energy modelling

A preliminary dataset for urban-scale building energy modelling was established through the comprehensive characterization of the existing building stock in the Piemonte region presented in the previous chapters. Building archetypes derived from the URBEM framework provide the thermophysical, geometric and system-related parameters required to represent the diversity of the regional building stock. Building upon this foundation, the present chapter develops a detailed URBEM for a selected district block in Turin, Italy, using CitySim. As highlighted in Chapter 1, CitySim is a widely adopted URBEM platform that enables the simulation of urban-scale energy performance while explicitly accounting for urban morphology, solar access, shading effects, and interactions among neighboring buildings. Its integrated approach makes it particularly suitable for evaluating both current energy performance and future climate resilience on a district scale. The case-study model was developed using publicly available information retrieved from the Geoportale Torino database. Essential building attributes, including building footprints, construction year, building function, building height, and available architectural drawings were collected and integrated into the modelling workflow (Sameer and Bringezu, 2021; Yang et al., 2018). These datasets provided the geometric and typological basis for the generation of the urban model.

The modelling process consisted of four main stages. First, technical drawing and associated building information were acquired and processed from Geoportale database. Second, three-dimensional building geometries were reconstructed in AutoCAD using the available footprint and height information. Third, the generated geometries were imported into Rhinoceros, where all surfaces were classified and labelled according to CitySim requirements, including facade, roof, and floor surfaces. Finally, the labelled model was exported in DXF format and imported into CitySim, where the urban energy model was generated.

Following the import of the geometric model into CitySim, representative archetype parameters derived from the URBEM database were assigned to each building according to its construction period and typological classification. These parameters included envelope thermal properties, glazing characteristics, occupancy schedules, domestic hot water demand profiles, and HVAC system specifications (Mora et al., 2018). The archetype-based model was then employed to evaluate baseline energy performance and to investigate the impacts of future climate conditions and retrofit strategies on urban energy demand. Figure 3. 1 presents a schematic overview of complete modelling workflow adopted in this study.

MODELLING WORKFLOW FOR URBAN ENERGY MODEL IN CITYSIMPRO

Technical workflow for developing a building energy model at urban scale (UBEM) for a district block in Turin, Piemonte, Italy, using CitySimSimPro and Python for post-processing.

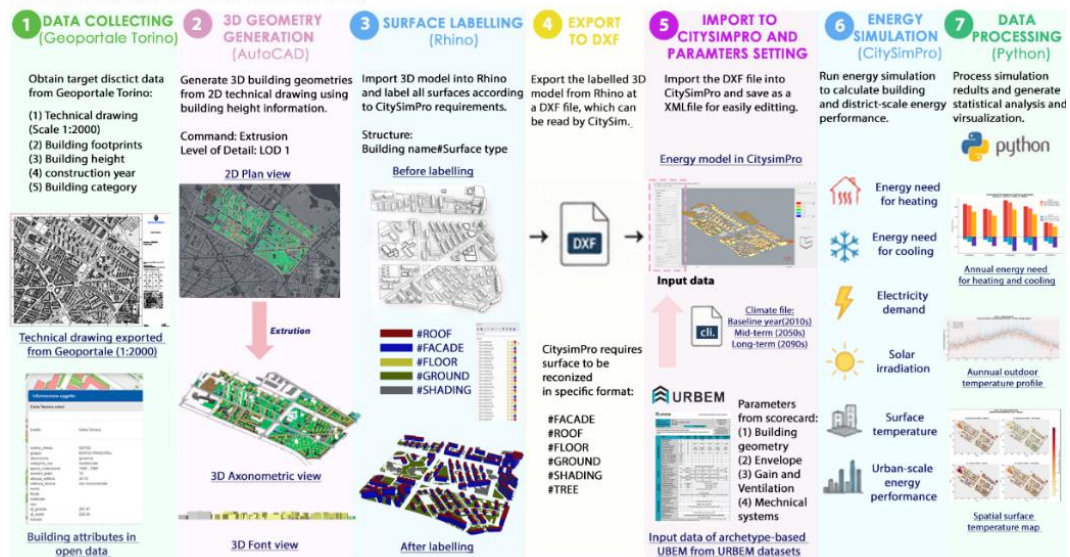


Figure 3. 1 Workflow adopted for the development of the urban building energy model (UBEM) of the selected district block in Turin

3.1 Archetype-based Urban energy model construction

3.1.1 The district block description

The selected district block is located in the northern part of Turin, Piemonte, Italy, and is bounded by Via Sandro Botticelli, Via Bologna, Via Gottardo, and Via Monte Rosa. The district was chosen as a representative urban case study due to the diversity of its building stock, the coexistence of different construction periods and typologies, and the availability of detailed geometric and cadastral information through the municipal Geoportale Torino database. Prior to model development, a comprehensive urban morphology assessment was conducted to characterize the spatial and environmental context of the district. As illustrated in Figure 3. 2, the analysis included the geographical location of the study area within the city of Turin, the spatial extent of the selected district block, prevailing wind conditions, solar exposure patterns, and the three-dimensional urban configuration of the neighborhood.

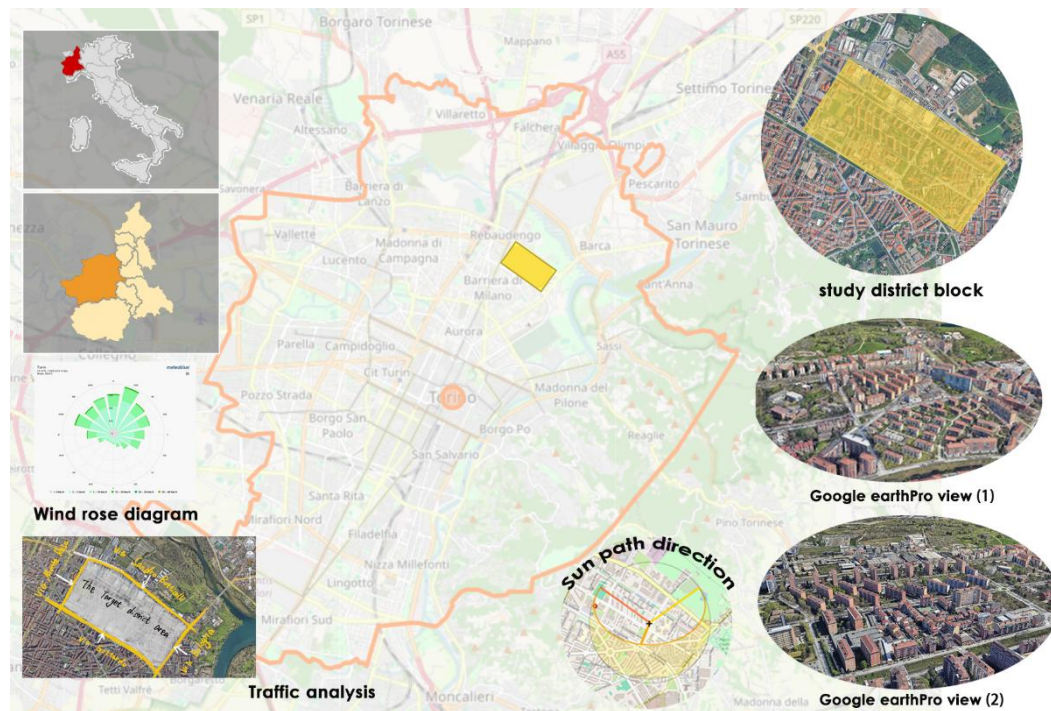


Figure 3. 2 The landscape analysis of targeted district block in Turin, Italy.

The selected district block comprises a total of 214 buildings, including 195 residential buildings and 19 office buildings, reflecting the predominantly

residential character of the area. The building stock exhibits substantial temporal heterogeneity, with construction periods ranging from 1919 to 2012, thereby encompassing several phases of urban development and building regulations in Turin. Figure 3. 3 presents the percentage distribution of buildings according to construction period. The analysis reveals that the majority of buildings were erected during the post-war urban expansion period. Specifically, buildings constructed between 1946 and 1960 represent the largest proportion of the building stock, accounting for 39.25% of all buildings, followed by those built between 1961 and 1970, which represents 35.05% of the total. Together, these two periods account for more than 74% of the district's building stock, highlighting the predominance of mid-twentieth-century construction practices within the study area.

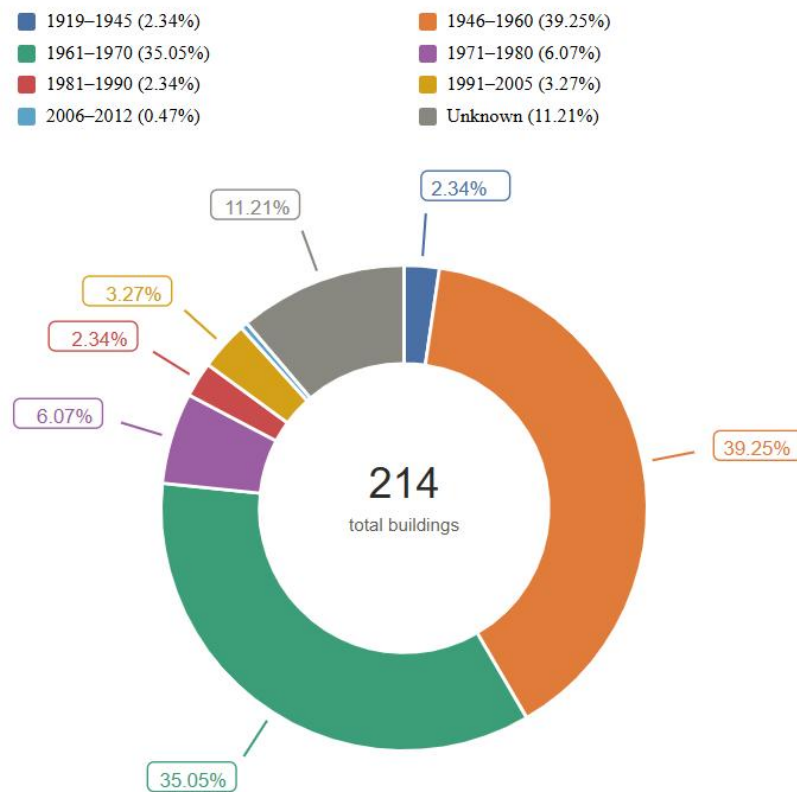


Figure 3. 3 The percentage of buildings distributed by construction year.

The spatial distribution of buildings according to their functional classification is illustrated in Figure 3. 4, where residential and office buildings

are identified within the CAD-based representation of the district block. The results indicate a clear predominance of residential buildings, confirming the residential character of the study area and supporting its suitability for assessing urban residential energy demand at district scale. To further characterize the building stock, Figure 3. 5 reports the distribution of buildings according to construction period using a three-dimensional Rhino-based model. The visualization highlights the coexistence of buildings from different development phases and reveals the spatial clustering of construction periods within the district. Such information is particularly relevant for archetype assignment, as building age constitutes one of the primary variables influencing envelope thermal performance, construction materials, glazing systems, and HVAC characteristics.



Figure 3. 4 The configuration of the district block distributed by usage (view in CAD).

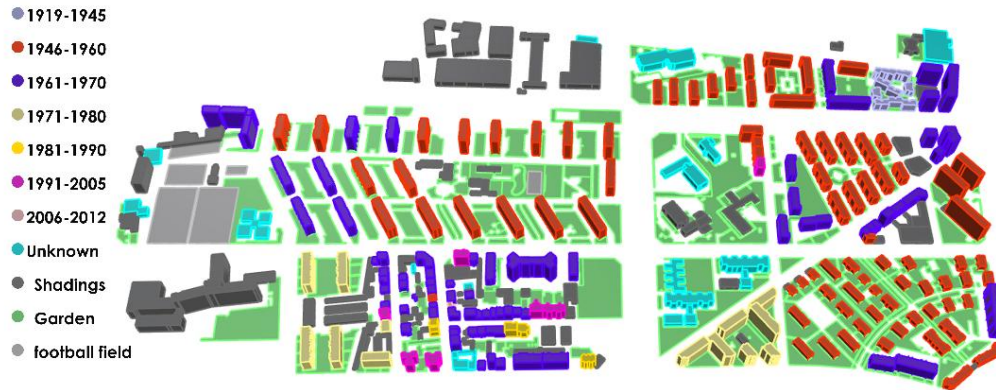


Figure 3. 5 The buildings in the district block distributed by construction year (view in RHINO).

The predominance of buildings constructed between 1946 and 1970 indicates that the district is largely characterized by mid-twentieth-century building typologies. This characteristic is particularly relevant for urban building energy modelling, as construction age strongly influences enveloping thermal properties, building materials, occupancy patterns, and overall energy performance. Consequently, the district provides a representative case study for evaluating retrofit strategies, assessing energy demand, and crucially evaluating climate resilience strategy at the urban scale.

3.1.2 UBEM Parameter Settings based on Archetype

3.1.2.1 Geometric configuration parameter

Based on the geographical context, building typologies, and construction periods identified within the selected district block, five representative building archetypes developed in Chapter 2 were assigned to the building stock. These archetypes, herein referred to as scorecards, provide the baseline thermal, geometric, and operational parameters required for the development of the district-scale UBEM. The selected archetypes collectively represent the predominant building categories and construction periods observed within the study area, thereby ensuring consistency between the archetype database and the urban building stock. The complete set of thermophysical and operational parameters adopted for the simulations is summarized in Table 3. 1. The dataset

includes envelope thermal transmittances (U-values), infiltration rates, glazing properties, and solar-related parameters for each archetype. These parameters were derived from the archetype database established in Chapter 2 and subsequently implemented within the CitySim modelling environment.

Table 3. 1 Summary of the complete set of thermophysical and operational parameters.

Archetype number	Scorecard	Building category-building age	Ventilation type	Air change rate	U_{wall}	U_{roof}	U_{floor}	U_{window}	g_{gl}	λ
				h^{-1}	W/m^2K	W/m^2K	W/m^2K	W/m^2K	-	
1	RES_APPBLOCK_1931-1940_E_PIE	Residential-1919-1945	Natural	0.50	1.23	0.34	2.01	1.92	0.75	0.10
2	RES_APPBLOCK_1951-1960_E_PIE	Residential-1946-1960	Natural	0.50	0.63	0.24	2.04	1.67	0.75	0.15
3	RES_APPBLOCK_1960-1988_E_PIE	Residential-1961-1990	Natural	0.50	0.73	1.53	1.15	3.10	0.75	0.15
4	RES_APPBLOCK_1995-_E_PIE	Residential-After 1995	Natural	0.50	0.41	1.12	1.11	2.85	0.75	0.15
5	OFF_BLDGS_Unknown_E_PIE	Office-Unknown	Natural	0.50	1.15	1.64	1.54	5.79	0.85	0.00

To characterize envelope thermal performance, opaque and transparent building components were parameterized according to their corresponding archetype (Corrado and Paduos, 2016). For opaque elements, including external walls, roofs, and floors, thermal transmittance values were derived from the representative construction assemblies identified during the archetype development phase. Within CitySim, the thermal performance of each construction element is calculated based on the thermal resistance of its constituent layers, allowing the overall U-value to be determined from the corresponding multilayer stratigraphy. Each material used from the database has its properties such as density and conductivity. Using these data together with thickness of the layers, the U-value is computed with the following formula:

$$U = \frac{1}{R_{Tot}} = \frac{1}{R_{se} + \sum_i \frac{d_i}{\lambda_i} + R_{si}} \left[\frac{W}{m^2K} \right] \quad (3)$$

Where R_{se} and R_{si} are respectively the external and internal surface resistance value. d_i is the thickness of layer i and λ_i stands for the corresponding thermal conductivity. d_i/λ_i is the thermal resistance of the i -element. According to the EN ISO 6946:2017, surfaces resistances are given and collected in the following Table 3. 2

Table 3. 2 Surface resistance parameters of various direction heat flow.

Surface resistance [m ² K/W]	Direction heat flow		
	Upwards	Horizontal	Downwards
R_{se}	0.10	0.13	0.17
R_{si}	0.04	0.04	0.04

Since orientation-specific WWR values were not available in the original archetype scorecards, additional information was extracted from six comparable archetypes within the URBEM database. These supplementary archetypes were selected based on similarities in construction period, building function, and envelope characteristics to ensure consistency with the primary archetype definitions.

The derived WWR values were subsequently incorporated into the UBEM parameterization to improve the representation of façade glazing distribution across the four cardinal orientations (North, East, South, and West). This refinement is particularly relevant for urban-scale energy simulations, where solar exposure and shading effects strongly depend on the orientation and extent of transparent envelope components. The final orientation-dependent WWR values adopted for each archetype are reported in Table 3. 3 and were used as input parameters in the CitySim model.

Table 3. 3 Summary of final WWR values for each archetype.

Archetype number	Scorecard	Building category-building year	WWR (NESWR*)	Description
1	RES_APPBLOCK_1931-1940_E_PIE	Residential-1919-1945	0.14-0.12-0.14-0.13-0	/
2	RES_APPBLOCK_1951-1960_E_PIE	Residential-1946-1960	0.11-0.10-0.12-0.1-0	/

3	RES_APPBLOCK_1962-1971_E_VAL	Residential-1961-1970	0.14-0.14-0.14-0.14-0	Supplementary scorecards
4	RES_APPBLOCK_1972-1981_E_VAL	Residential-1972-1981	0.13-0.13-0.13-0.13-0	
5	RES_APPBLOCK_1982-1991_E_PIE	Residential-1982-1991	0.13-0.13-0.13-0.13-0	
6	RES_APPBLOCK_1992-2005_E_VAL	Residential-1992-2005	0.14-0.14-0.14-0.14-0	
7	RES_APPBLOCK_2006-_E_VAL	Residential-After 2006	0.13-0.13-0.13-0.13-0	
8	OFF_1946-1981_E_VAL	Office-unknown	0.15-0.15-0.15-0.15-0	

To account for the impact of solar protection systems on building energy performance, movable shading devices were explicitly modelled within the CitySim environment using a logistic control function driven by incident solar irradiance as formula (4) below. The activation threshold was defined using a cut-off solar irradiance of 300 W/m², consistent with the default manual shading control assumptions recommended in the Italian National Annex of UNI EN ISO 52016-1 (ISO, 2017). Under this control strategy, shading devices remain inactive under low solar radiation levels and are progressively deployed as incident irradiance exceeds the prescribed threshold. Different λ values were assigned to represent the response characteristics of the shading systems: $\lambda = 0.10$ for blinds, $\lambda = 0.15$ for shutters and $\lambda = 0.0$ for non-shading buildings, as shown in Figure 3.6. The higher λ value for shutters reflects their more abrupt open–closed operation, whereas blinds exhibit a smoother and more gradual response to increasing solar radiation.

$$f(I) = \frac{1}{1 + e^{\lambda(I - I_{cut})}} \quad (4)$$

Where I , I_{cut} and λ refer to irradiance, cut-off irradiance and transition sharpness respectively.

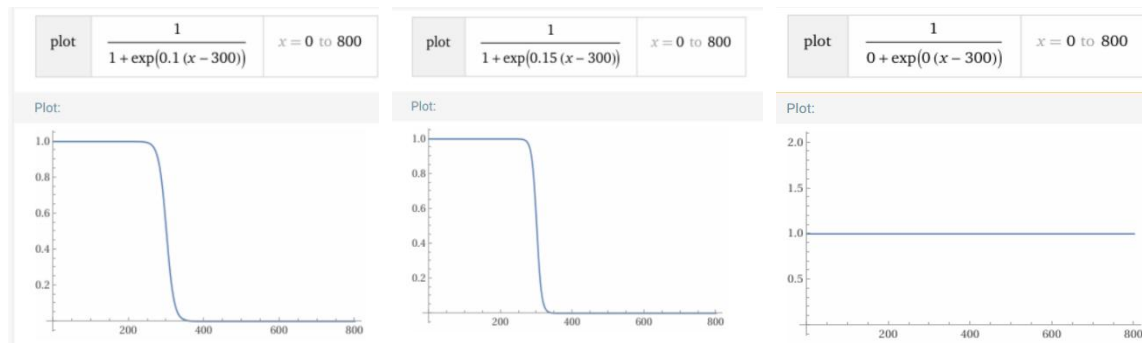


Figure 3. 6 Blinds, shutter and no shading device behaviour plot from left to right.

3.1.2.2 Mechanical System and Occupancy parameter input

Mechanical system and occupancy parameters constitute essential inputs to the CitySim-based UBEM, as they determine building operational characteristics and internal heat gains (Doma and Ouf, 2023). The values adopted in this study are summarized in Table 3. 4 and were assigned at the building archetype level to ensure consistency among buildings sharing similar construction periods, functions, and energy performance characteristics.

Table 3. 4 Various operational parameters for each archetype.

Archetype number	1	2	3	4	5
Scorecard	RES_APPBLOCK_1931-1940_E_PIE	RES_APPBLOCK_1951-1960_E_PIE	RES_APPBLOCK_1960-1988_E_PIE	RES_APPBLOCK_1995-_E_PIE	OFF_BLDGS_Unknown_E_PIE
Building category-building year	Residential-1919-1945	Residential-1946-1960	Residential-1961-1990	Residential-After 1991	Office-unknown
Occupancy density [m ² /P]	23.8	23.8	23.8	23.8	17
Sensible heat [W/P]	90	90	90	90	90
Latent heat [W/P]	60	60	60	60	60
Heating set point	20 °C	20 °C	20 °C	20 °C	20 °C
Cooling setpoint	26 °C	26 °C	26 °C	26 °C	26 °C
Heating generator type	Traditional boiler	Traditional boiler	Condensing boiler	Condensing boiler	Traditional boiler

Boller efficiency	80%	80%	95%	95%	80%
Cooling generation type	None	None	Air-air heat pump	None	Air-air heat pump
COP	0.0	0.0	3.3	0.0	3.3
DHW system type	Centralized, couple with heating system	Centralized, couple with heating system	Centralized, couple with heating system	Centralized, couple with heating system	Centralized, couple with heating system

Mechanical system inputs include heating and cooling set-point temperatures, system operating schedules, and HVAC operational assumptions (de Chalendar et al., 2023). These parameters directly influence the calculation of annual heating and cooling energy demand, peak thermal loads, and indoor thermal conditions. A centralized heating system was assumed for all buildings, while the generator type and energy carrier were defined according to the corresponding archetype specifications. Cooling and domestic hot water (DHW) system parameters were assigned following the archetype scorecards developed for the case study. The heating set-point temperature was fixed at 20 °C, and the heating season was defined from 15 October to 14 April, in accordance with Italian regulations for Climate Zone E. Furthermore, Italian legislation limits the daily operation of heating systems to a maximum of 14 hours. This requirement was implemented in CitySim through the definition of temperature profiles that regulate system operation throughout the day.

Occupancy parameters characterize building usage patterns through occupant density, occupancy schedules, and associated internal heat gains from occupants and appliances. Occupancy density values and temporal occupancy profiles were defined in accordance with EN 16798-1:2019 National Annex A (Ballerini, 2025; UNI, 2019a). For both residential and office buildings, separate occupancy schedules were specified for weekdays and weekends/holidays to accurately capture variations in user behaviour. These parameters play a significant role in building thermal balance and consequently affect both winter heating demand and summer overheating risk. Collectively, the adopted mechanical system and occupancy assumptions provide a realistic representation of building operation and support reliable district-scale energy performance simulations under present and future climate conditions.

3.1.2.3 External obstacle and surface parameter input

One of the distinct advantages of UBEM lies in its capability to capture inter-building thermal and radiative interactions at the district scale. Within a micro-climate urban block, the energy performance of a target building is governed not only by static external obstacles but also by mutual shading and reflection from adjacent structures. To accurately simulate these micro-urban phenomena, the microclimate simulation platform CitySim was utilized to define the radiative boundary conditions, specifically through the parameterization of short-wave reflectance (SR) and the soil moisture characteristic factor (K-factor).

The SR determines the fraction of incident solar radiation reflected by a surface, directly influencing the secondary radiative heat gains of surrounding facades. For all built structures and external obstacles, a baseline SR of 0.20 was applied, aligning with typical urban albedo standards for mixed-material facades. To capture the distinct hydrothermal properties of horizontal surfaces, two micro-urban ground surfaces were modeled: a green garden area and a football field (artificial turf), with SR values assumed 0.25 and 0.30, respectively. The higher reflectance of the football field accounts for its brighter synthetic or managed surface composition compared to the natural vegetative canopy of the garden.

Furthermore, the K-factor was integrated to regulate the soil latent heat flux via evapotranspiration within the simulation environment. Evapotranspiration significantly mitigates the UHI effect by converting sensible heat into latent heat. For the green garden zone, the K-factor was established at 0.5 to represent a dynamically moist soil condition capable of sustained evaporative cooling, thereby ensuring a robust representation of the local urban microclimate.

3.2 Simulation result of UBEM and discussion

Following the assignment of archetype-specific parameters and the implementation of the district model in CitySim, preliminary simulations were performed to verify the functionality of the UBEM and to visualize the spatial distribution of key thermal performance indicators.

Figure 3. 7 presents selected outputs generated by the CitySim simulation environment. Figure 3. 7(a) illustrates the fully parameterized three-dimensional district model after surface classification and labeling in Rhinoceros and

subsequent import into CitySim. The model incorporates geometric characteristics, envelope properties, and operational parameters assigned through the archetype-based methodology.

To demonstrate the capability of the model to capture spatial and temporal variations in building performance, Figure 3. 7(b) presents the simulated indoor air temperature (T_a) distribution at Hour 5966, while Figure 3. 7(c) shows the distribution of monthly heating demand ($Q_s > 0$) during December. Figure 3. 7(d) reports the distribution of daily surface temperature (T_{os}) simulation findings for Day 171. The results reveal noticeable variations among buildings, reflecting differences in construction period, envelope thermal quality, building geometry, solar exposure, and operational characteristics represented by the selected archetypes.

These outputs confirm that the developed UBEM is capable of representing the heterogeneity of the urban building stock and reproducing building-specific thermal behaviour at urban scale. Furthermore, the spatially resolved simulation results provide the analytical foundation for the subsequent assessment of future climate impacts, energy retrofit strategies, and urban climate resilience scenarios. Due to limited measured energy consumption data for this project, the model was verified for functional consistency rather than calibrated against empirical data; calibration is outlined as future work in Section 5.2.

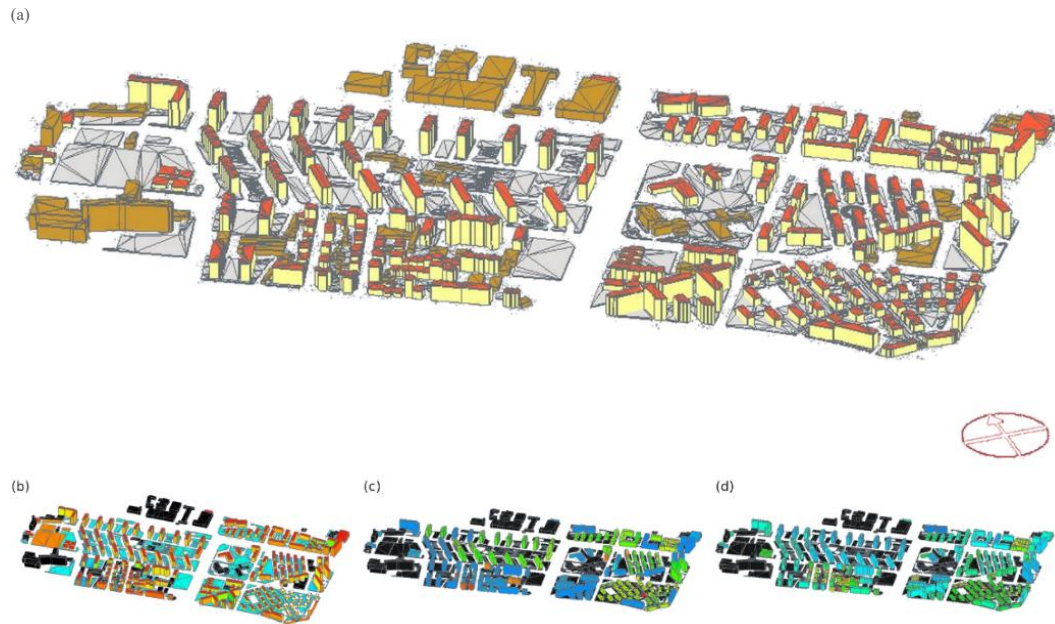


Figure 3. 7 CitySim simulation visual results of the urban district. (a) 3D district model in CitySim's user interface after surface labeling in Rhino; (b) hourly indoor air temperature (T_a) simulation results at Hour 5966; (c) monthly heating energy demand ($Q_s > 0$) simulation results for Month 12; (d) daily surface temperature (T_{os}) simulation results for Day 171.

Chapter 4 Evaluation of climate-resilient strategies

4.1 Climate-resilient strategies introduction

Climate change is increasingly recognized as one of the primary challenges affecting the future performance and resilience of the built environment. Although buildings have traditionally been designed and evaluated based on historical climate conditions, rising air temperatures and an increase in the frequency of extreme weather events are expected to significantly alter building energy demand patterns in the coming decades. Consequently, renovation strategies that are effective under current climate conditions may not remain effective under future climate scenarios.

The city of Torino, located in northern Italy and characterized by a heating-dominated climate, is projected to experience substantial climatic changes throughout the twenty-first century. According to recent climate projections, average outdoor temperatures are expected to increase progressively under all emission scenarios, accompanied by a significant rise in the intensity, duration, and frequency of summer heatwaves. At the same time, the number of cooling degree days is expected to increase, while heating degree days gradually decrease. Although these changes may reduce winter heating demand, they are likely to produce a substantial increase in cooling requirements and overheating risks,

particularly within existing buildings that were originally designed to address winter thermal conditions rather than summer heat stress.

These climatic shifts present a critical challenge for the existing building stock in Torino. A large proportion of residential and office buildings were constructed before the introduction of modern energy-efficiency regulations and therefore exhibit poor thermal insulation, inadequate solar protection, and limited passive cooling capacity. As outdoor temperatures continue to rise, such buildings become increasingly vulnerable to overheating, reduced thermal comfort, and higher cooling energy consumption. Consequently, the energy performance achieved under current climatic conditions may progressively deteriorate when evaluated under future weather scenarios.

The issue is particularly relevant on the urban scale, where the combined effects of climate change, urban morphology, and building characteristics may amplify cooling demand and increase peak electricity loads. As a result, future urban energy systems may face greater operational stress during summer periods, while the effectiveness of conventional retrofit measures focused primarily on heating reduction may decline. To address these challenges, the concept of climate resilience has emerged as a key objective in building retrofit design. Climate-resilient buildings are not only energy efficient under present-day conditions but are also capable of maintaining acceptable levels of performance, thermal comfort, and energy flexibility under future climate scenarios. This requires the adoption of adaptation-oriented retrofit strategies that explicitly consider long-term climatic evolution and the associated uncertainties.

Therefore, this chapter investigates a set of climate-resilient retrofit strategies applied to the selected urban blocks in Torino. The objective is to evaluate their effectiveness in mitigating future cooling demand, reducing overheating risks, and maintaining building energy performance under projected climate conditions. By comparing the performance of different adaptation measures across multiple climate scenarios, the study aims to identify robust retrofit solutions capable of enhancing the long-term resilience of urban building stock.

4.2 Future climate scenarios and key performance indicators (KPIs)

4.2.1 Climate scenarios description

The three climate scenarios adopted in this study are derived from Typical Meteorological Year (TMY) files developed for Turin within the CRiStAll project (Borelli et al., 2025). Future hourly weather projections were sourced from the CORDEX database using the GERICS_MPI-M-MPI-ESM-LR regional climate model under the RCP 8.5 emission pathway, and subsequently bias-corrected against measured data from the Bauducchi station (lat. 44.96° N, lon. 7.70° E) via the multivariate MBCn/QDM method (CRiStAll, 2025; François et al., 2020), following the UNI-EN-ISO 15927-4 standard (ISO/TC, 2005) for TMY generation. The three files correspond to a baseline reference period (2010s, 2013–2023), a mid-term projection (2050s, 2041–2060), and a long-term projection (2090s, 2081–2100). Each file already incorporates the UHI effect as modelled via the Urban Weather Generator (UWG), making them directly representative of urban thermal conditions at the district scale. These files are therefore adopted as the meteorological boundary conditions for the CitySim UBEM simulations in this study, without further microclimate modelling.

The annual outdoor temperature profiles of the three TMY files are presented in Figure 4. 1. The curves confirm a consistent upward shift in temperature across all seasons as the scenario progresses from historical to long-term. During winter months, the long-term (2090s) scenario exhibits noticeably milder conditions compared to the historical baseline (2010s), with minimum temperatures rarely falling below 0 °C. Conversely, summer peaks intensify progressively, with the 2090s profile exceeding 30 °C during July and August, compared to approximately 27 °C in the 2010s. The earlier crossing of the 18 °C base temperature threshold in spring and its later recession in autumn under future scenarios further signals a systematic extension of the cooling season and contraction of the heating season, which is quantitatively captured by the HDD and CDD indicators discussed in the following section.

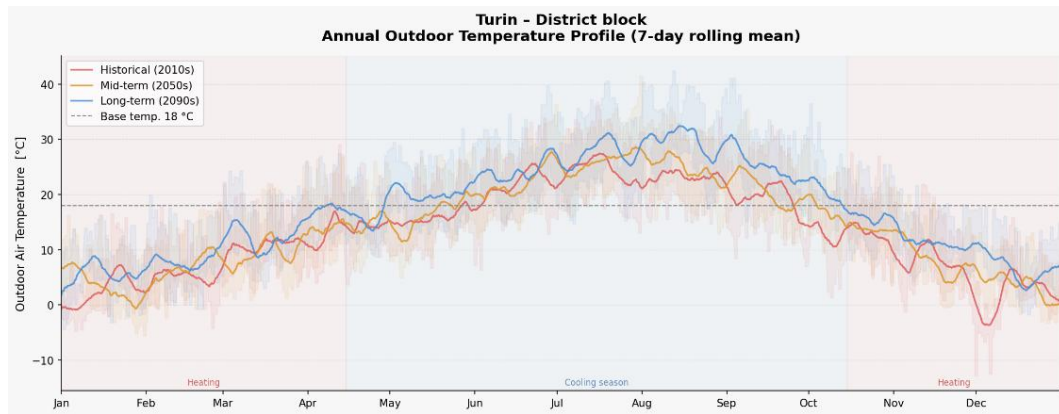


Figure 4. 1 Annual outdoor air temperature profiles of the three TMY weather files for Turin.

To calculate the key performance indicators presented in the following sections, the annual 8760-hour simulation period is divided into two distinct seasons: a heating season (4368 hours) and a cooling season (4392 hours), as detailed in Table 4. 1. The interval boundaries are defined according to the climatic conditions of Turin (latitude 45°N, climate Zone E under DPR 412/1993). The heating season comprises two sub-periods, January 1 to April 14 (hours 1–2,496) and October 15 to December 31 (hours 6,889–8,760), during which outdoor temperatures in Turin regularly fall below the indoor heating setpoint of 20°C. The intervening period from April 15 to October 14 (hours 2,497–6,888) constitutes the cooling season, characterized by elevated ambient temperatures and solar gains that drive mechanical cooling demand. This partitioning is consistent with the Zone E heating period defined in DPR 412/1993 (15 October – 15 April) (DPR, 1993), with climatic reference data sourced from UNI 10349-1:2016 (UNI, 2016).

Table 4. 1 Information on the heating and cooling seasons.

Season	Data range	Hour interval	Hours	Share
Heating(early)	Jan 1-Apr 14	1-2496	2496h	28.5%
Cooling	Apr15-Oct 14	2497-6888	4392h	50.1%
Heating(late)	Oct15-Dec 31	6889-8760	1872h	21.4%
Full year	365 days	-	8760h	100%

4.2.2 Key Performance indicators and visualization framework

4.2.2.1 Overview of selected KPIs

The assessment of climate change impacts on buildings requires a set of indicators capable of capturing variations in climatic conditions, building energy demand, thermal comfort, and climate vulnerability. Based on the literature review presented in Chapter 1 and the objectives of this study, a hierarchical KPI framework was developed to evaluate the performance of the studied urban block under current and future climate scenarios (Stavropoulos et al., 2014). The proposed framework comprises four complementary categories of indicators: (i) climate indicators, (ii) building energy performance indicators, (iii) indoor thermal comfort indicators, and (iv) climate vulnerability indicators. Together, these indicators provide a comprehensive representation of the causal chain linking future climatic changes to building performance and resilience.

4.2.2.2 Climate indicators

To characterize the evolution of climatic conditions independently from building characteristics, heating degree days (HDD) and cooling degree days (CDD) are calculated for each climate scenario. These indicators provide a synthetic representation of heating and cooling requirements driven solely by outdoor climatic conditions and are widely used in climate impact assessments. The comparison of HDD and CDD among the baseline (2010s), mid-term (2050s), and long-term (2090s) climate scenarios enables the quantification of the shift from a heating-dominated climate towards increasing cooling requirements in Turin.

4.2.2.3 Building energy performance indicators

Building energy performance is evaluated using both annual energy demand indicators and peak load indicators. The annual energy need for heating ($EP_{H,nd}$) and cooling ($EP_{C,nd}$) quantify the cumulative thermal energy required to maintain indoor comfort conditions over a typical year. These indicators provide information regarding operational energy consumption and the long-term effects of climate change on building performance. In addition to annual energy demand, peak heating load ($\phi_{H,ld}$) and peak cooling load ($\phi_{C,ld}$) are assessed to evaluate

changes in system sizing requirements and the intensity of thermal stress experienced by buildings during extreme weather conditions. The combined use of annual and peak indicators allows the assessment of both energy consumption and capacity-related impacts of future climate scenarios. Moreover, in this study, due to the LOD1 shoebox representation adopted in CitySim, each building is modelled as a single thermal zone. Therefore, the floor area is assumed to be equivalent to the conditioned area for all energy performance indicators.

4.2.2.4 Indoor thermal comfort indicator

Future climate warming is expected to significantly increase overheating risks in existing buildings. To assess indoor thermal comfort under free-floating conditions, the weighted warm hours of discomfort (WHDw) indicator is adopted. Unlike conventional overheating metrics based solely on the number of exceedance hours, WHDw incorporates the severity of thermal discomfort by weighing each exceedance hour according to the magnitude of the temperature deviation from adaptive comfort limits. Consequently, the indicator simultaneously captures both the frequency and intensity of overheating events. The indicator is calculated exclusively during the summer period (June–August) using a dedicated simulation without mechanical cooling, thereby representing the intrinsic thermal resilience of buildings.

4.2.2.5 Building climate vulnerability indicators

Although individual KPIs provide detailed information on specific aspects of building performance, they do not directly quantify the sensitivity of buildings to climate change. Therefore, a building climate vulnerability index (VI) is introduced (Choi et al., 2019; Lantada et al., 2009). Separate vulnerability indices are calculated for heating and cooling performance, namely, heating vulnerability index (VIH) and cooling vulnerability index (VIC) (Pham and Lin, 2025). These indices measure the relative variation in annual energy demand between the baseline and future climate scenarios. Buildings exhibiting larger changes are considered more vulnerable to climate change and therefore constitute priority targets for adaptation interventions. The vulnerability indicators provide a synthetic metric for identifying buildings most exposed to future climatic conditions and support the subsequent selection of climate-resilient retrofit strategies.

4.2.3 Mathematical definitions and calculations

(1) Heating and cooling degree days (HDD and CDD)

HDD and CDD are calculated according to UNI 10349-3:2016 (UNI, 2016) using hourly outdoor air temperature extracted from the corresponding typical meteorological year (TMY) files (Hamdy et al., 2017) following the equations (5) and (6). The heating base temperature ($\theta_{b,H}$) and cooling base temperature ($\theta_{b,C}$) are both set equal to 18 °C, consistent with the Italian standard.

$$HDD = \frac{\sum_{h=1}^n (\theta_{b,H} - \theta_{e,h})^+}{24} \quad (5)$$

Where HDD is heating degree days, °C·d; h is time step, h; n is total number of time steps, h; $\theta_{b,H}$ is heating base temperature, °C; $\theta_{e,h}$ is external air temperature of time step h, °C.

$$CDD = \frac{\sum_{h=1}^n (\theta_{e,h} - \theta_{b,C})^+}{24} \quad (6)$$

Where CDD is cooling degree days, °C·d; h is time step, h; n is total number of time steps, h; $\theta_{b,C}$ is cooling base temperature, °C; $\theta_{e,h}$ is external air temperature of time step h, °C.

The superscript ‘+’ denotes that only positive differences contribute to the sum (i.e., hours in which $\theta_{e,h}$ exceeds $\theta_{b,H}$ during the heating season, or falls below $\theta_{b,C}$ during the cooling season, are excluded). The resulting indicators are expressed in degree-days (°C · d) and provide a climate-normalized representation of thermal demand.

(2) Annual energy needs for heating and cooling ($EP_{H,nd}$ and $EP_{C,nd}$)

According to literature (Hamdy et al., 2017), for each building i , the annual thermal energy need for space heating/cooling ($EP_{H/C,nd}$) per unit conditioned floor area is calculated as:

$$EP_{H/C,nd} = \sum_{h=1}^n EP_{H/C,nd,h} \quad (7)$$

Where $EP_{H/C;nd}$ is thermal energy need for space heating/cooling, $\text{kWh} \cdot \text{m}^{-2}$; h is time step counter, n is total number of time step; $EP_{H/C;nd;h}$ is hourly thermal energy need for space heating/cooling, $\text{kWh} \cdot \text{m}^{-2}$.

At the district scale, results are aggregated per building archetype using an area-weighted mean, defined as:

$$EP_{H/C;nd;arc} = \frac{\sum (EP_{H/C;nd;i} \cdot A_{f,i})}{\sum A_{f,i}} \quad (8)$$

Where $EP_{H/C;nd;arc}$ represents annual heating and cooling energy demand of architecture, $\text{kWh} \cdot \text{m}^{-2}$; A_f is the condition floor area, m^2 .

This formulation ensures that buildings with larger floor areas contribute proportionally more to the archetype mean, avoiding bias introduced by differences in building size. Results are presented as grouped bar charts with the five archetypes (Archetype 1-Archetype5) on the x-axis and the three climate scenarios represented by distinct color shades within each group.

(3) Peak heating and cooling loads ($\phi_{H;nd}$ and $\phi_{C;nd}$)

The peak heating load is defined as the maximum hourly heating power required during the heating season:

$$\phi_{H;ld} = \max(0, \phi_{H;ld;h}) \quad h \in \text{heating season} \quad (9)$$

Where $\phi_{H;ld}$ is peak heating load per unit conditioned floor area, $\text{W} \cdot \text{m}^{-2}$; $\phi_{H;ld;h}$ is hourly heating load per unit conditioned floor area, $\text{W} \cdot \text{m}^{-2}$. For heating season $h \in [1, 2496] \cup [6889, 8760]$.

Similarly, peak cooling load is calculated as:

$$\phi_{C;ld} = \min(0, \phi_{C;ld;h}) \quad h \in \text{cooling season} \quad (10)$$

Where, $\phi_{C;ld}$ is peak cooling load per unit conditioned floor area, $\text{W} \cdot \text{m}^{-2}$; $\phi_{C;ld;h}$ is hourly cooling load per unit conditioned floor area, $\text{W} \cdot \text{m}^{-2}$. For cooling season, $h \in [2497, 6888]$

To facilitate comparison among archetypes, representative buildings are selected based on the highest peak heating load observed under baseline climatic conditions.

The negative sign converts the result to a negative value for graphical representation, consistent with the cooling demand convention. For visualization, three representative buildings per archetype are selected based on the highest peak load ($\phi_{H;ld;i} + |\phi_{C;ld;i}|$) under the baseline scenario (2010s). This selection criterion ensures that the most thermally stressed buildings, those with the greatest instantaneous heating demand, are consistently tracked across all three climate scenarios. Results are presented as grouped bar charts, with building labels on the x-axis grouped by archetype.

(4) Weighted warm hours of discomfort (WHD_w)

The WHD_w indicator quantifies the severity and frequency of indoor overheating during the summer period (June–August) by weighting exceedance hours according to the degree of thermal discomfort. The calculation follows the adaptive comfort approach defined in EN 16798-1:2019 and UNI EN ISO 7730:2005. The running mean outdoor temperature θ_{rm} is computed daily for the summer period using the preceding seven days of mean outdoor air temperature sourced from the TMY climate file, capped at 30 °C, as specified in EN 16798-1:

$$\theta_{rm} = (\theta_{ed-1} + 0.8\theta_{ed-2} + 0.6\theta_{ed-3} + 0.5\theta_{ed-4} + 0.4\theta_{ed-5} + 0.3\theta_{ed-6} + 0.2\theta_{ed-7})/3.8 \quad (11)$$

Where θ_{rm} is running mean outdoor temperature, °C. θ_{ed-1} is daily mean outdoor temperature for previous day, °C; θ_{ed-i} is the daily mean outdoor air temperature for the $i - th$ previous day, sourced from the corresponding TMY climate, °C;

The upper limit operative temperature ($\theta_{0;limit;upper}$), optimal operative temperature (θ_c), and outdoor running mean temperature (θ_{rm}) are calculated according to UNI EN 16798-1:2019 (UNI, 2019a). The $\theta_{0;limit;upper}$ and θ_c are calculated by means of equation (12) and (13):

$$\theta_{0;limit;upper} = 0.33 \cdot \theta_{rm} + 18.8 + 3 \quad (12)$$

$$\theta_c = 0.33 \cdot \theta_{rm} + 18.8 \quad (13)$$

For each summer hour h in which the indoor operative temperature θ_0 exceeds $\theta_{0;limit;upper}$, a weighting factor (wf), for $\theta_0 - \theta_{0;limit;upper} > 0$, is calculated according to UNI EN ISO 7730:2005 (UNI, 2006), by means of equation (14):

$$wf = 1 + \frac{\theta_0 - \theta_{0;limit;upper}}{\theta_{0;limit;upper} - \theta_c} \quad (14)$$

Where wf is the weighting factor; θ_0 is the indoor operative temperature, °C, which assume as indoor air temperature in this case; $\theta_{0;limit;upper}$ is the upper limit of operative temperature, °C; θ_c is the optimal operative temperature, °C.

The total WHD_w for a given building and climate scenario is obtained by cumulative summation over all exceedance hours:

$$WHD_w = \sum wf \cdot t \text{ for } \theta_0 > \theta_{0;limit;upper} \quad (15)$$

Where WHD_w is the weighted warm hours of discomfort, h; wf is the weighting factor; t is the time, h; all $h \in [\text{June 1} - \text{August 31}]$. The building exhibiting the highest WHD_w under the 2010s baseline is identified as the most thermally vulnerable and is selected for detailed cross-scenario analysis.

(5) Building vulnerability index (VI)

To provide a synthetic measure of each building's sensitivity to long-term climate change, a Building Vulnerability Index is defined separately for heating and cooling (Choi et al., 2019; Hamdy et al., 2017; Lantada et al., 2009):

$$VI_H = |EP_{H;nd,2090s} - EP_{H;nd,2010s}| / EP_{H;nd,2010s} \quad (16)$$

$$VI_C = |EP_{C;nd,2090s} - EP_{C;nd,2010s}| / |EP_{C;nd,2010s}| \quad (17)$$

Both indices are dimensionless positive values: a higher VI indicates a greater relative change in energy demand between the baseline and long-term scenario, reflecting stronger climate sensitivity. For VI_H , higher values correspond to a greater reduction in heating demand; for VI_C , higher values indicate a greater increase in cooling demand — both representing buildings are more exposed to the effects of climate warming.

For each archetype, the buildings with the highest VI_H are selected as representative vulnerable cases: five buildings for the two largest residential archetypes (AT2 and AT3) and three buildings for the remaining archetypes (AT1, AT4, AT5). These representative buildings are presented in grouped bar charts showing VI_H and VI_C side by side. In addition, a spatial Vulnerability Map is generated by overlaying the VI_H values onto the building footprint geometries

extracted from the CitySim XML model, with colour intensity proportional to vulnerability. Representative buildings are labelled directly on the map to facilitate spatial interpretation and to guide the selection of priority targets for climate resilience strategy assessment in the subsequent phase of the study.

4.2.4 Simulation result analysis at baseline condition (without strategy adopted)

4.2.4.1 Heating and cooling degree days

As shown in Figure 4. 2 , $HDD_{18^{\circ}C}$ decreases steadily from 2039 $^{\circ}C \cdot d$ in the historical period to 1483 $^{\circ}C \cdot d$ in the 2090s, while $CDD_{18^{\circ}C}$ increases from 615 $^{\circ}C \cdot d$ to 1218 $^{\circ}C \cdot d$. This indicates that future climate warming in Turin is expected to reduce heating needs and increase cooling requirements.

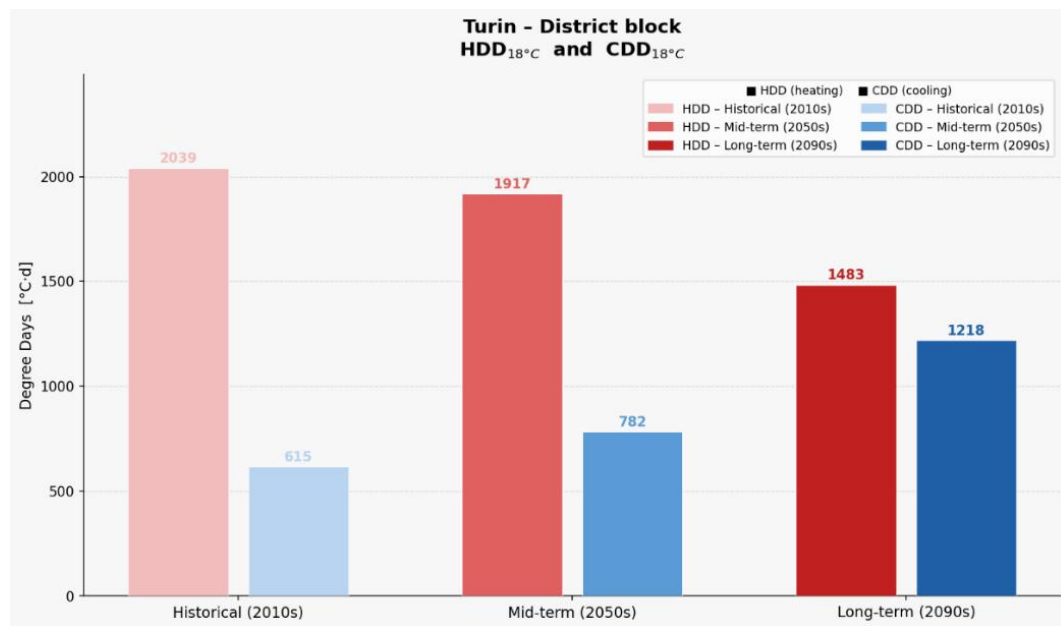


Figure 4. 2 HDD and CDD results of district block in Turin from 2010s to 2090s.

4.2.4.2 Annual thermal energy need

As shown in Figure 4. 3, Figure 4. 4 and Figure 4. 5, under the 2010s baseline, heating energy need dominates across all buildings, with Archetype 3 exhibiting the highest values of building RES25. As the climate progresses toward 2050s and

2090s, heating demand shows a consistent decline across all buildings, while cooling demand increases in magnitude, indicating a gradual shift in thermal load driven by climate warming.

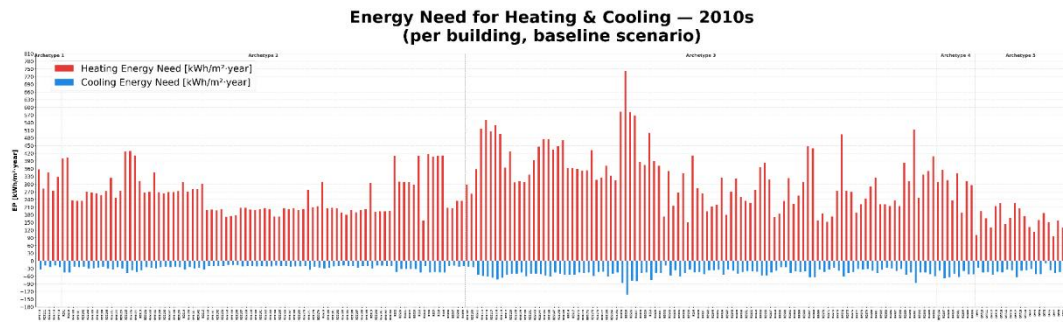


Figure 4. 3 Energy needs for heating and energy need for cooling per building at 2010s.

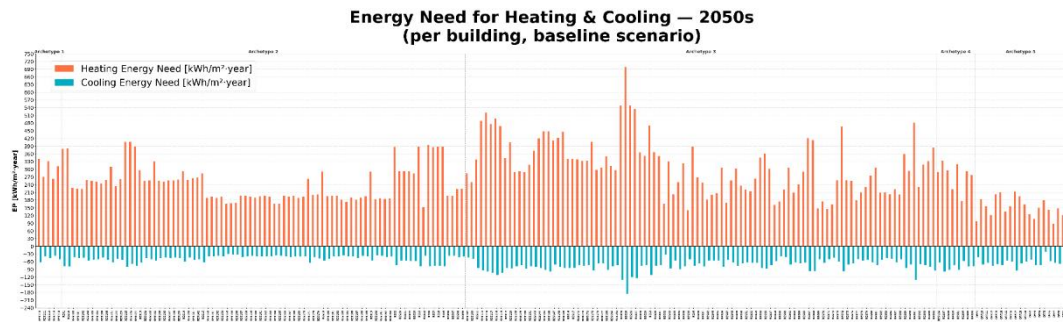


Figure 4. 4 Energy need for heating and energy need for cooling per buildings at 2050s.

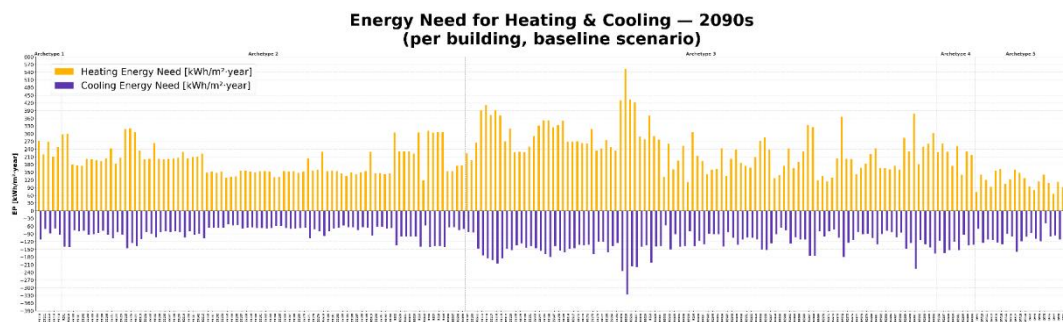


Figure 4. 5 Energy needs for heating and energy need for cooling per building on 2090s

The comparison across all three climate periods reveals a clear and consistent trend at the individual building level in Figure 4. 6: heating energy need decreases while cooling energy need increases from 2010s to 2090s.

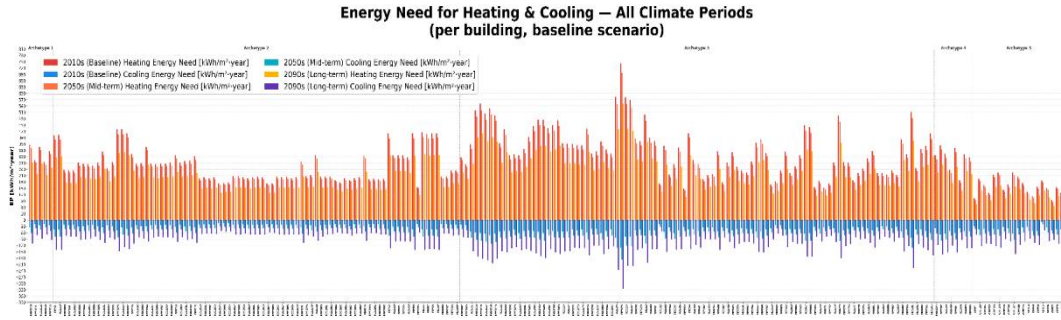


Figure 4. 6 Comparison of energy needs for heating and energy need for cooling per building across three climate scenarios

Figure 4. 7 illustrates the annual thermal energy need for space heating ($EP_{H,nd}$) and space cooling ($EP_{C,nd}$) aggregated at the archetype level using area-weighted averages for the baseline (2010s), and mid-term (2050s), and long-term (2090s) climate scenarios. A consistent reduction in heating demand can be observed across all building archetypes as the climate becomes progressively warmer. The decrease in $EP_{H,nd}$ reflects the reduction in winter heating requirements caused by rising outdoor temperatures and the corresponding decline in heating degree days. Although the magnitude of change differs among archetypes, the overall trend remains similar, indicating that climate change exerts a systematic influence on the thermal performance of the entire building stock. Conversely, cooling demand increases under future climate scenarios. The increase becomes more evident under the 2090s scenario, suggesting that future summer conditions will impose greater cooling requirements on buildings. The simultaneous decrease in heating demand and increase in cooling demand indicate a gradual transition from a predominantly heating-dominated energy profile towards a more balanced heating-cooling regime.

To further investigate the variability within the district, Figure 4. 8 presents the annual heating and cooling demand at the individual-building level (representative buildings of each archetype). While the overall trends remain consistent with the archetype-based results, noticeable differences can be observed among buildings belonging to the same archetype. These variations are primarily associated with differences in building geometry, orientation, compactness ratio, solar exposure, and envelope characteristics. The results demonstrate that archetype-based analysis provides a useful overview of district behaviour, while individual-building analysis reveals the heterogeneity of climate-change impacts within each archetype group. Overall, the results indicate that future building energy assessments should increasingly account for cooling-

related energy consumption and summer performance in addition to traditional heating demand considerations.

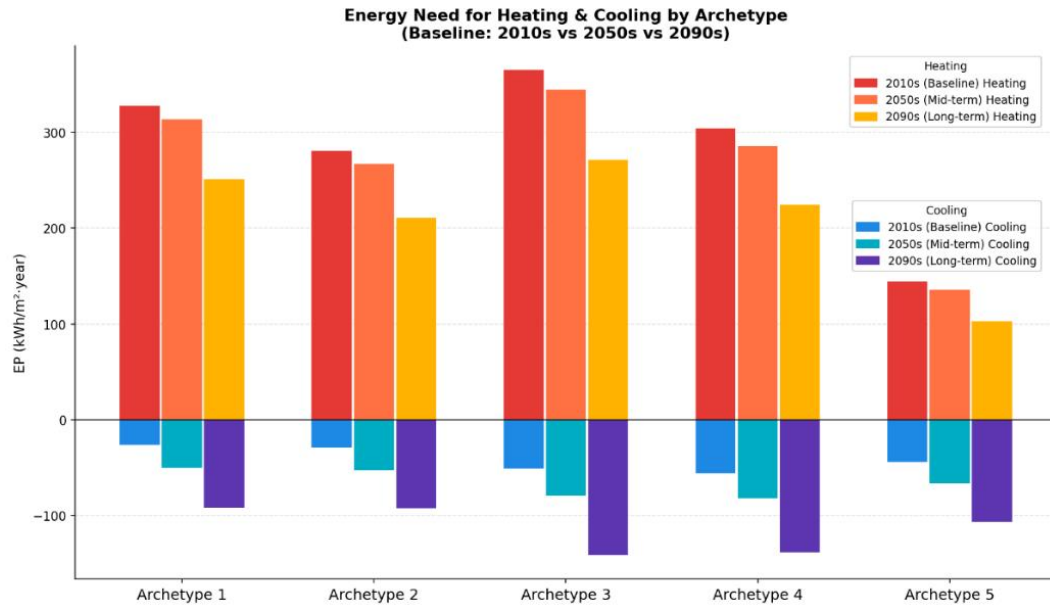


Figure 4. 7 Thermal energy needs for space heating (a) and cooling (b) per archetype using an area-weighted mean for the baseline (2010s), mid-term (2050s), and long-term (2090s) periods for the target district block (Turin).

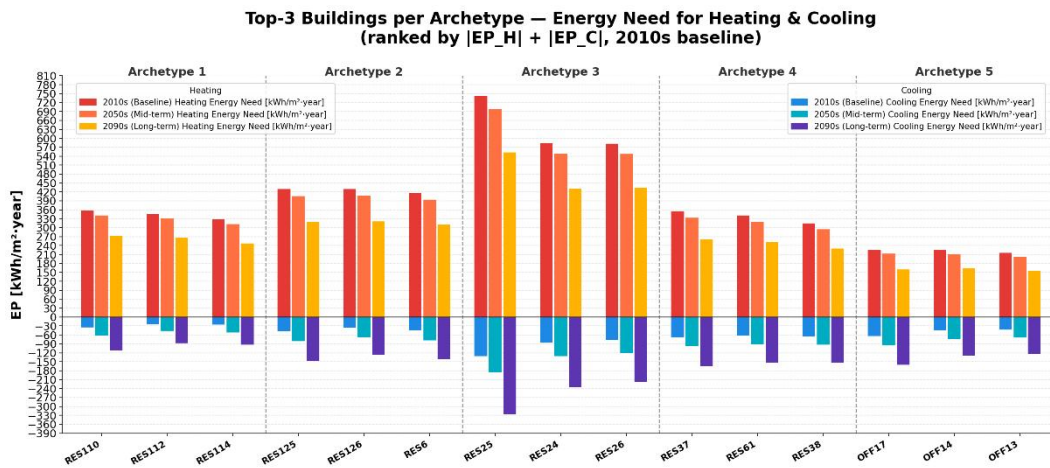


Figure 4. 8 Thermal energy need for space heating (a) and cooling (b) per building for the baseline (2010s), mid-term (2050s), and long-term (2090s) periods for the target district block (Turin).

4.2.4.3 Peak heating and cooling load

Figure 4. 9, Figure 4. 10 and Figure 4. 11 present the per-building peak heating and cooling loads under the three climate scenarios. Under the 2010s baseline, peak heating loads range from 137.2 to 765.2 W/m² with a mean of 307.7 W/m². This declines to 271.9 W/m² in 2050s and 245.3 W/m² in 2090s, representing reductions of 11.6% and 20.3% respectively, consistent with reduced winter heating demand under a warming climate. Archetype 3 consistently records the highest peak heating loads across all periods, while Archetype 5 office buildings show the lowest value among all archetypes.

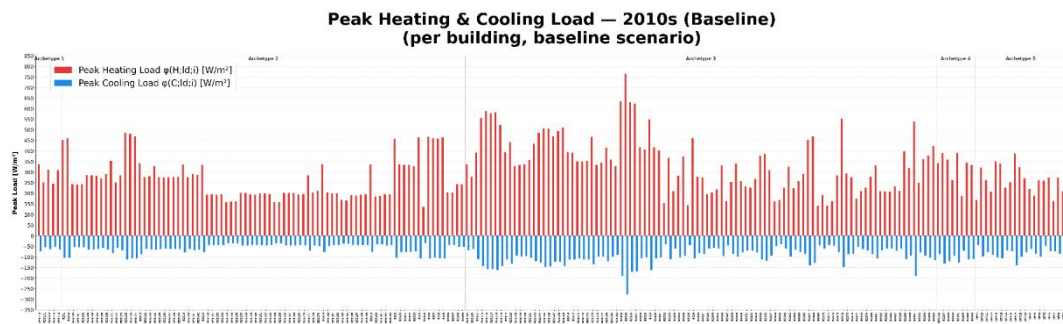


Figure 4. 9 Peak heating load and peak cooling load per building in 2010s.

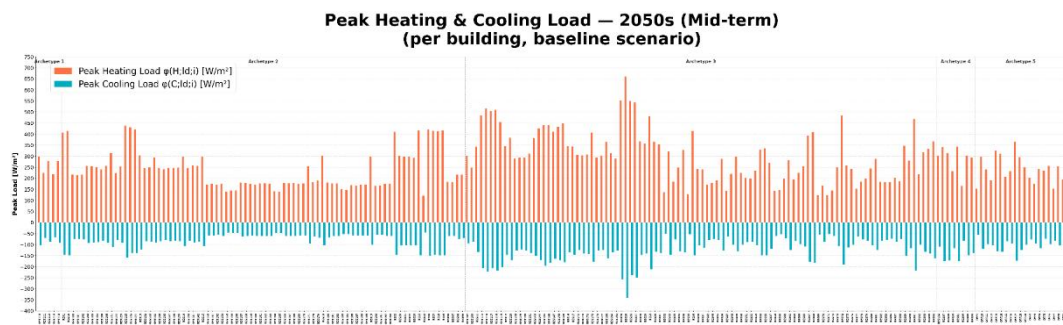


Figure 4. 10 Peak heating load and peak cooling load per building in 2050s.

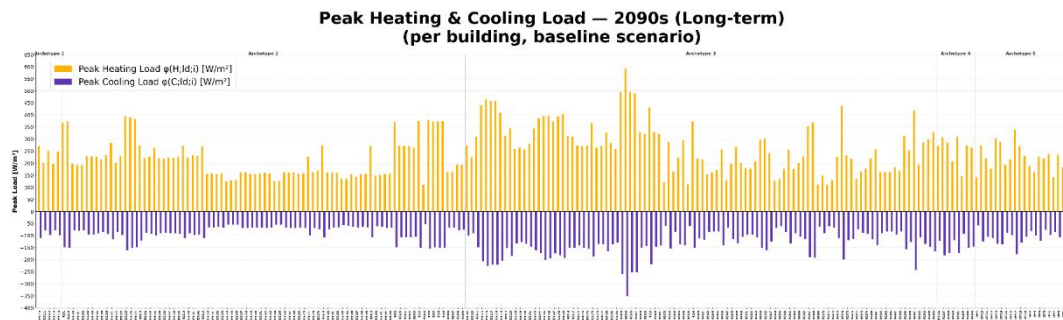


Figure 4. 11 Peak heating load and peak cooling load per building in 2090s.

As shown in Figure 4. 12, peak cooling load means absolute magnitude increases from 82.6 W/m² in 2010s to 108.8 W/m² in 2050s and 115.4 W/m² in 2090s. The increment between 2050s and 2090s is notably smaller than that between 2010s and 2050s, suggesting that instantaneous cooling peaks are less sensitive to long-term mean temperature rise than accumulated cooling energy need, likely due to the thermal buffering capacity of building envelopes.

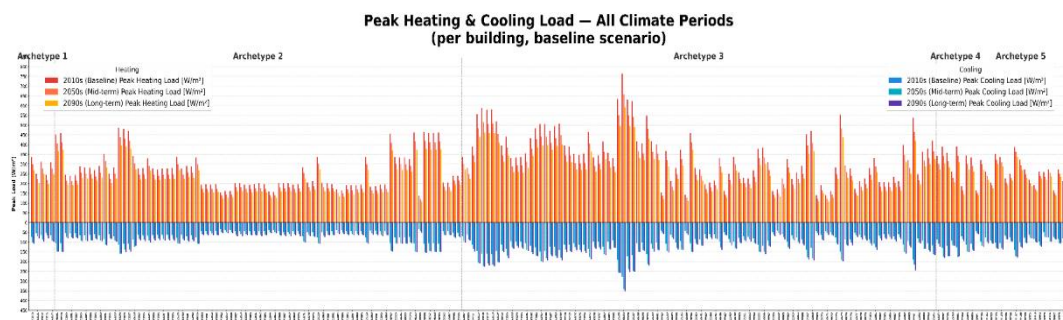


Figure 4. 12 Peak heating load and peak cooling load per building of comparison at 2010s, 2050s and 2090s.

Figure 4. 13 consolidates all three periods for direct comparison, confirming the progressive decline in peak heating demand and the moderate but consistent increase in peak cooling load across all archetypes and climate scenarios.

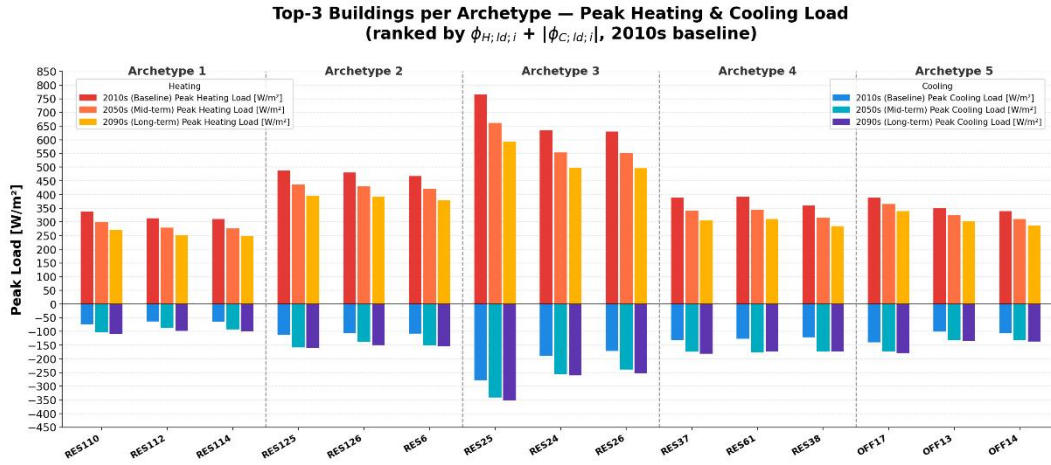


Figure 4. 13 Peak heating and cooling loads for representative buildings within each archetype at three climate scenarios.

4.2.4.4 Indoor thermal comfort

Figure 4. 14(a) presents the total WHD_w for building RES43 (Archetype 4), which records the highest thermal discomfort under the baseline scenario. In the 2010s, the total WHD_w amounts to 1,403.0 h, indicating a substantial number of overheating hours weighted by the degree of exceedance above the adaptive comfort upper limit. Under the 2050s mid-term scenario, this value increases to 1,930.6 h, representing a rise of approximately 37.6%. The most pronounced change occurs in the 2090s long-term scenario, where WHD_w reaches 3,201.7 h, more than double the baseline value (+128.2%) reflecting a severe intensification of indoor overheating risk driven by projected climate warming.

Figure 4. 14(b) shows the daily WHD_w distribution for RES43 under the 2090s scenario across June–August. Since the weighting factor w_f exceeds 1.0 when indoor temperature significantly surpasses the adaptive comfort upper limit, daily WHD_w values can exceed 24 h/day, reflecting the severity of thermal stress rather than simply the number of hours. Two peaks of elevated discomfort are visible: one in late June to early July, and another in late July to mid-August, with individual days reaching approximately 60 h/day during the most extreme episodes. A relative reduction in mid-July suggests temporary moderation in outdoor thermal conditions. Overall, the profile confirms that overheating under the 2090s scenario constitutes a persistent and severe condition throughout the summer period.

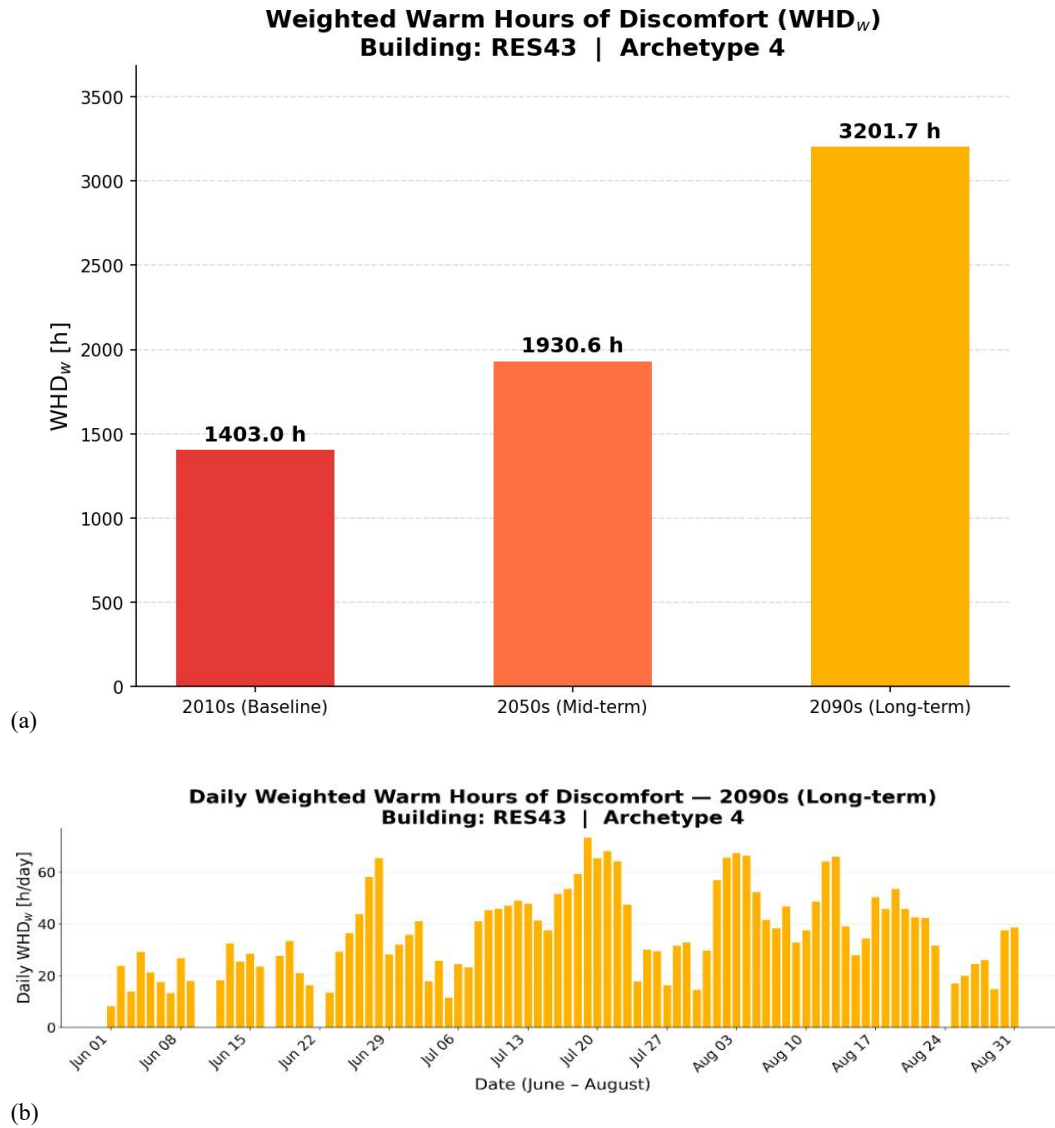


Figure 4. 14 Weighted warm hours of discomfort (WHD_w) of most vulnerable building in the target district block (Turin) (a); daily cumulative temporal distribution of WHD_w for the long-term (2090s) based on the target district block data (RES43) (b).

4.2.4.5 Building climate vulnerability

Figure 4. 15(a) presents the heating vulnerability index (VI_H), which quantifies the relative change in annual heating demand between the baseline and long-term climate scenarios. Buildings exhibiting higher VI_H values are more strongly influenced by future reductions in winter heating requirements and therefore display greater sensitivity to climatic warming.

Figure 4. 15(b) presents the cooling vulnerability index (VI_C), which quantifies the relative increase in annual cooling demand under future climate conditions. Buildings characterized by high VI_C values are expected to experience the largest increase in cooling requirements and may therefore face elevated overheating risks and higher future cooling energy consumption.

The results reveal considerable variability in vulnerability among buildings, indicating that climate change impacts are not uniformly distributed across the district. This heterogeneity highlights the importance of building-specific adaptation measures and demonstrates that vulnerability assessments cannot be based solely on district-average indicators.

Figure 4. 16 presents the spatial distribution of building vulnerability within the target district block by linking climate sensitivity to the physical location of individual buildings. Differences in vulnerability can be observed throughout the district, reflecting the combined influence of building age, morphology, orientation, solar exposure, and urban context. The spatial visualization highlights the presence of buildings that are strongly affected by climate change and therefore constitute priority candidates for adaptation interventions. The map also demonstrates that climate vulnerability is not solely determined by construction characteristics but is influenced by the interaction between buildings and the surrounding urban environment.

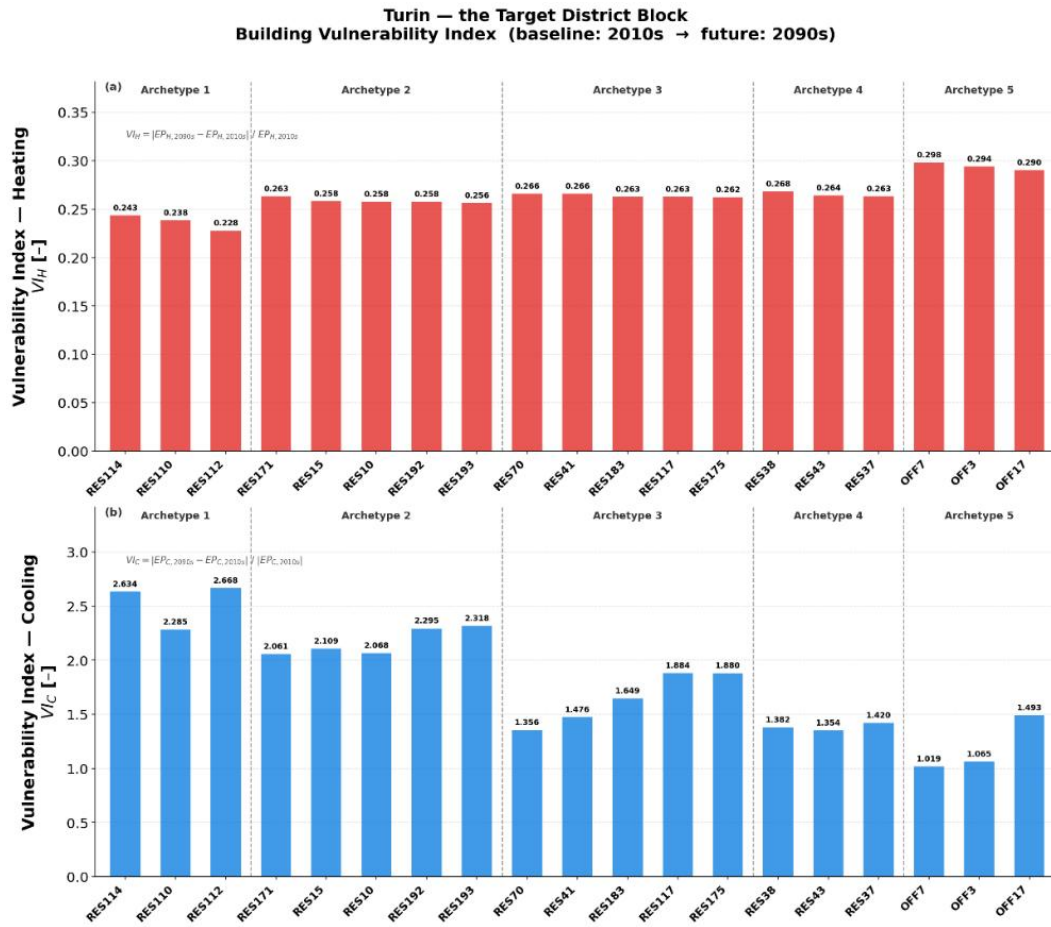


Figure 4. 15 Building vulnerability index (VI) on heating (a) and cooling (b) from baseline (2010s) to future (2090s) for the target district block (Turin).



Figure 4. 16 The target district block (Turin) of building vulnerability maps.

4.3 Climate-resilient strategies proposal for studied urban block

Based on the climate resilience framework established in Chapter 1.2.3, a set of urban-scale and building-scale climate-resilient strategies was developed for the studied urban block. Considering the computational cost of the CitySim simulations, which require approximately three hours for each annual simulation, the selected strategies were integrated into three simulation scenarios rather than being assessed individually for all climate-resilience strategies (CRSs). The CRSs were subsequently simulated under three climatic conditions, namely the baseline (2010s), mid-term (2050s), and long-term (2090s) scenarios.

4.3.1 Urban-level strategies

The selection of urban-scale strategies was guided by the analysis of ground surface temperatures under both current and future climate conditions. Figure 4. 17 and Figure 4. 18 show mean monthly ground surface temperature and spatial surface temperature map of target district block in Turin, respectively. The results

indicate that the existing green garden areas already exhibit strong climate resilience. Compared with the football field, the green garden maintains relatively stable surface temperatures under both baseline and future scenarios, with average August surface temperatures remaining below 30°C even under the projected 2090s climate conditions. This behaviour can be attributed to the combined effects of vegetation shading, evapotranspiration, and reduced heat storage within the soil.

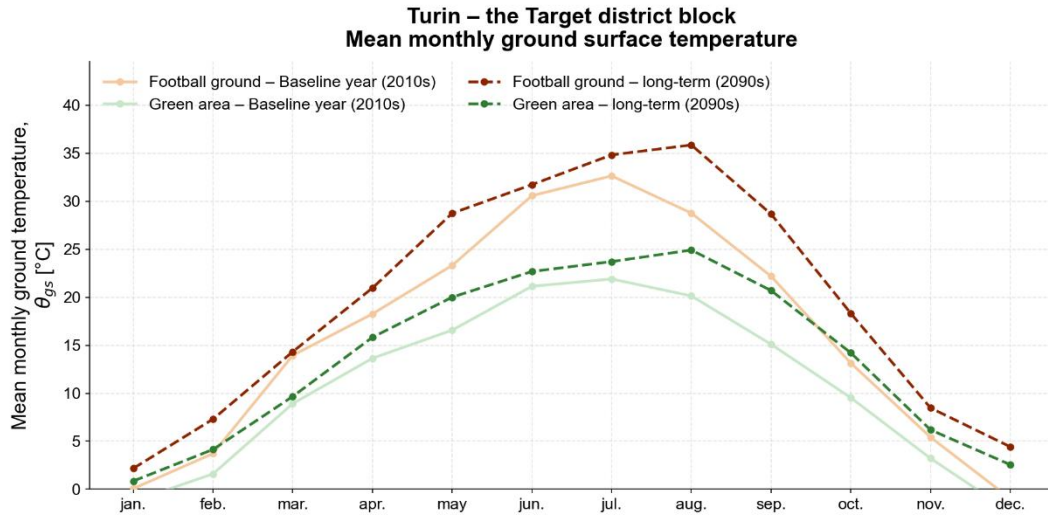


Figure 4. 17 Mean monthly ground surface temperature of the target district block in Turin.

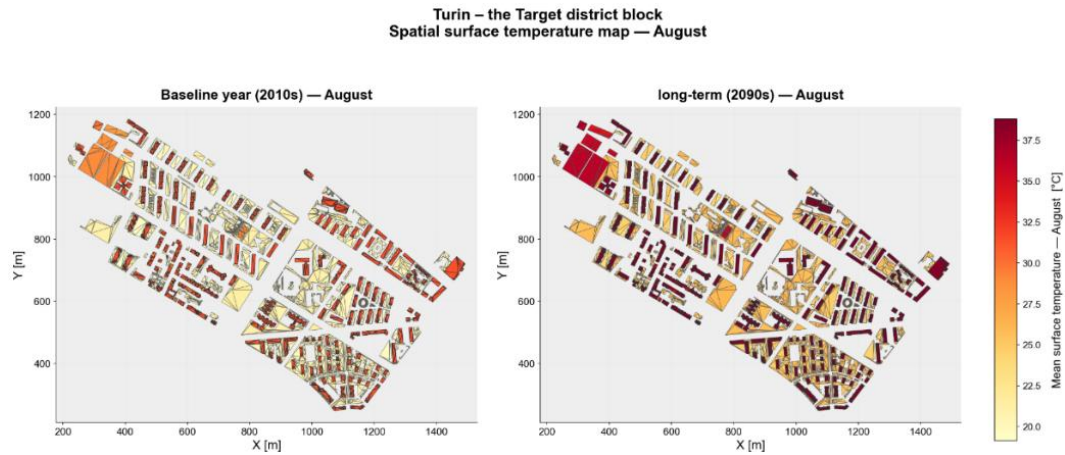


Figure 4. 18 Spatial surface temperature map of the target district block in August in Turin.

Although the existing green areas already perform well, further enhancement is proposed through the implementation of a high-evaporative green garden strategy. Measures such as rainwater harvesting for landscape irrigation during extreme weather periods, permeable surfaces, and drought-resistant vegetation

with higher water-retention capacity can increase soil moisture availability and sustain evapotranspiration during prolonged hot periods. Beyond improving the thermal performance of the green areas themselves, enhanced evaporative cooling may contribute to reducing surrounding air temperatures and improving the microclimatic conditions experienced by adjacent buildings.

In contrast, the football field, representing impervious urban surfaces such as pavements, roads, and public squares, exhibits considerably higher surface temperatures and greater sensitivity to future warming. Therefore, a reflective surface strategy is proposed by increasing the short-wave reflectance of the surface. This approach is used to represent the implementation of cool materials in urban hardscapes. By reflecting a larger proportion of incoming solar radiation, cool materials can reduce surface heat accumulation and contribute to mitigating the UHI effect. In this study, the football field is used as a proxy to evaluate the effectiveness of cool pavements and other reflective urban surfaces. By reflecting a greater proportion of incoming solar radiation, cool materials reduce surface temperatures and contribute to mitigating the UHI effect.

4.3.2 Building-level strategies

At the building level, retrofitting envelope was identified as the most effective adaptation strategy for the existing building stock. Sustainable insulation materials are proposed to reduce the thermal transmittance of opaque building elements in accordance with the Italian NZEB requirements for Climate Zone E. Besides reducing annual heating and cooling demand, improved insulation can enhance indoor thermal stability, reduce peak loads, and increase resilience against future temperature extremes.

The surface temperature analysis further reveals significant heat accumulation on roofs and facades, particularly under future climate scenarios, as shown in Figure 4. 19. Consequently, cool roofs and cool façade technologies are included in the CRS. Given the predominance of pitched roofs within the study area, green roofs were considered impractical for large-scale implementation. Instead, reflective coatings and cool finishing materials are adopted to increase the short-wave reflectance of roofs and external walls, thereby reducing solar heat absorption and summer overheating.

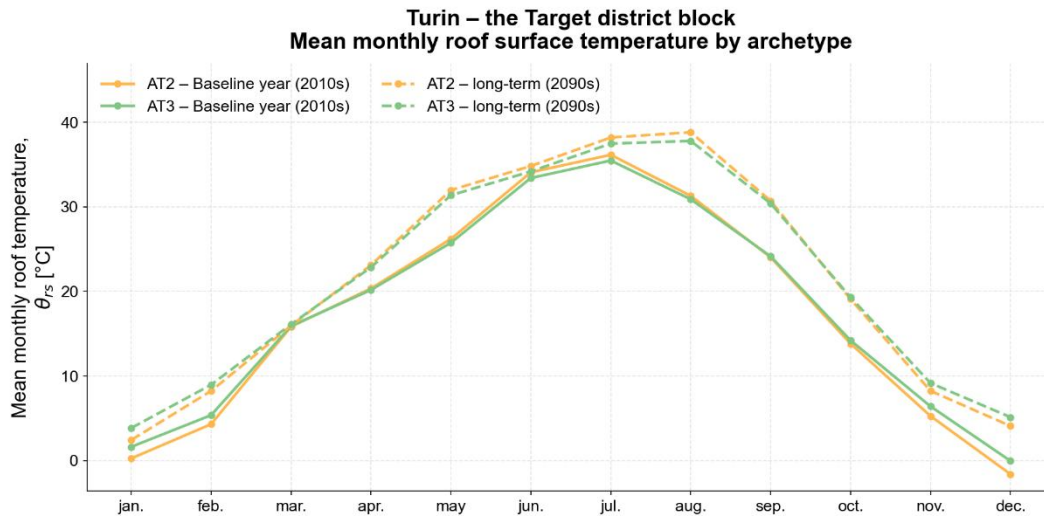


Figure 4. 19 Mean monthly roof surface temperature by archetype 2 (AT2) and archetype 3 (AT3) of the target district block in Turin.

Passive solar control measures are also incorporated. Existing glazing systems are upgraded to high-performance solar-control double glazing with improved thermal insulation and reduced solar heat gain. Lower U-values reduce winter heat losses, while lower g-values limit excessive solar gains during summer, thereby improving indoor comfort and reducing cooling demand. Finally, internal blinds are introduced for Archetype 5 (see Table 4. 2), which currently lacks any shading devices. External shading systems were excluded due to architectural and regulatory constraints associated with the renovation of existing buildings. Internal blinds provide a practical and minimally invasive solution for reducing solar gains while preserving the original facade appearance.

Table 4. 2 Climate-resilient strategies and adopted modelling parameters.

Climate resilient strategies (CRSs) – Urban scale					
CRS	CitySim parameters	Baseline value	CRS value	Description	KPIs
CRS1 Reflective football field	Short-wave reflectance	0.30	0.70	Represents cool pavements and reflective urban surfaces to reduce heat storage and UHI intensity	Mean monthly ground surface temperature
CRS2 High-evaporative green garden	Soil humidity level (K-factor)	0.50	0.70	Rainwater harvesting, permeable surfaces and water-retentive vegetation to sustain evapotranspiration	Mean monthly ground surface temperature

Climate resilient strategies (CRSs) – Building scale

CRS3 Envelope retrofit - Wall	U-value [W/(m ² ·K)]	Existing	0.26	NZEB requirement for Climate Zone E	$EP_{H;nd;arc}$ and $EP_{C;nd;arc}$
CRS4 Envelope retrofit - Roof	U-value [W/(m ² ·K)]	Existing	0.22	NZEB requirement for Climate Zone E	$EP_{H;nd;arc}$ and $EP_{C;nd;arc}$
CRS5 Envelope retrofit - floor	U-value [W/(m ² ·K)]	Existing	0.26	NZEB requirement for Climate Zone E	$EP_{H;nd;arc}$ and $EP_{C;nd;arc}$
CRS6 Cool roof	Short-wave reflectance	0.20	0.6	Reflective roof coating to reduce solar heat absorption	Mean monthly roof surface temperature
CRS7 Cool facade	Short-wave reflectance	0.20	0.6	Reflective façade finish to reduce external surface temperature	Mean monthly facade surface temperature
CRS8a Solar-control glazing	U_{window} [W/(m ² ·K)]	Existing	1.40	High-performance solar- control double glazing	$EP_{H;nd;arc}$ and $EP_{C;nd;arc}$
CRS8b Solar-control glazing	g-value [-]	Existing	0.40	Reduced solar heat gain while maintaining daylight access	$EP_{H;nd;arc}$ and $EP_{C;nd;arc}$
CRS9 Internal blinds (Archetype 5)	Shading device λ	0	0.10	Internal shading to reduce solar gains where no shading currently exists	$EP_{H;nd;arc}$ and $EP_{C;nd;arc5}$

4.4 Climate-resilient strategies analysis

4.4.1 Simulation Framework

Three simulation scenarios are evaluated across the baseline year (2010s) and long-term (2090s) climate horizons, as summarized in Table 4. 3. Simulation 1 (Baseline) serves as the unmitigated reference. Simulation 2 applies cooling material strategies both at urban scale (CRS1–CRS2) and Building-scale (CRS6–CRS7), targeting ground/envelope surface radiative and evaporative properties, assessed via mean monthly surface temperature. Simulation 3 deploys all nine CRSs at both urban and building scales, assessed through surface temperature, $EP_{H;nd;arc}$, $EP_{C;nd;arc}$, and the total thermal energy demand trajectory ($EP_{H;nd} + |EP_{C;nd}|$).

Table 4. 3 Summary of simulation matrix and evaluation indicators.

Simulation scenario	Strategy implemented	Level	CRS number	Climate scenarios	KPIs
Simulation 1*	Baseline (Without strategy adopted)	Baseline level	[-]	Baseline(2010s) Mid-term (2050s) Long-term(2090s)	Mean surface temperature and $EP_{H,nd}$ & $EP_{C,nd}$
Simulation 2	Cooling material only	Urban	CRS1 CRS2 CRS6 CRS7	Baseline(2010s) Long-term(2090s)	Mean surface temperature
Simulation 3	All CRSs adopted	Urban + Building level	ALL CRSs (1-9)	Baseline(2010s) Mid-term (2050s) Long-term(2090s)	Mean surface temperature and $EP_{H,nd}$ & $EP_{C,nd}$

Note: The results of Simulation 1* for all KPIs have already been visualized on 4.2.4.

4.4.2 Impact on Ground and Roof Surface Temperatures

Ground and roof surface temperatures were evaluated during the summer period (June–August) under both the baseline (2010s) and long-term future (2090s) climate scenarios. Two adaptation configurations were assessed: (i) the implementation of cooling materials only, and (ii) the complete CRS, which combines all selected urban- and building-scale adaptation measures. The results are summarized in Table 4. 4, and provide a quantitative assessment of the effectiveness of the proposed strategies in mitigating surface heat accumulation under present and future climatic conditions.

Table 4. 4 Surface temperature comparison.

		Baseline year (2010s)						
Category	Surface / Archetype	Baseline	Cooling material only	ΔT Cooling material	Reduction – Cooling material	All strategies adopted	ΔT All strategies	Reduction – All strategies
		[°C]	[°C]	[°C]	[%]	[°C]	[°C]	[%]
Ground surface	Football ground	30.66	22.57	-8.08	26.37	22.53	-8.13	26.53
Ground surface	Green area ground	21.06	19.75	-1.31	6.21	19.59	-1.47	6.99
Roof surface (AT1)	AT1 Roof	33.87	25.65	-8.22	24.27	25.52	-8.34	24.63
Roof surface (AT2)	AT2 Roof	33.83	25.57	-8.27	24.43	25.52	-8.31	24.57
Roof surface (AT3)	AT3 Roof	33.25	25.55	-7.69	23.14	25.32	-7.92	23.83
Roof surface (AT4)	AT4 Roof	33.71	25.83	-7.88	23.38	25.47	-8.24	24.44
Roof surface (AT5)	AT5 Roof	32.98	25.43	-7.55	22.91	25.18	-7.81	23.67
		Long-term (2090s)						
Category	Surface / Archetype	Baseline	Cooling material only	ΔT Cooling material	Reduction – Cooling material	All strategies adopted	ΔT All strategies	Reduction – All strategies
		[°C]	[°C]	[°C]	[%]	[°C]	[°C]	[%]
Ground surface	Football ground	34.17	26.44	-7.72	22.61	26.40	-7.77	22.73
Ground surface	Green area ground	23.78	22.40	-1.39	5.83	22.24	-1.54	6.48
Roof surface (AT1)	AT1 Roof	37.25	29.50	-7.75	20.81	29.32	-7.93	21.28
Roof surface (AT2)	AT2 Roof	37.30	29.46	-7.84	21.01	29.36	-7.94	21.28
Roof surface (AT3)	AT3 Roof	36.50	29.16	-7.34	20.1	29.15	-7.35	20.13
Roof surface (AT4)	AT4 Roof	37.00	29.72	-7.27	19.66	29.31	-7.69	20.78
Roof surface (AT5)	AT5 Roof	36.19	28.98	-7.19	19.89	28.95	-7.23	19.99

For the football field, the baseline summer mean surface temperature decreases from 30.66 °C under the 2010s climate scenario to 22.57 °C following the implementation of cooling materials, corresponding to a reduction of 8.08 °C (26.4%). When all climate-resilient strategies are applied simultaneously, the reduction reaches 8.13 °C (26.5%), indicating only a marginal additional benefit compared with the cooling-material intervention alone. A similar trend is observed under future climate conditions. Although the baseline surface temperature increases to 34.17 °C under the 2090s scenario, the cooling-material strategy continues to achieve a substantial reduction of 7.72 °C (22.6%), while the integrated CRS provides only an additional 0.04 °C decrease. By contrast, the green area exhibits considerably smaller temperature reductions under both climate scenarios. Under the baseline climate, average summer temperatures decrease by 1.31 °C (6.2%) and 1.47 °C (7.0%) for the cooling-material and integrated CRS scenarios, respectively. Similar reductions are observed under future climate conditions, ranging from 1.39 °C (5.8%) to 1.54 °C (6.5%).

These results demonstrate that the thermal behaviour of exposed ground surfaces is primarily controlled by surface radiative properties rather than by building-scale interventions. The high effectiveness of CRS1 therefore confirms that increasing surface reflectivity is a robust and climate-independent strategy for mitigating urban heat accumulation. More importantly, the cooling performance remains largely unchanged despite the significant warming projected for the end of the century, highlighting the long-term resilience of this adaptation measure.

The relatively limited response of the green area can be explained by its inherently resilient thermal characteristics. Vegetated surfaces already benefit from shading, evapotranspiration, and lower heat-storage capacity, resulting in substantially lower baseline temperatures than those observed for exposed artificial surfaces. Consequently, the potential for additional cooling through reflective materials is inherently constrained. Nevertheless, the consistently lower temperatures maintained by the green area under both the 2010s and 2090s scenarios reinforce the important role of urban vegetation in enhancing climate resilience and reducing future heat stress at the district scale.

Despite differences in building geometry and construction characteristics, all roof archetypes exhibit remarkably similar thermal behaviour, indicating that roof surface temperature is primarily controlled by solar exposure and surface optical properties rather than by archetype-specific characteristics. Under the baseline climate scenario (2010s), average roof surface temperatures range between

32.98 °C and 33.87 °C across the five archetypes. The implementation of cool roof and cool facade coatings (CRS6–CRS7) leads to substantial temperature reductions of 7.55–8.27 °C, corresponding to relative reductions of 22.9–24.4%. These results demonstrate the strong effectiveness of reflective surface technologies in limiting solar heat absorption and reducing summer heat accumulation on building envelopes.

A similar pattern is observed under the future climate scenario. As projected warming intensifies, baseline roof temperatures increase to 36.18–37.30 °C by the 2090s, representing an average increase of approximately 3.3–3.5 °C compared with the present-day climate. Nevertheless, the cooling-material strategy continues to achieve reductions of 7.19–7.93 °C, equivalent to 19.7–21.3% of the baseline temperature. The relatively small decrease in percentage reduction is mainly attributable to the higher background temperatures under future climate conditions rather than to a loss of effectiveness of the reflective materials themselves.

4.4.3 Impact on thermal energy needs for heating and cooling

4.4.3.1 Total energy demand trajectory

The trajectories of total thermal energy demand ($EP_{H,nd} + |EP_{C,nd}|$) per archetype are shown in Figure 4. 20. For residential archetypes (AT1–AT4), total demand remains approximately stable across all three climate horizons under the baseline scenario, ranging from 354.0 to 342.8 kWh/m² for AT1, and from 359.6 to 362.2 kWh/m² for AT4, reflecting a progressive offset between declining heating demand and intensifying cooling demand driven by climate warming. AT5 (Office) is the only archetype exhibiting a clear upward total demand trajectory (188.5 → 201.9 → 209.7 kWh/m² across 2010s, 2050s, and 2090s), driven by its stronger sensitivity to rising internal and solar cooling loads.

The cooling material strategy (Simulation 2) yields negligible effects on total energy demand for residential archetypes under 2010s and 2050s conditions (+0.4% to +1.1% in 2010s; approximately 0% in 2050s for AT1–AT4), as the reduction in cooling load is fully offset by the heating penalty induced by increased surface reflectance. AT5 shows a progressively discernible benefit across all horizons: −3.7% (2010s), −6.3% (2050s), and −10.1% (2090s),

reflecting its higher cooling-to-heating ratio and the growing dominance of cooling demand over time.

The all-CRS scenario (Simulation 3) delivers substantial and consistent reductions across all time horizons: from -32.1% (AT4) to -59.2% (AT5) in 2010s, from -33.2% (AT4) to -60.8% (AT5) in 2050s, and from -34.5% (AT4) to -61.9% (AT5) in 2090s. The gradual deepening of reductions from 2010s to 2090s reflects the compounding benefit of envelopes and solar-control interventions as climate-driven loads intensify, with AT5 the highest due to its glazing-dominated envelope.

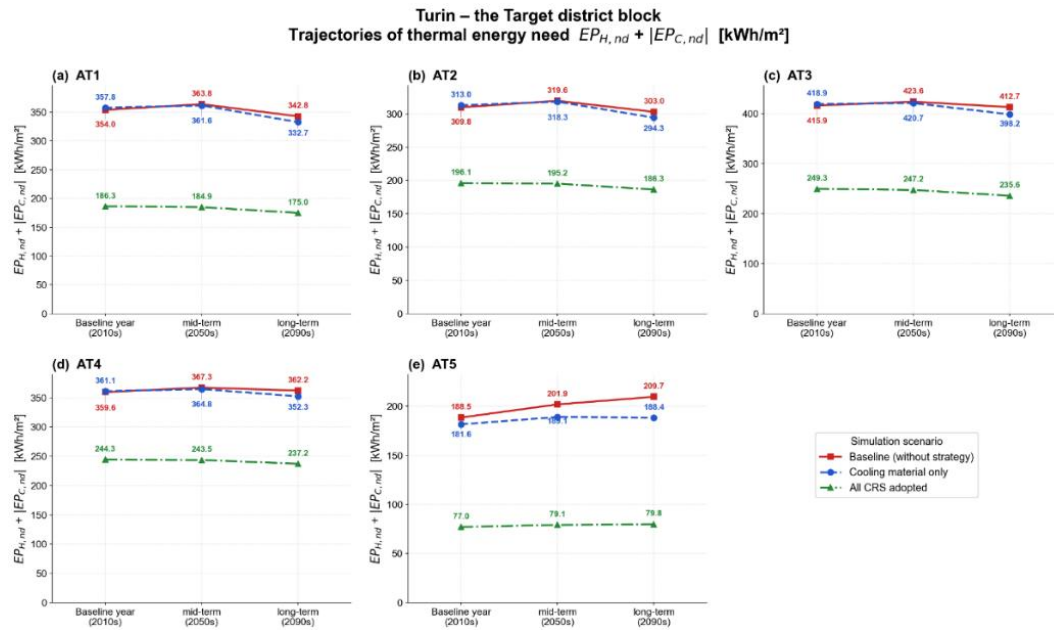


Figure 4. 20 Trajectories of thermal energy need $EP_{H,nd} + |EP_{C,nd}|$ of the target district block in Turin.

4.4.3.2 Heating energy demand

As shown in Figure 4. 21, the cooling material strategy introduces a consistent and progressively amplified heating penalty across all archetypes and time horizons. Under 2010s conditions, $EP_{H,nd}$ increases range from $+4.8\%$ (AT1) to $+8.0\%$ (AT5); under 2050s conditions from $+5.4\%$ (AT1) to $+8.1\%$ (AT5); and under 2090s conditions from $+6.2\%$ (AT1) to $+9.5\%$ (AT5). This progressive amplification is attributable to the declining baseline heating demand with warming, which makes the absolute penalty from reduced winter solar heat gain

proportionally larger over time. This trade-off is well documented for cool surface strategies in heating-dominated climates and confirms that urban-scale reflectance measures must be complemented by building-scale interventions to avoid adverse winter energy impacts.

The all-CRS scenario achieves substantial and temporally stable reductions in $EP_{H;nd}$ across all three horizons. Under 2010s conditions, reductions range from -29.9% (AT4) to -54.2% (AT5); under 2050s conditions from -30.4% (AT4) to -54.7% (AT5); and under 2090s conditions from -30.5% (AT4) to -55.4% (AT5). The near-invariance of these percentage reductions across time horizons indicates that building-scale envelopes and solar-control interventions maintain consistent absolute effectiveness even as baseline heating demand declines with climate warming. AT5 consistently records the highest relative reduction across all horizons, reflecting its elevated sensitivity to solar-control-glazing strategies given its high glazing ratio and internal heat gain profile.

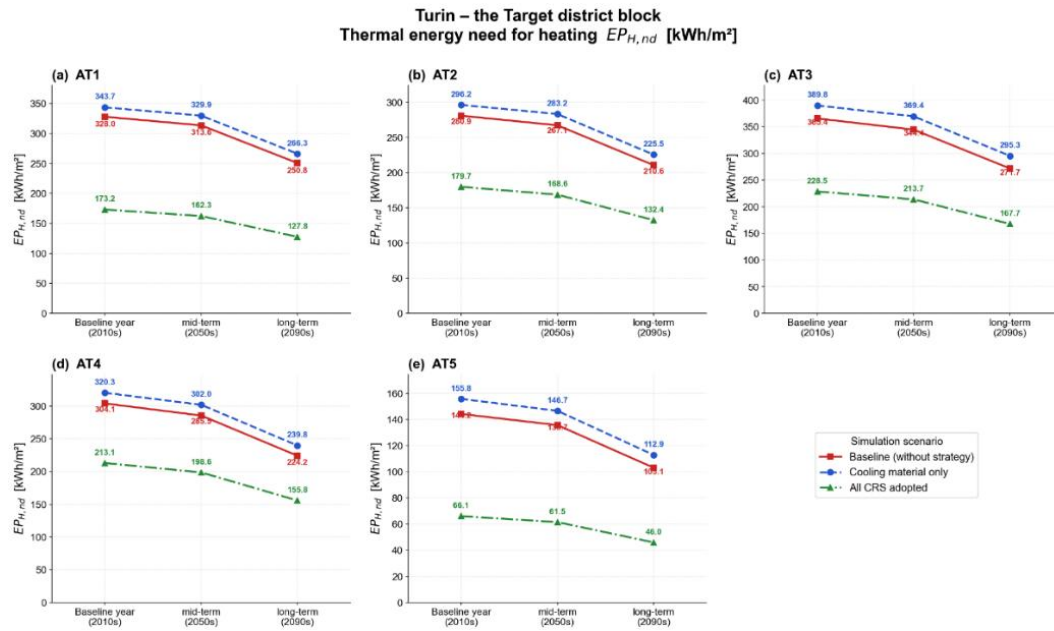


Figure 4. 21 Trajectories of thermal energy need $EP_{H;nd}$ of the target district block in Turin.

4.4.3.3 Cooling energy demand

The cooling energy trajectory reveals a pronounced and progressive divergence across all three simulation scenarios, as shown in Figure 4. 22. Under

the baseline condition, cooling demand intensifies substantially across all time horizons: AT3 escalates from -50.5 (2010s) to -79.2 (2050s) to -141.0 kWh/m² (2090s), and AT4 from -55.5 to -80.8 to -138.1 kWh/m², representing the largest absolute increases among residential archetypes. AT5 follows a similarly steep trajectory ($-44.3 \rightarrow -66.2 \rightarrow -106.5$ kWh/m²), driven by high internal gains and glazing ratio.

The cooling material strategy (Simulation 2) achieves moderate cooling reductions relative to the baseline, primarily through the reduction of solar heat gain at the urban surface level (CRS1–CRS2). Under 2010s conditions, $EP_{C;nd}$ reductions range from -26.6% (AT4) to -46.1% (AT1); under 2050s conditions from -22.3% (AT4) to -36.7% (AT1); and under 2090s conditions from -18.5% (AT4) to -27.7% (AT1). The systematic decline in relative cooling effectiveness across time horizons — consistent across all archetypes — confirms that climate-driven intensification of cooling loads progressively erodes the mitigation benefit of surface-level interventions alone.

The all-CRS scenario achieves the most substantial cooling reductions across all archetypes and time horizons. Under 2010s conditions, $EP_{C;nd}$ reductions range from -43.6% (AT2) to -75.4% (AT5); under 2050s conditions from -49.3% (AT2) to -73.4% (AT5); and under 2090s conditions from -41.1% (AT4) to -68.2% (AT5). The comparatively higher relative effectiveness under 2050s versus 2090s for most archetypes reflects a non-linear interaction between the growing baseline cooling load and the finite capacity of the intervention package to offset it. AT5 consistently records the highest cooling savings, due to the combined effect of solar-control glazing and cool roof coatings acting on a high-gain envelope.

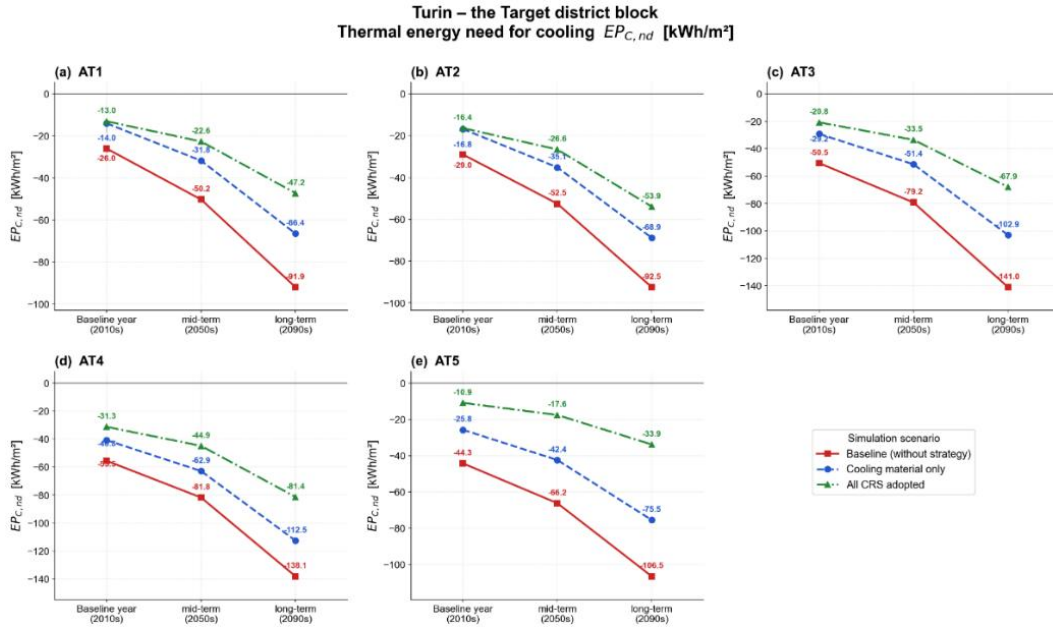


Figure 4.22 Trajectories of thermal energy need $EP_{C,nd}$ of the target district block in Turin.

A comparative overview of $EP_{H,nd}$ and $EP_{C,nd}$ across all archetypes and time horizons is provided in Figure 4.23 which highlights the divergent trajectories between the Baseline and All-CRS scenarios and underscores the asymmetric response of heating and cooling loads to the intervention package.

Overall, the results demonstrate that urban-scale cooling materials deliver robust surface temperature reductions but limited and climatically eroding building energy benefits in isolation. The comprehensive deployment of all CRSs is required to achieve meaningful reductions in both heating and cooling energy needs across all climate horizons, with building-scale interventions, particularly envelope insulation and solar-control glazing, constituting the primary drivers of energy performance improvement across all archetypes.

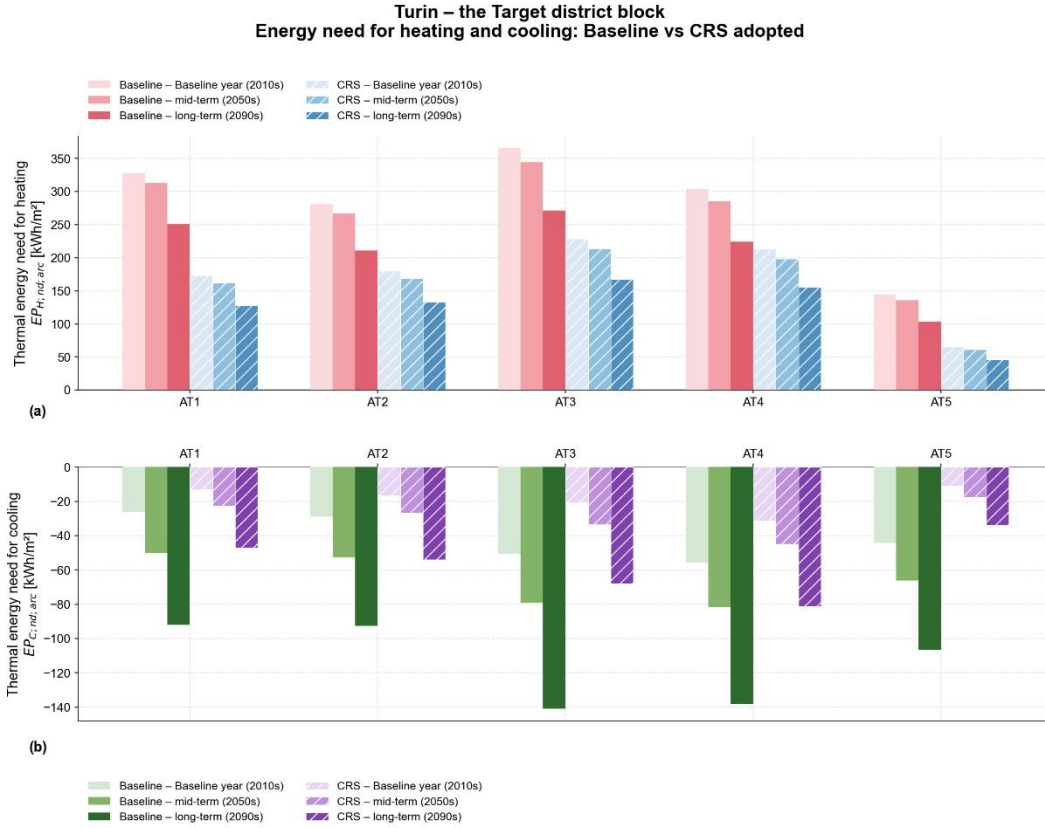


Figure 4. 23 Energy need for heating (a) and cooling of baseline (b) vs CRS adopted of the target district block in Turin.

4.4.3.4 Energy performance of thermally vulnerable buildings

To further evaluate the effectiveness of the integrated CRS, Figure 4. 24 presents the annual thermal energy needs for heating ($EP_{H,nd}$) and cooling ($EP_{C,nd}$) for the nineteen thermally vulnerable buildings identified in Section 4.2.4.5. The comparison is performed between the baseline configuration and the scenario in which all climate-resilient measures are implemented, under the historical (2010s), mid-term (2050s), and long-term (2090s) climate conditions. While the results generally confirm the trends observed at the archetype level, they also reveal substantial variability among individual buildings, reflecting differences in geometry, solar exposure, and operational conditions.

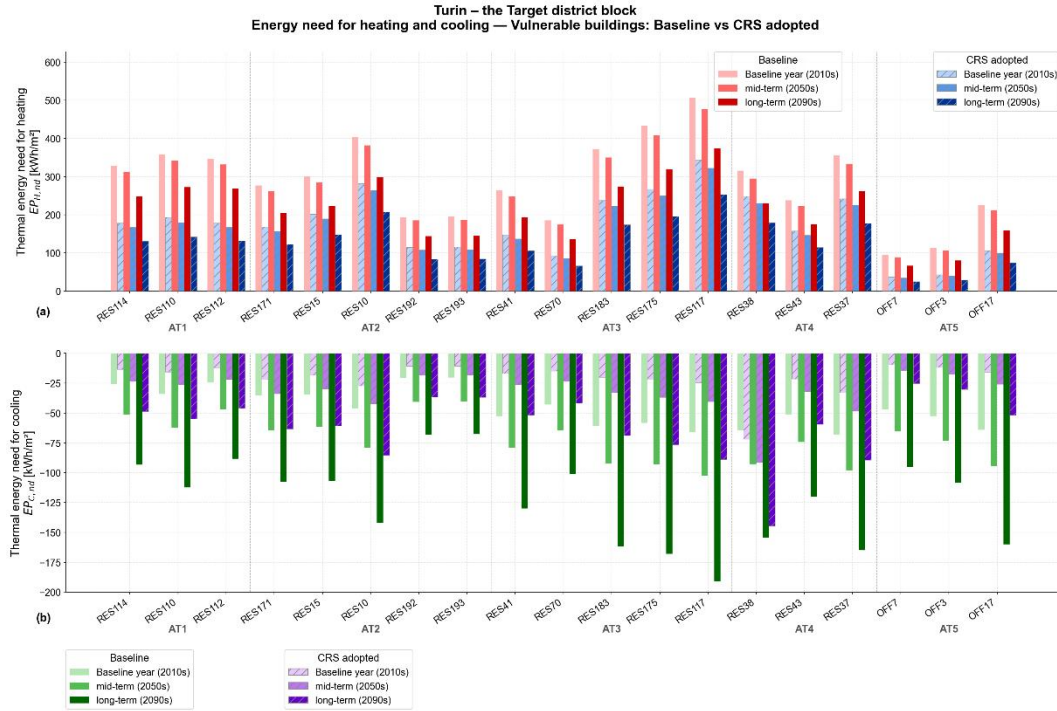


Figure 4. 24 Thermal energy needs for heating and cooling of 19 vulnerable buildings: baseline (without improvements) VS all strategies adopted.

For heating demand, the integrated CRS consistently delivers significant reductions across all investigated buildings and climate scenarios. Relative savings range from approximately 21% to 63%, confirming the effectiveness of the proposed envelope improvements, solar-control measures, and glazing upgrades in reducing winter heat losses. The largest reductions are observed for office buildings belonging to Archetype AT5, where heating demand decreases by 52–63%. This behaviour can be attributed to the comparatively larger façade areas, higher glazing ratios, and greater sensitivity of office buildings to improvements in envelope thermal performance. In contrast, buildings belonging to Archetype AT4 exhibit the lowest relative reductions, ranging from 21% to 34%, indicating a lower sensitivity to the implemented retrofit measures. An important observation is that the relative heating savings remain stable, and in some cases increase slightly, under future climate conditions. Although absolute heating demand decreases as outdoor temperatures rise, the effectiveness of the retrofit package is largely preserved. This behaviour demonstrates the long-term robustness of the proposed adaptation measures and suggests that their benefits are not limited to present-day climatic conditions.

The impact of the CRS on cooling demand is even more pronounced. Under the baseline climate scenario (2010s), cooling energy reductions range from 38% to 80%, with the highest savings again observed for Archetype AT5 buildings. The strong cooling performance reflects the combined influence of solar-control measures, improved glazing systems, reflective surfaces, and reduced heat transfer through the building envelope.

Under the long-term climate scenario (2090s), cooling demand increases substantially for all buildings due to the projected rise in outdoor temperatures and the extension of the cooling season. For example, building RES117 (Archetype AT3) reaches a baseline cooling demand of approximately 190.7 kWh/m², notably higher than the area-weighted archetype average (see Figure 4. 22), reflecting its specific geometry and exposure. Despite this significant increase in cooling requirements, the integrated CRS continues to achieve reductions of 40–75%, demonstrating a high degree of climate resilience. In other words, although future climate change intensifies cooling loads, the proposed adaptation measures remain effective in limiting their growth and mitigating overheating-related energy consumption.

The building-level results further highlight the importance of considering intra-archetype variability when assessing climate resilience. While archetype-based analyses provide a useful representation of average performance, individual buildings may respond differently depending on their specific geometric characteristics, orientation, compactness, and exposure conditions. Nevertheless, the consistently positive performance observed across all nineteen vulnerable buildings confirms that the integrated CRS provides a robust adaptation pathway capable of improving both current and future energy performance.

Chapter 5 Conclusion and outlook

5.1 Conclusion

This thesis developed an archetype-based UBE framework to evaluate the impacts of future climate change on existing urban building stocks and to assess the effectiveness of climate-resilient retrofit strategies at the district scale. By integrating the UBE archetype methodology with CitySim simulations, the proposed framework combines building stock characterization, district-scale energy modelling, climate vulnerability assessment, and retrofit evaluation within a unified workflow. The research demonstrates that archetype-based UBE provides an effective means of bridging the gap between detailed building simulations and large-scale urban analyses, offering a practical solution for supporting climate-resilient urban renovation.

The results demonstrate that climate change will fundamentally reshape the energy behaviour of existing buildings. Although warmer climatic conditions are projected to reduce annual heating demand, they also lead to substantial increases in cooling demand, overheating risks, and peak summer loads. Rather than representing a simple shift in energy consumption, these changes indicate a transition in the priorities of building renovation. Future renovation strategies should therefore move beyond the traditional emphasis on reducing winter heat losses and instead adopt a more balanced approach that simultaneously improves winter energy efficiency, summer thermal performance, and long-term climate resilience.

This study also highlights that climate vulnerability is highly heterogeneous across the urban building stock. While the archetype-based approach effectively represents the general characteristics of typical buildings, the assessment identified nineteen thermally vulnerable buildings whose responses differed considerably despite belonging to similar archetypes. These variations are primarily associated with differences in geometry, orientation, glazing

configuration, and local urban context, demonstrating that average archetype performance alone cannot fully capture climate vulnerability. Consequently, reliable urban adaptation planning should combine archetype-level modelling with building-specific assessments to support the prioritization of renovation actions and the allocation of limited renovation resources.

Another important conclusion is that integrated adaptation strategies provide greater long-term benefits than isolated retrofit measures. The proposed CRS, which combines urban-scale interventions with building-scale improvements, consistently enhanced building performance under both present and future climate conditions. The coordinated application of reflective urban materials, increased vegetation, improved building envelopes, solar-control glazing, and shading systems substantially reduced thermal energy demand while mitigating future overheating. More importantly, the results demonstrate that the interaction between urban microclimate improvements and building-level retrofits can significantly enhance the overall resilience of existing districts, highlighting the importance of considering buildings and their surrounding urban environment as an integrated system.

The findings further indicate that the effectiveness of individual retrofit measures evolves as climatic conditions change. Conventional insulation-based improvements remain essential for reducing heating demand; however, their relative contribution gradually decreases as winters become milder. In contrast, passive cooling measures, including solar-control glazing, reflective envelope materials, and effective shading systems, become increasingly important for maintaining indoor thermal comfort and limiting future cooling demand. This suggests that renovation strategies should be designed not only to satisfy current performance requirements but also to remain effective under the climatic conditions expected throughout the service life of existing buildings.

Overall, this research demonstrates that archetype-based UBEM is not only a reliable urban energy modelling approach but also a practical decision-support framework for identifying vulnerable buildings, evaluating future climate risks, and prioritizing long-term retrofit strategies. Beyond its methodological contribution, the proposed framework illustrates the importance of integrating future climate projections into urban renovation planning and provides quantitative evidence to support more informed decision-making by municipalities, urban planners, and policymakers. These capabilities are closely aligned with the objectives of the revised EPBD, particularly its emphasis on

accelerating the renovation of existing building stocks, improving energy performance, and enhancing climate resilience. By linking urban-scale energy modelling with future climate adaptation, this research contributes to the development of more sustainable, resilient, and climate-neutral built environments while providing a transferable methodology for supporting long-term urban energy transition.

5.2 Future outlook

Although the proposed framework demonstrated strong capability in evaluating climate vulnerability and retrofit effectiveness at the district scale, several opportunities remain for further development.

First, future research could expand the archetype database to cover a wider range of building typologies and climatic regions across Italy. The archetypes developed in this study primarily represent buildings located in northern Italy and climate zones E and F. Extending the database to other regions would improve the representativeness and transferability of the methodology and support large-scale applications at the regional or national level. Besides, the current modelling approach relies on standardized occupancy schedules and operational assumptions. Since occupant behaviour significantly influences energy consumption and thermal comfort, future studies should integrate stochastic occupancy models and adaptive behavioral responses. This would enable a more realistic representation of building operation under both current and future climatic conditions.

Another important direction for future research is the calibration of the UBE. While the archetype-based modelling approach adopted in this study provides a consistent basis for comparative analyses, model calibration is essential for reducing parameter uncertainty and improving the credibility of urban-scale energy simulations. Recent advances have demonstrated that Bayesian calibration, coupled with Gaussian Process surrogate models (Darvishvand et al., 2025; Worthy et al., 2025), provides an efficient methodology for calibrating computationally intensive UBEMs using limited measured energy data. Incorporating such a calibration framework would strengthen the predictive capability of the proposed methodology and provide a more robust foundation for future climate resilience assessments.

Future investigations also should extend the assessment beyond energy performance alone. Integrating indicators such as indoor thermal comfort, carbon

emissions, renewable energy integration, and energy flexibility would provide a more comprehensive evaluation of building climate resilience and support the development of holistic renovation strategies.

Finally, the framework could be combined with economic and environmental assessment methods, such as life-cycle cost analysis and life-cycle carbon assessment. Such integration would facilitate the identification of cost-effective and low-carbon retrofit pathways, providing stronger support for urban renovation policies and long-term climate adaptation planning.

Overall, the methodology developed in this thesis provides a robust foundation for future climate-resilient urban energy studies and offers significant potential for supporting sustainable renovation strategies in existing building stocks. Building upon this work, future research integrating economic assessment, renewable energy systems, and digital building databases could further enhance the applicability and decision-support capability of the proposed framework. Such developments would contribute to the effective implementation of the revised EPBD by facilitating evidence-based renovation planning and supporting Europe's transition towards climate-neutral and climate-resilient built environment.

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Annexes

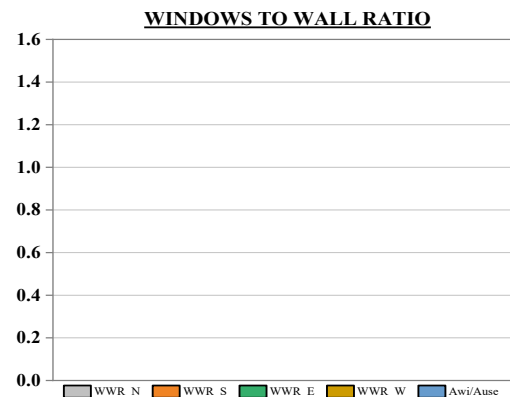
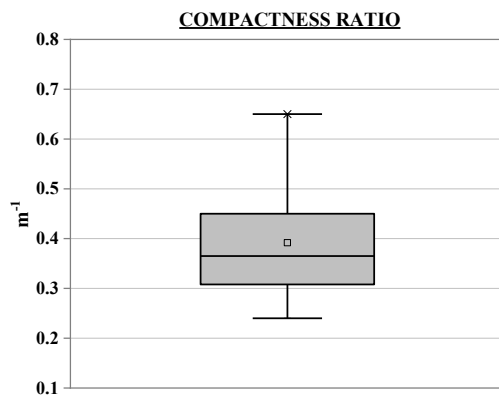
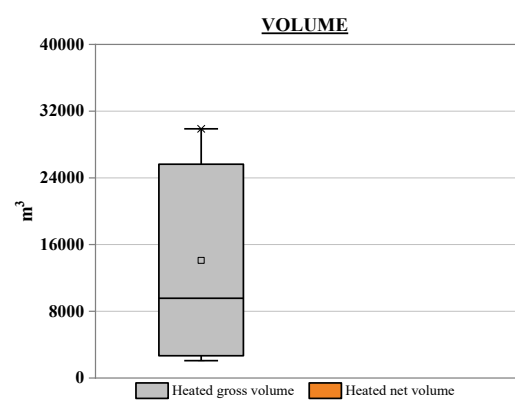
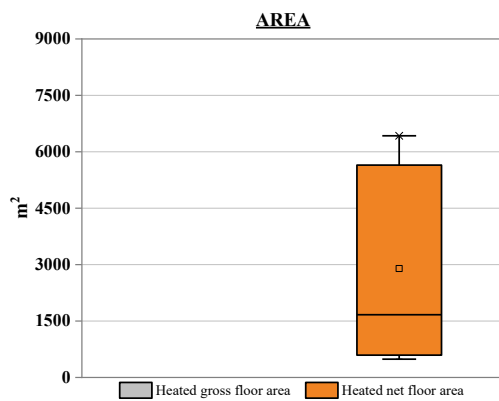
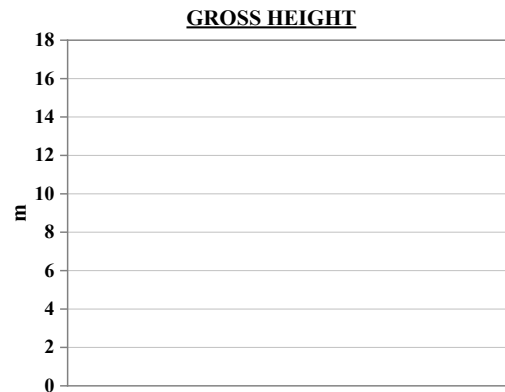
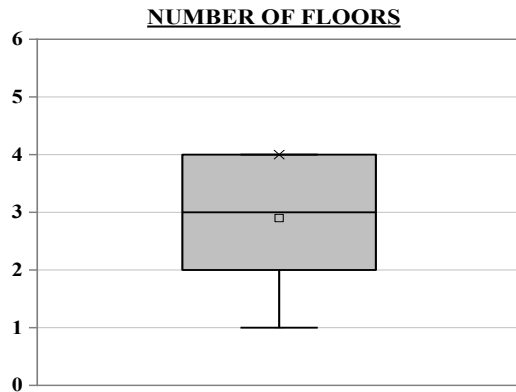
All building archetype's PDF files are named below, and the more detailed information, data and parameters are seen in the following pages.

1. OFF_BLDGS_-1933_E_PIE
2. OFF_BLDGS_1973-1990_E_PIE
3. OFF_BLDGS_2000-_E_PIE
4. OFF_BLDGS_Unknown_E_PIE
5. RES_APPBLOCK_1931-1940_E_PIE
6. RES_APPBLOCK_1951-1960_E_PIE
7. RES_APPBLOCK_1960-1988_E_PIE
8. RES_APPBLOCK_1995-_E_PIE
9. RES_BLDGS_1960-1991_F_PIE

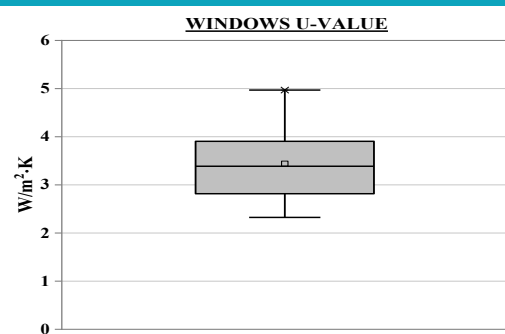
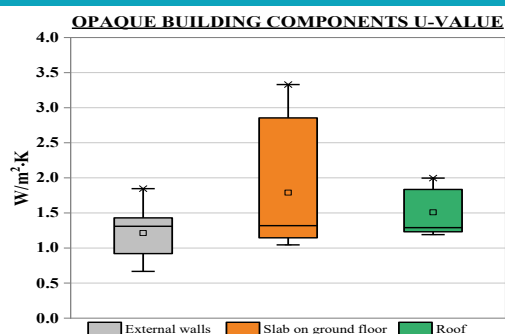
Region:	Piemonte						Archetype code: OFF_BLDGS_-1933_E_PIE	
Building category:	Non-residential buildings – Offices							
Period of construction:	< 1933							
Climatic zone:	E	Number of records:				10		
Description (the codes associated with walls and slabs refer to the structures described in UNI/TR 11552:2014): External walls: Solid brick masonry (cod. MLP01). Roof slabs: Pitched wooden roof (cod. CIN05).							Data sources: Energy audit: 46%; CENED database (APE): 44%; Municipal database: 10%	
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
BUILDING GEOMETRY	Number of floors	n_f	-	3.00	1.10	2.00	3.00	4.00
	Gross height	H_g	m	-	-	-	-	-
	Footprint area	$A_{\text{footprint}}$	m ²	1048.00	651.31	482.50	964.48	1670.00
	Heated gross floor area	$A_{H,g}$	m ²	-	-	-	-	-
	Heated net floor area	$A_{H,n}$	m ²	2894.54	2613.25	596.21	1667.94	5462.04
	Heated gross volume	$V_{H,g}$	m ³	14108.48	11848.20	3286.87	9562.27	25290.32
	Heated net volume	$V_{H,n}$	m ³	-	-	-	-	-
	Compactness ratio	$A_{\text{env}}/V_{H,g}$	m ⁻¹	0.39	0.13	0.31	0.37	0.44
	WWR – North orientation	WWR_N	-	-	-	-	-	-
	WWR – South orientation	WWR_S	-	-	-	-	-	-
	WWR – East orientation	WWR_E	-	-	-	-	-	-
	WWR – West orientation	WWR_W	-	-	-	-	-	-
	Window to useful floor area ratio	A_{wi}/A_{use}	-	-	-	--	-	-
ENVELOPE	Roof type ***	Brick-concrete slab: 50%; Unknown: 40%; Wood structure and planking with tiles: 10%						
	U-value of the roof **	$U_{\text{fi,up}}$	W/(m ² ·K)	1.51	0.38	1.23	1.29	1.84
	External walls type	Solid brick masonry: 54%; Hollow brick masonry: 15%; Hollow brick masonry, medium insulation: 8%; Unknown: 23%						
	U-value of the wall	U_{wi}	W/(m ² ·K)	1.13	0.42	0.77	1.02	1.43
	Slab on ground floor type	Vault floor with bricks and steel beams: 40%; Concrete floor: 20%; Reinforced concrete slab: 10%; Unknown: 30%						
	U-value of the floor **	$U_{\text{fi,lw}}$	W/(m ² ·K)	1.79	0.91	1.21	1.32	2.21
	Windows type	Single glazing, wooden frame: 20%; Double glazing, wooden frame: 20%; Double glazing, aluminum frame with thermal break: 23%; Other: 37%						
	U-value of the windows	U_{w}	W/(m ² ·K)	3.23	0.82	2.79	2.95	3.64
GAINS and VENTILATION	Shading system type	Curtain: 15%; Shutter: 33%; Unknown: 23%; Other: 29%						
	Occupancy density *	O_{C}	person/m ²	UNI EN 16798-1 - Table A.19				
	Lighting power density *	W_{L}	W/m ²	UNI EN 16798-1 - A.8.3				
	Equipment power density *	W_{A}	W/m ²	UNI EN 16798-1 - A.8.3				
	Type of ventilation	Natural: 80%; Mechanical: 20%						
THERMAL SYSTEMS	Air exchange rate *	n	h ⁻¹	-	-	--	-	-
	Heating system type	Centralized: 46%; Autonomous: 27%; Unknown: 27%						
	Heating generator	Traditional boiler: 62%; Condensing boiler: 23%; Unknown: 15%						
	Daily operating time of the heating system *	t_{H}	h	-	-	--	-	-
	Energy carrier	Natural gas: 91%; Gas oil: 9%						
	Heating emission sub-system	Radiators: 40%; Fan coil: 33%; Unknown: 20%; Other: 7%						
	Cooling system type	Air-cooled chiller: 50%; Absent: 50%						
	Daily operating time of the cooling system *	t_{C}	h	-	-	-	-	-
	Cooling emission sub-system	Multisplit: 30%; Fan coil: 10%; Unknown: 10%; Absent: 50%						
	DHW system type	Autonomous, detached from heating: 40%; Centralized, coupled with heating: 30%; Absent: 20%; Unknown: 10%						
DHW generator	Natural gas boiler: 54%; Electric boiler: 31%; Absent: 15%							
*These values are derived from UNI EN ISO standards; ** U-values of the upper and lower slabs face unconditioned spaces (i.e., attic, basement, etc.); ***Roof type in the envelopes refers to the slab towards unconditioned space (i.e., attic)								

Region:	Piemonte	Archetype code: OFF_BLDGS_-1933_E_PIE
Building category:	Non-residential buildings – Offices	
Period of construction:	< 1933	
Climatic zone:	E	
Number of records:		10

Numerical variables – GEOMETRY



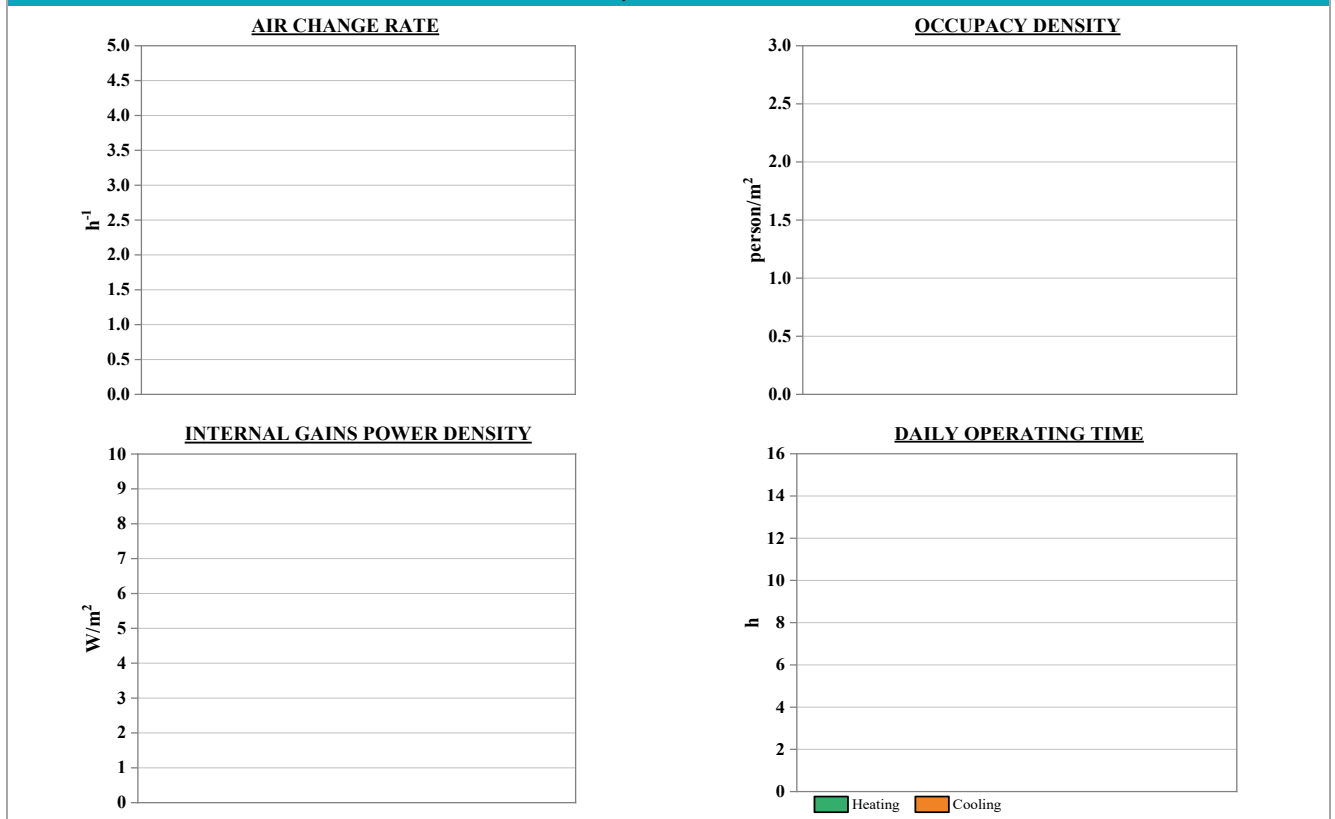
Numerical variables – ENVELOPE



Region:	Piemonte	Archetype code: OFF_BLDGS_-1933_E_PIE	
Building category:	Non-residential buildings – Offices		
Period of construction:	< 1933		
Climatic zone:	E	Number of records:	10

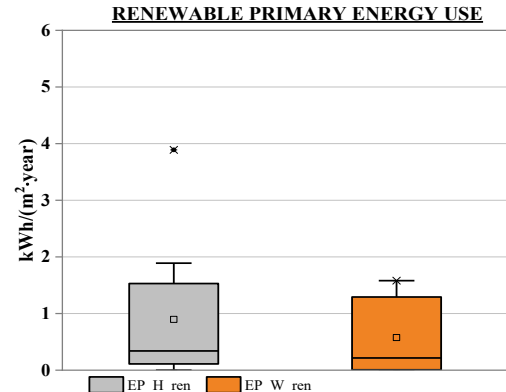
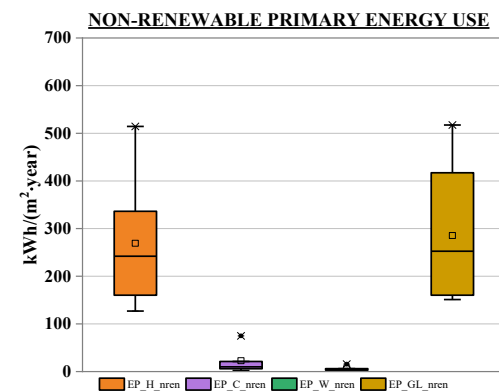
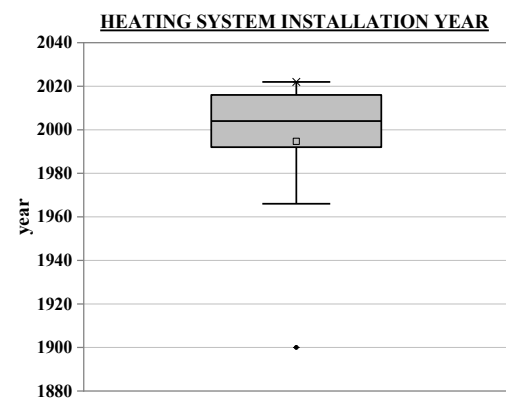
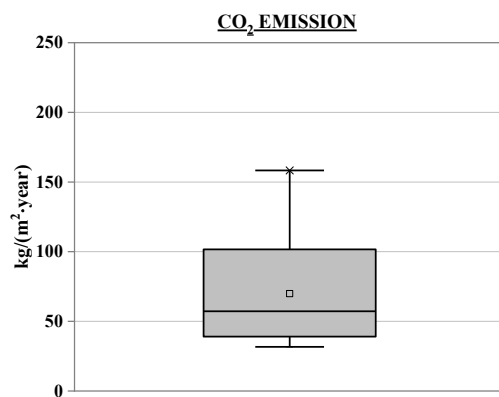
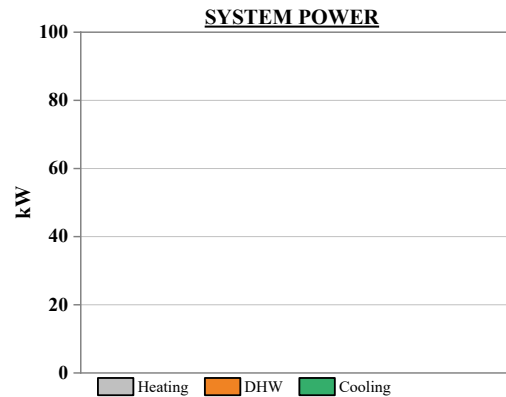
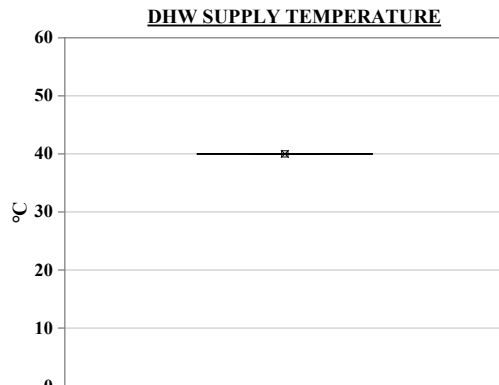
ADDITIONAL DATA								
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
THERMAL SYSTEMS	Heating efficiency or <i>COP</i>	$\eta_{H,gen}$ or $COP_{H,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total heating power	$P_{H,gen}$	kW	-	-	-	-	-
	Cooling efficiency or <i>EER</i>	$\eta_{C,gen}$ or $EER_{C,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total cooling power	$P_{C,gen}$	kW	-	-	-	-	-
	Temperature of DHW	θ_w	°C	40.0	0.0	40.0	40.0	40.0
	DHW system power	$P_{W,gen}$	kW	-	-	-	-	-
* This value refers to the building scale. Distinction between apartment and building scale is only necessary in the “Residential” category.								

Numerical variables – GAINS, VENTILATION and SYSTEMS USAGE



Region:	Piemonte	Archetype code: OFF_BLDGS_-1933_E_PIE
Building category:	Non-residential buildings – Offices	
Period of construction:	< 1933	
Climatic zone:	E	
Number of records:		10

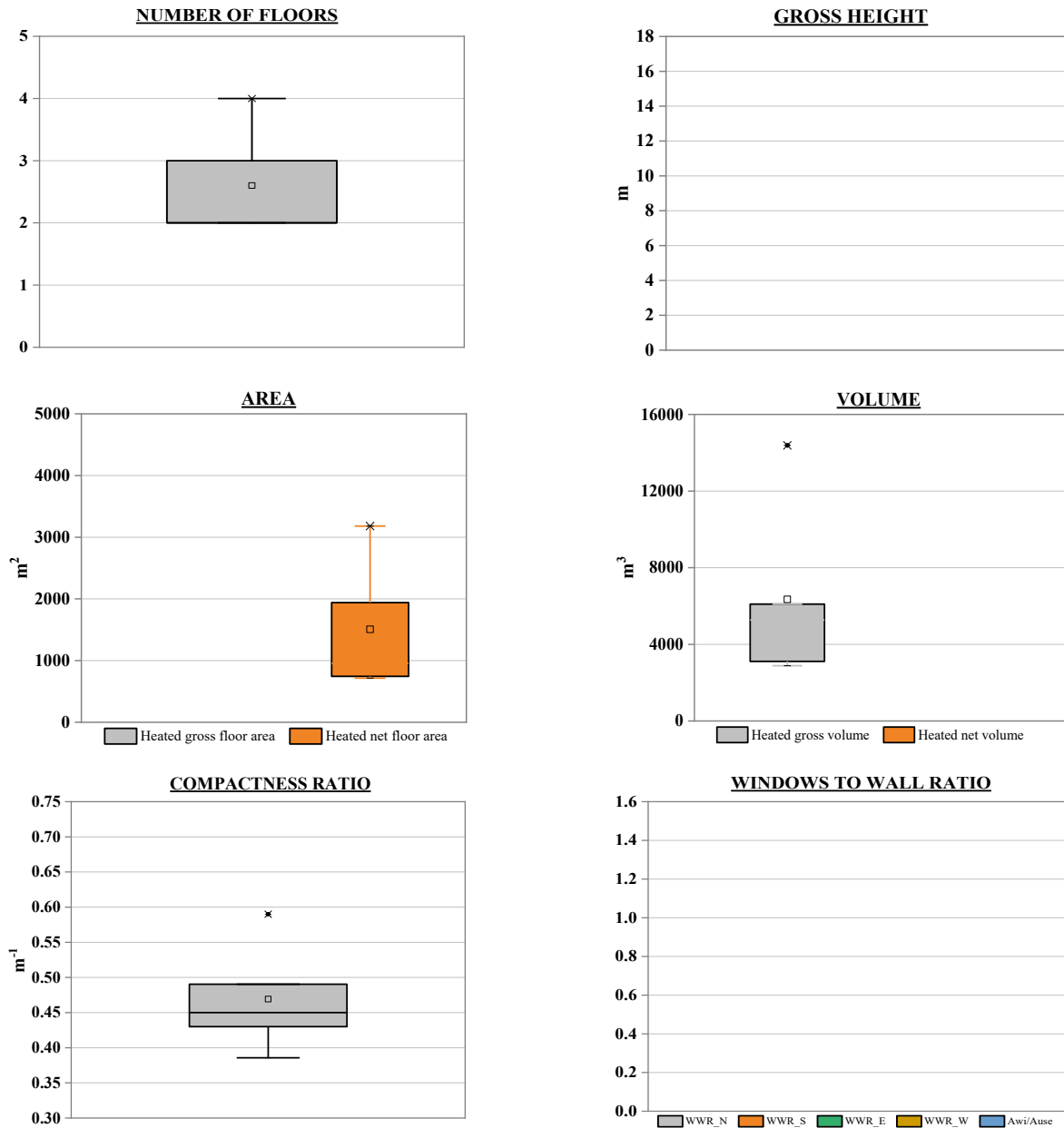
Additional data: other numerical variables that are not included in the archetype



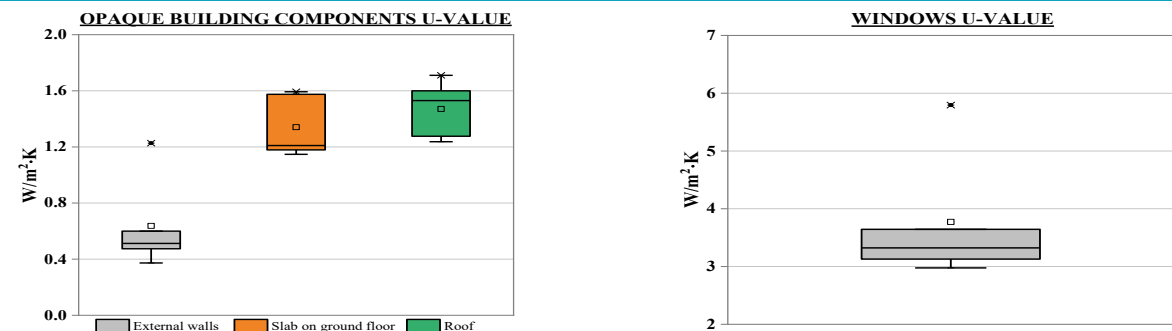
Region:	Piemonte						Archetype code: OFF_BLDGS_1973-1990_E_PIE	
Building category:	Non-residential buildings – Offices							
Period of construction:	1973-1990							
Climatic zone:	E	Number of records:				5		
Description (the codes associated with walls and slabs refer to the structures described in UNI/TR 11552:2014): External walls: Prefabricated insulated concrete wall (cod. MPF03). Roof slabs: Pitched reinforced brick-concrete roof (cod. CIN03) or Inclined wooden roof with insulation (cod. CIN03).							Data sources: Energy audit: 73%; CENED database (APE): 24%; Municipal database: 3%	
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
BUILDING GEOMETRY	Number of floors	n_f	-	3.00	0.89	2.00	2.00	3.00
	Gross height	H_g	m	-	-	-	-	-
	Footprint area	$A_{\text{footprint}}$	m ²	989.47	991.86	415.00	691.00	811.00
	Heated gross floor area	$A_{H,g}$	m ²	-	-	-	-	-
	Heated net floor area	$A_{H,n}$	m ²	1507.12	1061.09	744.00	953.80	1940.32
	Heated gross volume	$V_{H,g}$	m ³	6349.40	4698.46	3110.00	5270.90	6099.52
	Heated net volume	$V_{H,n}$	m ³	-	-	-	-	-
	Compactness ratio	$A_{\text{env}}/V_{H,g}$	m ⁻¹	0.47	0.08	0.43	0.45	0.49
	WWR – North orientation	WWR_N	-	-	-	-	-	-
	WWR – South orientation	WWR_S	-	-	-	-	-	-
	WWR – East orientation	WWR_E	-	-	-	-	-	-
	WWR – West orientation	WWR_W	-	-	-	-	-	-
	Window to useful floor area ratio	A_{wi}/A_{use}	-	-	-	--	-	-
ENVELOPE	Roof type ***	Reinforced brick-concrete slab: 100%						
	U-value of the roof **	$U_{fi,up}$	W/(m ² ·K)	1.47	0.21	1.28	1.53	1.60
	External walls type	Hollow brick masonry, medium insulation: 60%; Hollow brick masonry, low insulation: 40%						
	U-value of the wall	U_{wl}	W/(m ² ·K)	0.64	0.34	0.47	0.51	0.60
	Slab on ground floor type	Reinforced brick-concrete slab: 80%; Brick-concrete slab: 20%						
	U-value of the floor **	$U_{fi,lfw}$	W/(m ² ·K)	1.34	0.22	1.18	1.21	1.58
	Windows type	Double glazing, aluminum frame with thermal break: 80%; Single glazing, aluminum frame: 20%						
	U-value of the windows	U_W	W/(m ² ·K)	3.77	1.16	3.13	3.12	3.64
Shading system type	Shutter: 83%; Roller blinds: 17%							
GAINS and VENTILATION	Occupancy density *	O_C	person/m ²	UNI EN 16798-1 - Table A.19				
	Lighting power density *	W_L	W/m ²	UNI EN 16798-1 - A.8.3				
	Equipment power density *	W_A	W/m ²	UNI EN 16798-1 - A.8.3				
	Type of ventilation	Natural: 60%; Mechanical: 40%						
	Air exchange rate *	n	h ⁻¹	-	-	--	-	-
THERMAL SYSTEMS	Heating system type	Centralized: 100%						
	Heating generator	Traditional boiler: 33%; Boiler (unknown type): 33%; Air-source heat pump: 17%; Condensing boiler: 17%						
	Daily operating time of the heating system *	t_H	h	-	-	--	-	-
	Energy carrier	Natural gas: 83%; Electricity: 17%						
	Heating emission sub-system	Radiators: 83%; Fan coil: 17%						
	Cooling system type	Water-cooled chiller: 60%; Air-cooled chiller: 20%; Absent: 20%						
	Daily operating time of the cooling system *	t_C	h	-	-	-	-	-
	Cooling emission sub-system	Multisplit: 60%; Fan coil: 20%; Absent: 20%						
	DHW system type	Centralized, coupled with heating: 60%; Centralized, detached from heating: 40%						
	DHW generator	Natural gas boiler: 100%						
*These values are derived from UNI EN ISO standards; ** U-values of the upper and lower slabs face unconditioned spaces (i.e., attic, basement, etc.); ***Roof type in the envelopes refers to the slab towards unconditioned space (i.e., attic)								

Region:	Piemonte	Archetype code: OFF_BLDGS_1973- 1990_E_PIE
Building category:	Non-residential buildings – Offices	
Period of construction:	1973-1990	
Climatic zone:	E	
Number of records:		5

Numerical variables – GEOMETRY



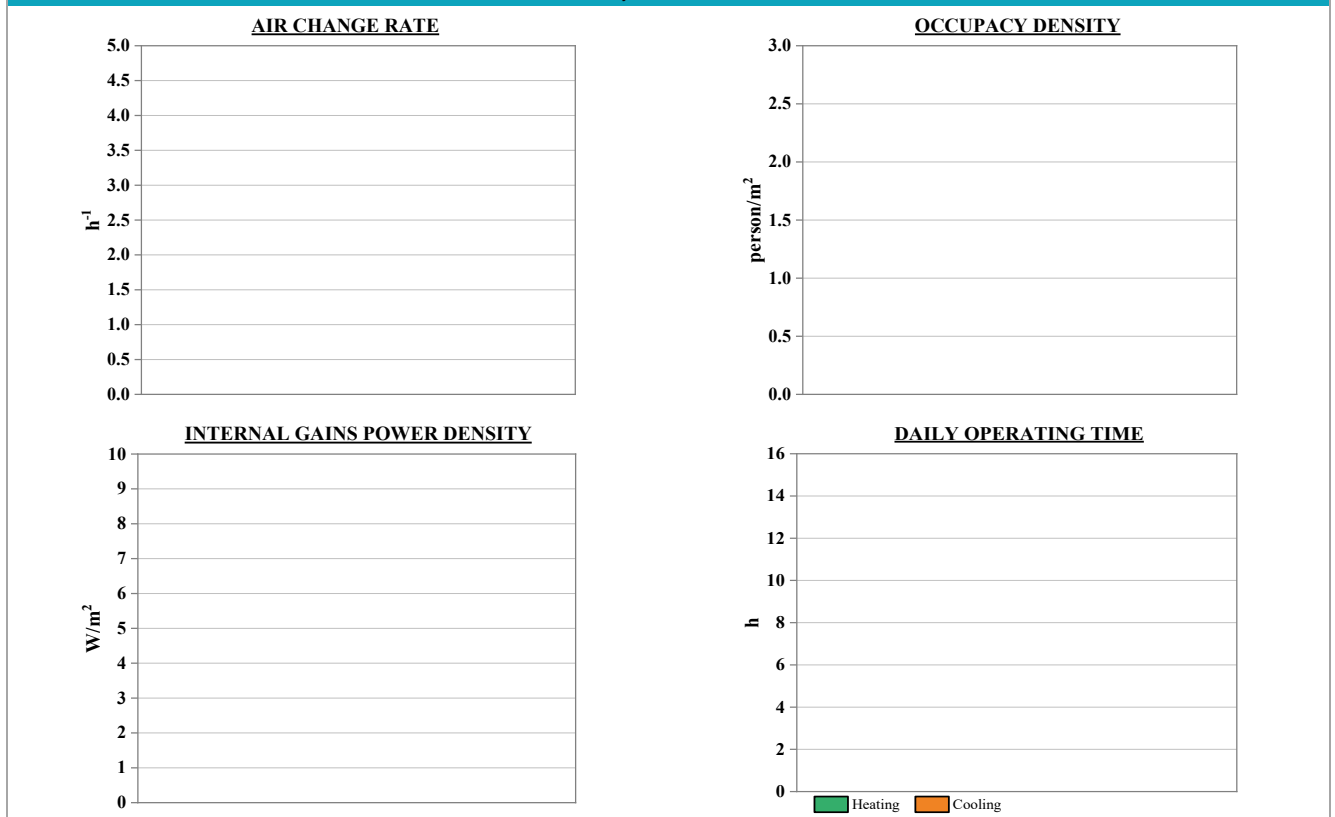
Numerical variables – ENVELOPE



Region:	Piemonte	Archetype code: OFF_BLDGS_1973- 1990_E_PIE
Building category:	Non-residential buildings – Offices	
Period of construction:	1973-1990	
Climatic zone:	E	
Number of records:		5

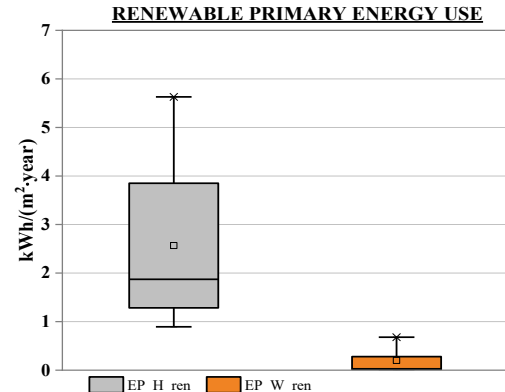
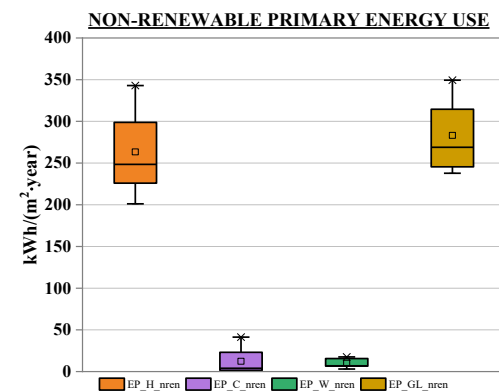
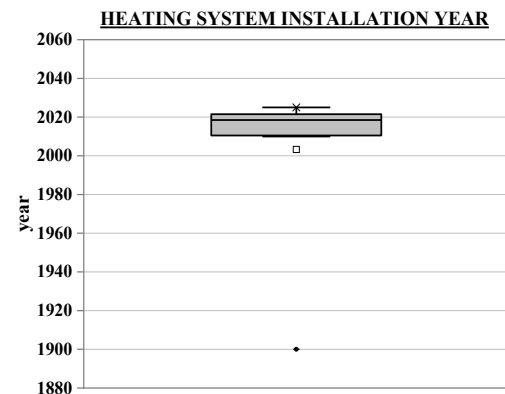
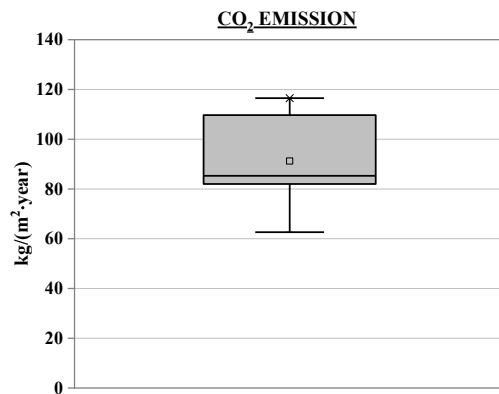
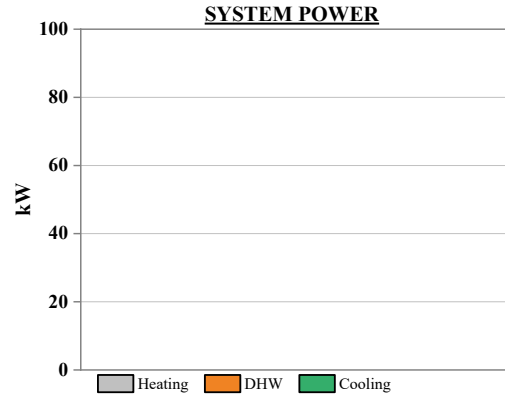
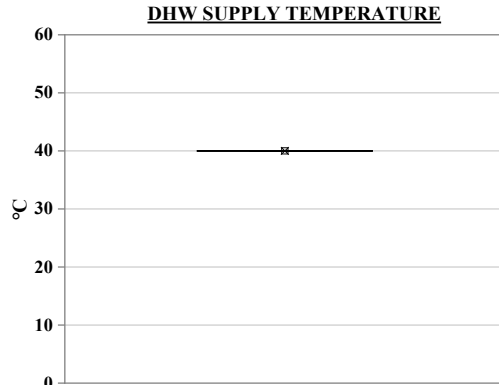
ADDITIONAL DATA								
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
THERMAL SYSTEMS	Heating efficiency or <i>COP</i>	$\eta_{H,gen}$ or $COP_{H,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total heating power	$P_{H,gen}$	kW	-	-	-	-	-
	Cooling efficiency or <i>EER</i>	$\eta_{C,gen}$ or $EER_{C,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total cooling power	$P_{C,gen}$	kW	-	-	-	-	-
	Temperature of DHW	θ_w	°C	40.0	0.0	40.0	40.0	40.0
	DHW system power	$P_{W,gen}$	kW	-	-	-	-	-
* This value refers to the building scale. Distinction between apartment and building scale is only necessary in the “Residential” category.								

Numerical variables – GAINS, VENTILATION and SYSTEMS USAGE



Region:	Piemonte	Archetype code: OFF_BLDGS_1973- 1990_E_PIE
Building category:	Non-residential buildings – Offices	
Period of construction:	1973-1990	
Climatic zone:	E	
Number of records:		5

Additional data: other numerical variables that are not included in the archetype

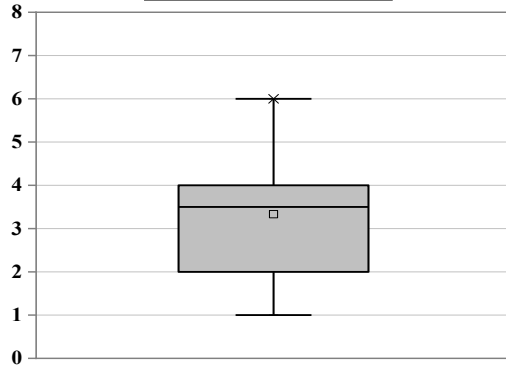


Region:	Piemonte						Archetype code: OFF_BLDGS_2000-_E_PIE	
Building category:	Non-residential buildings – Offices							
Period of construction:	> 2000							
Climatic zone:	E	Number of records:				6		
Description (the codes associated with walls and slabs refer to the structures described in UNI/TR 11552:2014): External walls: Prefabricated insulated concrete wall (cod. MPF03). Roof slabs: Insulated reinforced concrete floor slab for walkable flat roof (cod. COP03) or Pitched reinforced brick-concrete roof (cod. CIN03).							Data sources: Energy audit: 62%; CENED database (APE): 35%; Municipal database: 3%	
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
BUILDING GEOMETRY	Number of floors	n_f	-	4.00	1.75	3.00	4.00	4.00
	Gross height	H_g	m	-	-	-	-	-
	Footprint area	$A_{\text{footprint}}$	m ²	1335.67	938.59	701.75	900.65	1950.58
	Heated gross floor area	$A_{H,g}$	m ²	-	-	-	-	-
	Heated net floor area	$A_{H,n}$	m ²	3582.75	4601.90	1025.28	1396.60	3893.16
	Heated gross volume	$V_{H,g}$	m ³	14613.34	16971.56	4426.98	6221.65	18050.47
	Heated net volume	$V_{H,n}$	m ³	-	-	-	-	-
	Compactness ratio	$A_{\text{env}}/V_{H,g}$	m ⁻¹	0.46	0.18	0.40	0.46	0.48
	WWR – North orientation	WWR_N	-	-	-	-	-	-
	WWR – South orientation	WWR_S	-	-	-	-	-	-
	WWR – East orientation	WWR_E	-	-	-	-	-	-
	WWR – West orientation	WWR_W	-	-	-	-	-	-
	Window to useful floor area ratio	A_{wi}/A_{use}	-	-	-	--	-	-
ENVELOPE	Roof type ***	Reinforced brick-concrete slab: 33%; Reinforced brick-concrete slab with medium insulation: 33%; Unknown: 34%						
	U-value of the roof **	$U_{fi,up}$	W/(m ² ·K)	1.01	0.36	0.74	1.00	1.27
	External walls type	Reinforced brick concrete wall, medium insulation: 17%; Hollow brick masonry, medium insulation: 17%; Concrete wall: 17%; Unknown: 49%						
	U-value of the wall	U_{wl}	W/(m ² ·K)	1.39	0.97	0.72	1.48	1.57
	Slab on ground floor type	Brick-concrete slab: 33%; Concrete floor: 17%; Unknown: 50%						
	U-value of the floor **	$U_{fi,lw}$	W/(m ² ·K)	1.00	0.39	0.76	0.96	1.21
	Windows type	Double glazing, aluminum frame with thermal break: 50%; Unknown: 50%						
	U-value of the windows	U_W	W/(m ² ·K)	4.12	1.35	3.53	4.48	4.77
	Shading system type	Shutter: 17%; Roller blinds: 17%; No shading: 17%; Unknown: 49%						
GAINS and VENTILATION	Occupancy density *	O_C	person/m ²	UNI EN 16798-1 - Table A.19				
	Lighting power density *	W_L	W/m ²	UNI EN 16798-1 - A.8.3				
	Equipment power density *	W_A	W/m ²	UNI EN 16798-1 - A.8.3				
	Type of ventilation	Natural: 50%; Mechanical: 50%						
	Air exchange rate *	n	h ⁻¹	-	-	--	-	-
THERMAL SYSTEMS	Heating system type	Centralized: 83%; Autonomous: 17%						
	Heating generator	Traditional boiler: 29%; Boiler (unknown type): 29%; Heat exchanger of district heating/cooling: 14%; Other: 28%						
	Daily operating time of the heating system *	t_H	h	14	14	14	14	14
	Energy carrier	Natural gas: 57%; District heating: 14%; LPG: 14%; Other: 15%						
	Heating emission sub-system	Radiator and fan coil: 67%; Radiators: 17%; Mechanical ventilation vents: 16%						
	Cooling system type	Water-cooled chiller: 50%; Air-cooled chiller: 33%; Absent: 17%						
	Daily operating time of the cooling system *	t_C	h	-	-	-	-	-
	Cooling emission sub-system	Multisplit: 50%; Fan coil: 17%; Mechanical ventilation vents: 17%; Absent: 16%						
	DHW system type	Centralized, coupled with heating: 50%; Centralized, detached from heating: 17%; Autonomous, detached form heating: 33%						
	DHW generator	Natural gas boiler: 50%; Electric boiler: 33%; District heating: 17%						
*These values are derived from UNI EN ISO standards; ** U-values of the upper and lower slabs face unconditioned spaces (i.e., attic, basement, etc.); ***Roof type in the envelopes refers to the slab towards unconditioned space (i.e., attic)								

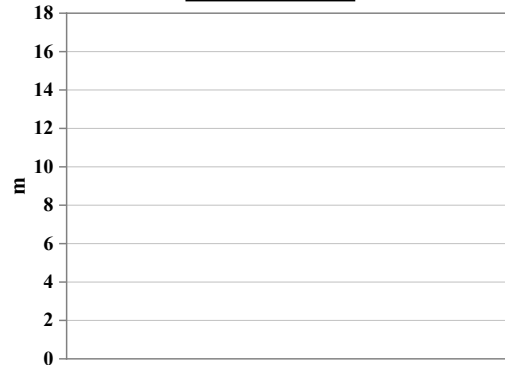
Region:	Piemonte	Archetype code: OFF_BLDGS_2000-_E_PIE
Building category:	Non-residential buildings – Offices	
Period of construction:	> 2000	
Climatic zone:	E	
Number of records:		6

Numerical variables – GEOMETRY

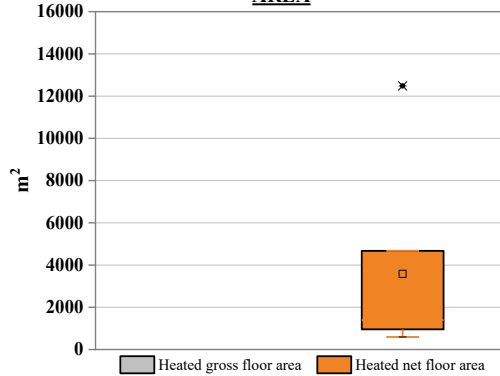
NUMBER OF FLOORS



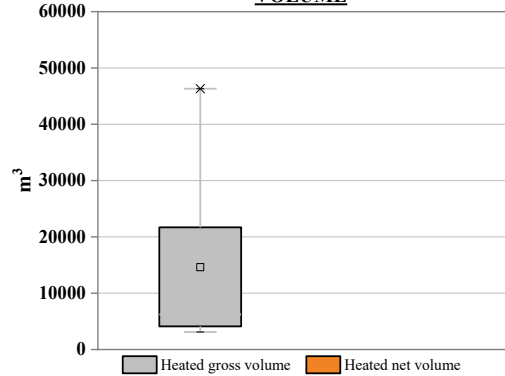
GROSS HEIGHT



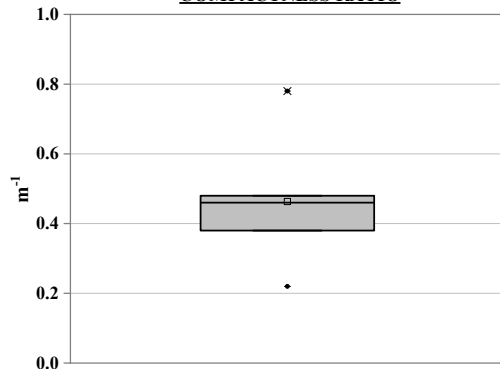
AREA



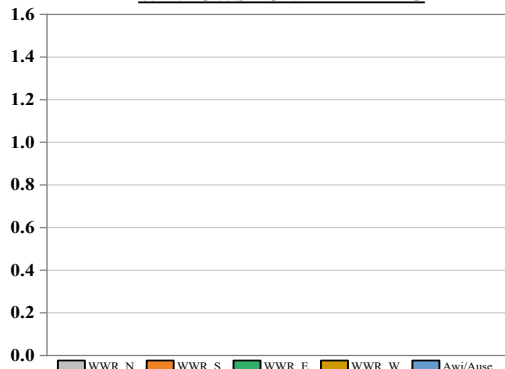
VOLUME



COMPACTNESS RATIO

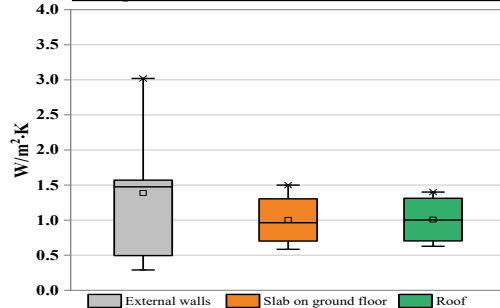


WINDOWS TO WALL RATIO

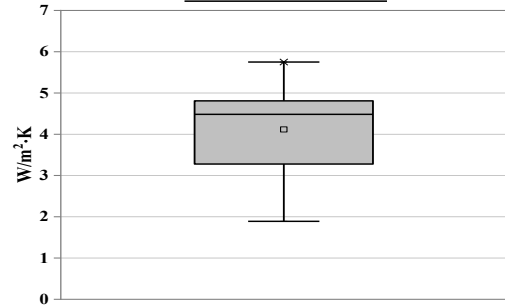


Numerical variables – ENVELOPE

OPAQUE BUILDING COMPONENTS U-VALUE



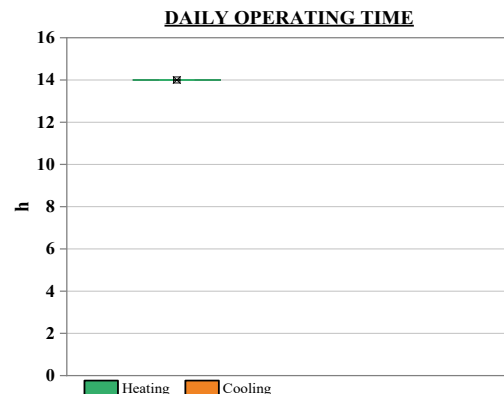
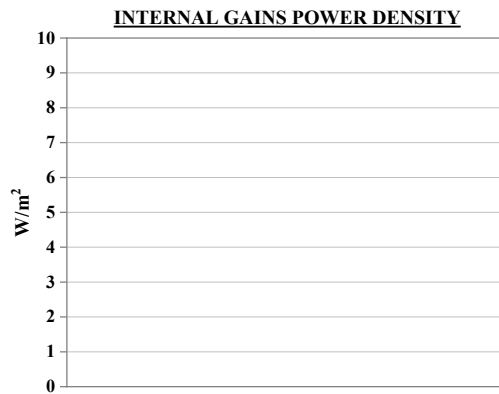
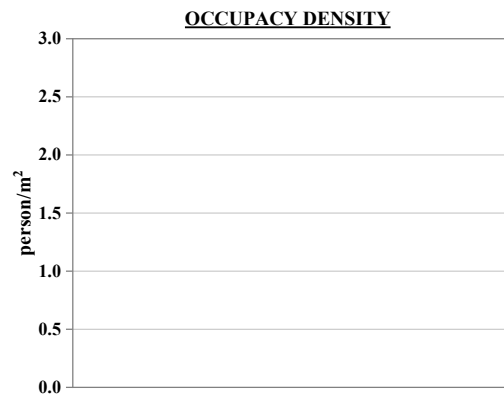
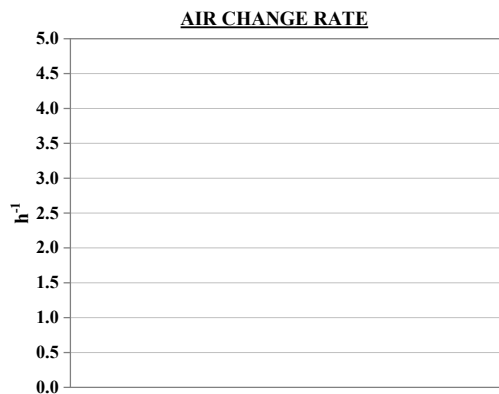
WINDOWS U-VALUE



Region:	Piemonte	Archetype code: OFF_BLDGS_2000-_E_PIE
Building category:	Non-residential buildings – Offices	
Period of construction:	> 2000	
Climatic zone:	E	
Number of records:		6

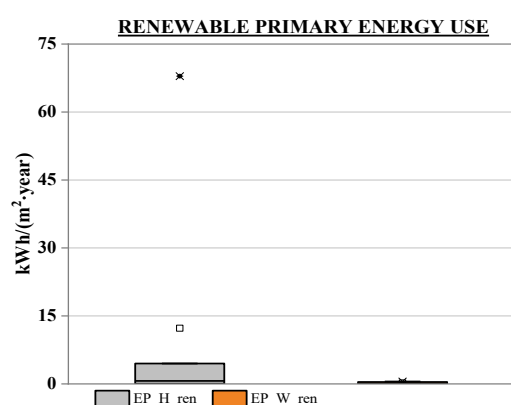
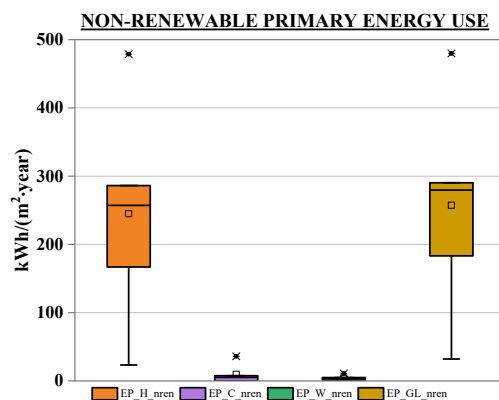
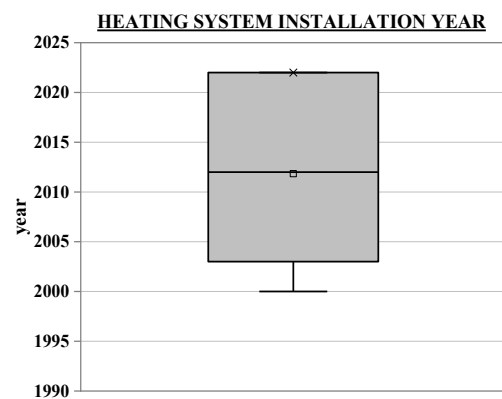
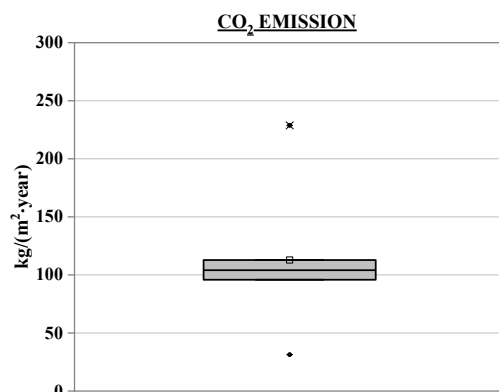
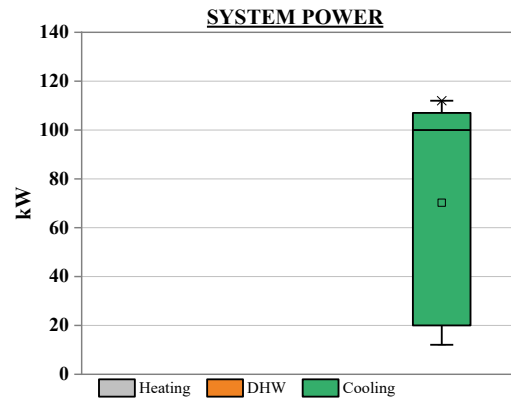
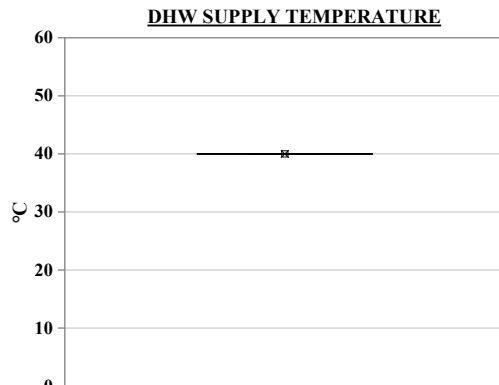
ADDITIONAL DATA								
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
THERMAL SYSTEMS	Heating efficiency or <i>COP</i>	$\eta_{H,gen}$ or $COP_{H,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total heating power	$P_{H,gen}$	kW	-	-	-	-	-
	Cooling efficiency or <i>EER</i>	$\eta_{C,gen}$ or $EER_{C,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total cooling power	$P_{C,gen}$	kW	70.22	49.71	20.00	100.00	107.00
	Temperature of DHW	θ_w	°C	40.0	0.0	40.0	40.0	40.0
	DHW system power	$P_{W,gen}$	kW	-	-	-	-	-
* This value refers to the building scale. Distinction between apartment and building scale is only necessary in the “Residential” category.								

Numerical variables – GAINS, VENTILATION and SYSTEMS USAGE



Region:	Piemonte	Archetype code: OFF_BLDGS_2000-_E_PIE
Building category:	Non-residential buildings – Offices	
Period of construction:	> 2000	
Climatic zone:	E	
Number of records:		6

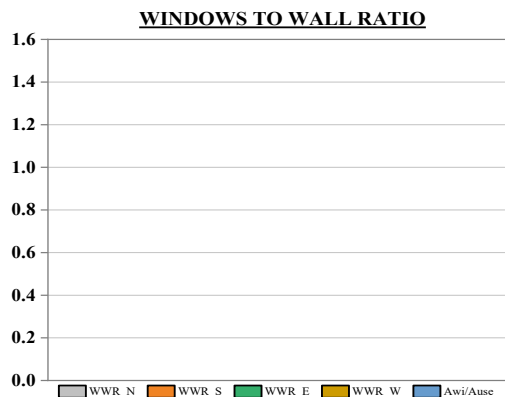
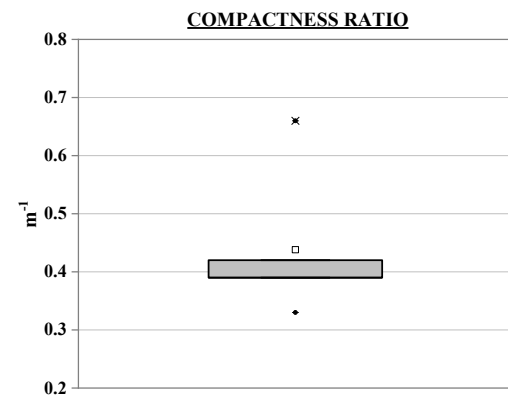
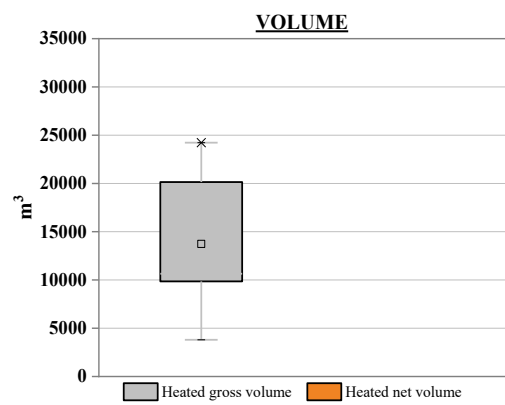
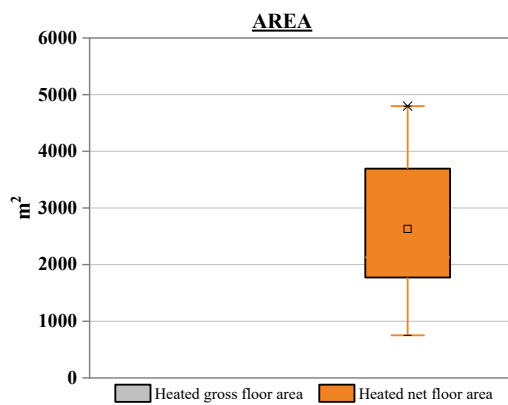
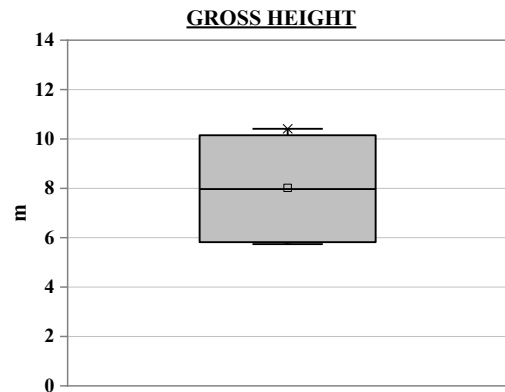
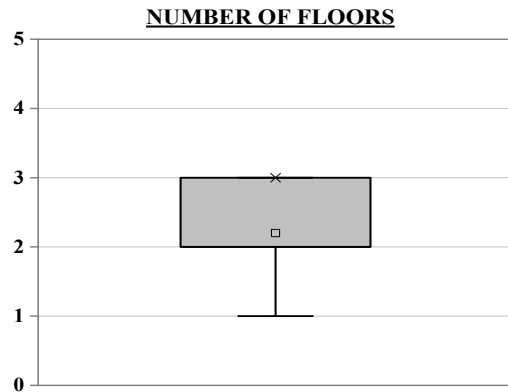
Additional data: other numerical variables that are not included in the archetype



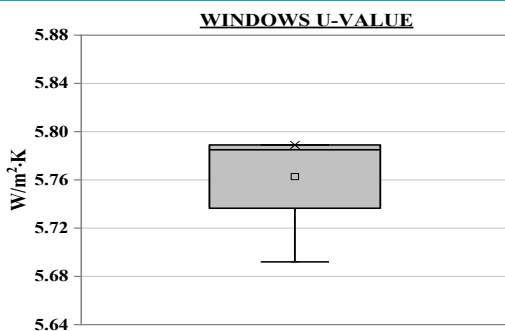
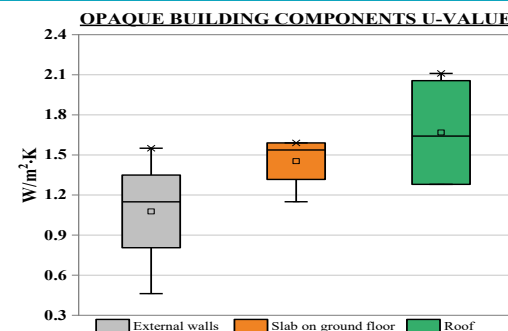
Region:	Piemonte						Archetype code: OFF_BLDGS _Unknown_E_PIE	
Building category:	Non-residential buildings – Offices							
Period of construction:	Unknown							
Climatic zone:	E	Number of records:				5		
Description (the codes associated with walls and slabs refer to the structures described in UNI/TR 11552:2014): External walls: No data available. Roof slabs: No data available.							Data sources: Energy audit: 62%; CENED database (APE): 35%; Municipal database: 3%	
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
BUILDING GEOMETRY	Number of floors	n_f	-	3.00	0.84	2.00	2.00	3.00
	Gross height	H_g	m	8.02	2.25	5.82	7.97	10.15
	Footprint area	$A_{\text{footprint}}$	m²	1367.67	1200.02	693.00	966.00	1841.50
	Heated gross floor area	$A_{H,g}$	m²	-	-	-	-	-
	Heated net floor area	$A_{H,n}$	m²	2619.12	1608.27	1773.10	2128.70	3694.80
	Heated gross volume	$V_{H,g}$	m³	13736.56	8280.93	9857.00	10648.60	20146.00
	Heated net volume	$V_{H,n}$	m³	-	-	-	-	-
	Compactness ratio	$A_{\text{env}}/V_{H,g}$	m ⁻¹	0.44	0.13	0.39	0.39	0.42
	WWR – North orientation	WWR_N	-	-	-	-	-	-
	WWR – South orientation	WWR_S	-	-	-	-	-	-
	WWR – East orientation	WWR_E	-	-	-	-	-	-
	WWR – West orientation	WWR_W	-	-	-	-	-	-
	Window to useful floor area ratio	A_{wi}/A_{use}	-	-	-	--	-	-
ENVELOPE	Roof type ***	Brick-concrete slab: 40%; Reinforced brick-concrete slab: 40%; Unknown: 20%						
	U-value of the roof **	$U_{\text{fi,up}}$	W/(m²·K)	1.67	0.45	1.28	1.64	2.03
	External walls type	Solid brick masonry: 60%; Prefabricated panels: 20%; Unknown: 20%						
	U-value of the wall	U_{wl}	W/(m²·K)	1.08	0.45	0.98	1.15	1.25
	Slab on ground floor type	Brick-concrete slab: 40%; Reinforced brick-concrete slab: 20%; Concrete floor: 20%; Unknown: 20%						
	U-value of the floor **	$U_{\text{fi,lw}}$	W/(m²·K)	1.45	0.21	1.40	1.54	1.59
	Windows type	Single glazing, aluminum frame: 80%; Unknown: 20%						
	U-value of the windows	U_W	W/(m²·K)	5.76	0.05	5.76	5.79	5.79
Shading system type	Curtain and shutter: 20%; No shading: 40%; Curtain: 20%; Unknown: 20%							
GAINS and VENTILATION	Occupancy density *	O_C	person/m²	UNI EN 16798-1 - Table A.19				
	Lighting power density *	W_L	W/m²	UNI EN 16798-1 - A.8.3				
	Equipment power density *	W_A	W/m²	UNI EN 16798-1 - A.8.3				
	Type of ventilation	Natural: 100%						
	Air exchange rate *	n	h ⁻¹	-	-	--	-	-
THERMAL SYSTEMS	Heating system type	Centralized: 100%						
	Heating generator	Traditional boiler: 100%						
	Daily operating time of the heating system *	t_H	h	14	14	14	14	14
	Energy carrier	Natural gas: 100%						
	Heating emission sub-system	Radiators: 100%						
	Cooling system type	Water-cooled chiller: 60%; Absent: 40%						
	Daily operating time of the cooling system *	t_C	h	-	-	-	-	-
	Cooling emission sub-system	Multisplit: 20%; Mechanical ventilation vents: 40%; Absent: 40%						
	DHW system type	Autonomous, detached form heating: 60%; Centralized, detached from heating: 20%; Centralized, coupled with heating: 20%						
	DHW generator	Natural gas boiler: 60%; Electric boiler: 40%						
	*These values are derived from UNI EN ISO standards; ** U-values of the upper and lower slabs face unconditioned spaces (i.e., attic, basement, etc.); ***Roof type in the envelopes refers to the slab towards unconditioned space (i.e., attic)							

Region:	Piemonte	Archetype code: OFF_BLDGS_Unknown_E_PIE
Building category:	Non-residential buildings – Offices	
Period of construction:	Unknown	
Climatic zone:	E	
Number of records:		5

Numerical variables – GEOMETRY



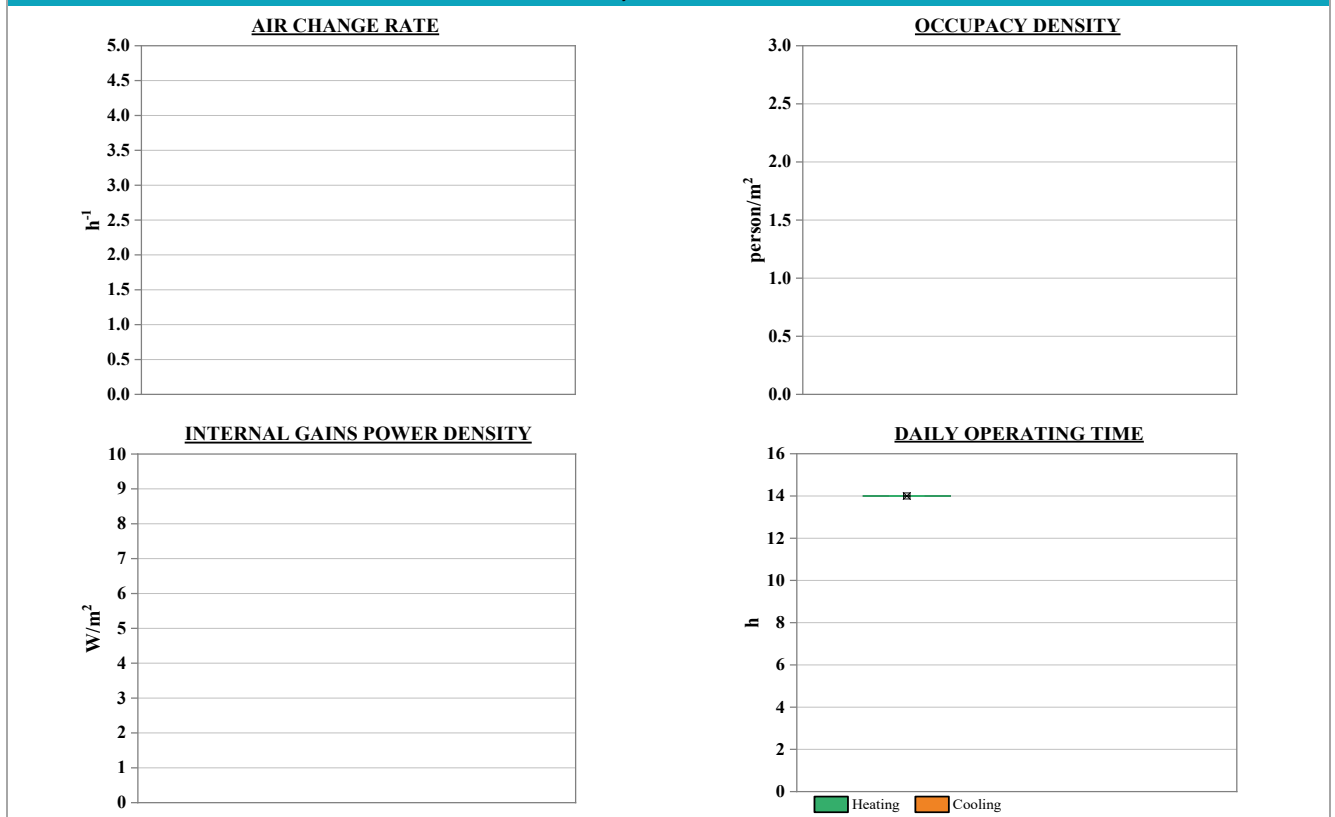
Numerical variables – ENVELOPE



Region:	Piemonte	Archetype code: OFF_BLDGS_Unknown_E_PIE
Building category:	Non-residential buildings – Offices	
Period of construction:	Unknown	
Climatic zone:	E	
Number of records:		5

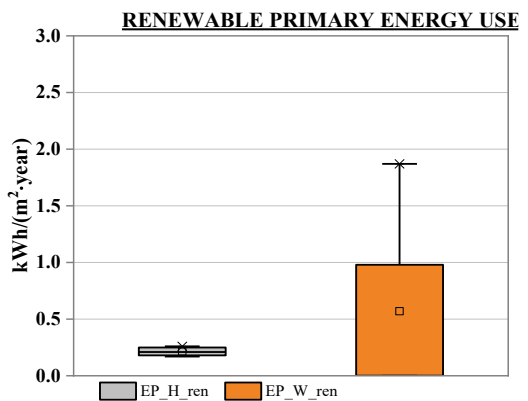
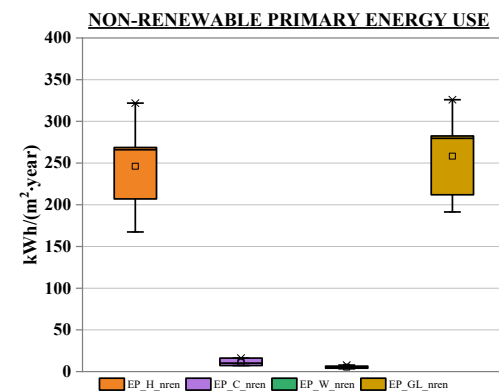
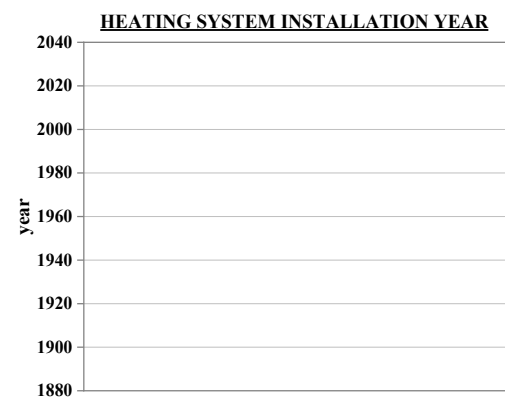
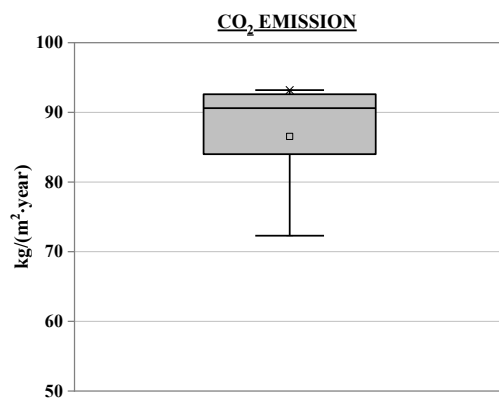
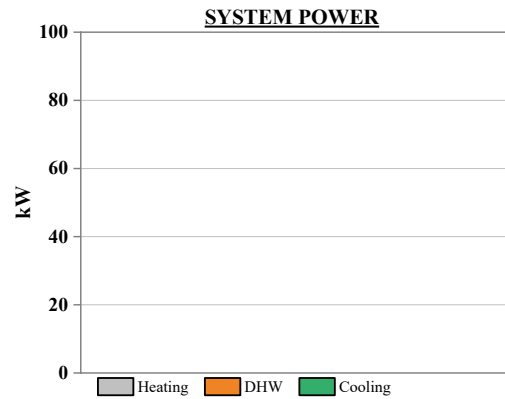
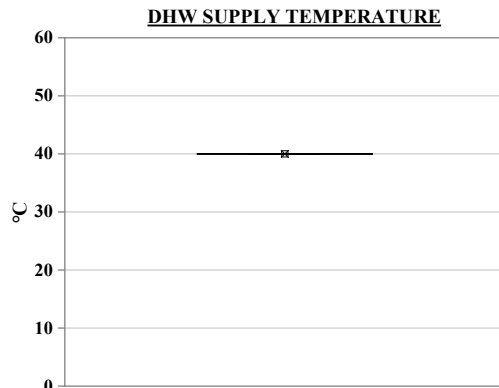
ADDITIONAL DATA								
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
THERMAL SYSTEMS	Heating efficiency or <i>COP</i>	$\eta_{H,gen}$ or $COP_{H,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total heating power	$P_{H,gen}$	kW	-	-	-	-	-
	Cooling efficiency or <i>EER</i>	$\eta_{C,gen}$ or $EER_{C,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total cooling power	$P_{C,gen}$	kW	-	-	-	-	-
	Temperature of DHW	θ_w	°C	40.0	0.0	40.0	40.0	40.0
	DHW system power	$P_{W,gen}$	kW	-	-	-	-	-
* This value refers to the building scale. Distinction between apartment and building scale is only necessary in the “Residential” category.								

Numerical variables – GAINS, VENTILATION and SYSTEMS USAGE



Region:	Piemonte	Archetype code: OFF_BLDGS_Unknown_E_PIE
Building category:	Non-residential buildings – Offices	
Period of construction:	Unknown	
Climatic zone:	E	
Number of records:		5

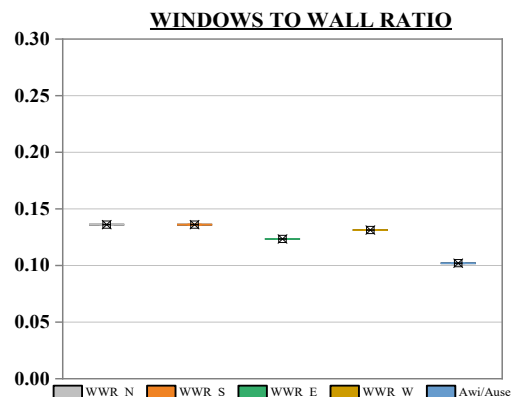
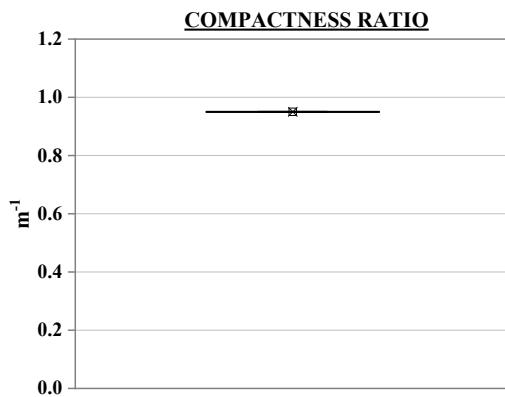
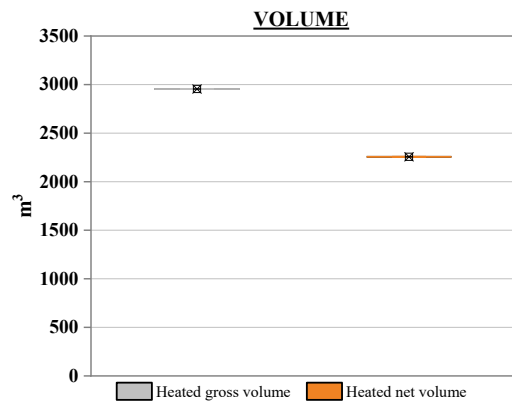
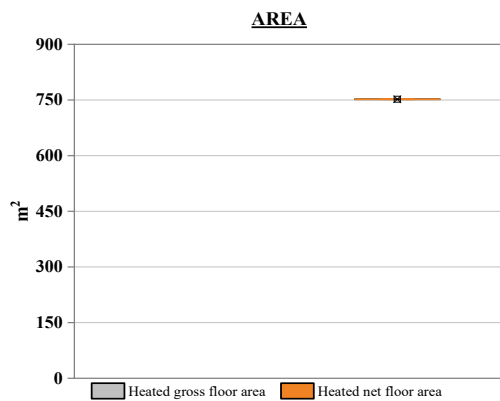
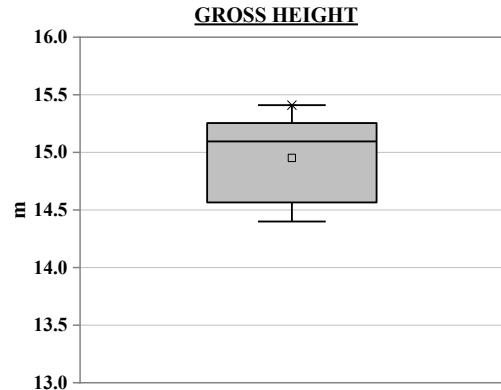
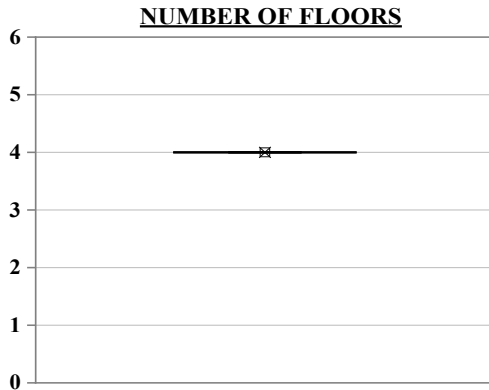
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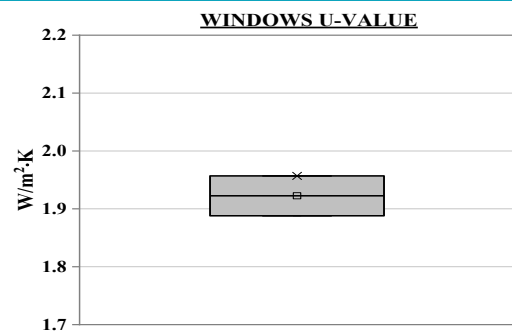
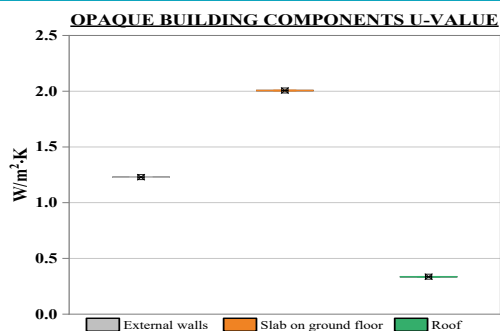
Region:	Piemonte						Archetype code: RES_APPBLOCK_1931-1940_E_PIE	
Building category:	Residential buildings – Apartment blocks							
Period of construction:	1931-1940							
Climatic zone:	E	Number of records:				16		
Description (the codes associated with walls and slabs refer to the structures described in UNI/TR 11552:2014): External walls: Solid brick masonry (cod. MLP01). Roof slabs: Pitched wooden roof (cod. CIN05).							Data sources: Energy audit: 86%; Municipal database: 9%; Measured data: 5%	
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
BUILDING GEOMETRY	Number of floors	n_f	-	4.00	0.00	4.00	4.00	4.00
	Gross height	H_g	m	14.95	0.37	14.62	15.10	15.24
	Footprint area	$A_{\text{footprint}}$	m ²	-	-	-	-	-
	Heated gross floor area	$A_{H;g}$	m ²	-	-	-	-	-
	Heated net floor area	$A_{H;n}$	m ²	752.13	0.00	752.13	752.13	752.13
	Heated gross volume	$V_{H;g}$	m ³	2954.44	0.00	2954.44	2954.44	2954.44
	Heated net volume	$V_{H;n}$	m ³	2256.40	0.00	2256.40	2256.40	2256.40
	Compactness ratio	$A_{\text{env}}/V_{H;g}$	m ⁻¹	0.95	0.00	0.95	0.95	0.95
	WWR – North orientation	WWR_N	-	0.14	0.00	0.14	0.14	0.14
	WWR – South orientation	WWR_S	-	0.14	0.00	0.14	0.14	0.14
	WWR – East orientation	WWR_E	-	0.12	0.00	0.12	0.12	0.12
	WWR – West orientation	WWR_W	-	0.13	0.00	0.13	0.13	0.13
	Window to useful floor area ratio	A_{wi}/A_{use}	-	0.10	0.00	0.10	0.10	0.10
ENVELOPE	Roof type ***	Reinforced brick-concrete slab, high insulation: 100%						
	U-value of the roof **	$U_{fi;up}$	W/(m ² ·K)	0.34	0.00	0.34	0.34	0.34
	External walls type	Solid brick masonry: 100%						
	U-value of the wall	U_{wl}	W/(m ² ·K)	1.23	0.00	1.23	1.23	1.23
	Slab on ground floor type	Brick-concrete slab: 100%						
	U-value of the floor **	$U_{fi;lw}$	W/(m ² ·K)	2.01	0.00	2.01	2.01	2.01
	Windows type	Double glazing, PVC frame: 100%						
	U-value of the windows	U_W	W/(m ² ·K)	1.92	0.05	1.91	1.92	1.94
GAINS and VENTILATION	Shading system type	Blinds: 100%						
	Occupancy density *	O_C	person/m ²	UNI EN 16798-1 - Table A.19				
	Lighting power density *	W_L	W/m ²	UNI EN 16798-1 - A.8.3				
	Equipment power density *	W_A	W/m ²	UNI EN 16798-1 - A.8.3				
	Type of ventilation	Natural: 100%						
THERMAL SYSTEMS	Air exchange rate *	n	h ⁻¹	-	-	--	-	-
	Heating system type	Centralized: 100%						
	Heating generator	Heat exchanger of district heating/cooling: 100%						
	Daily operating time of the heating system *	t_H	h	-	-	-	-	-
	Energy carrier	District heating (upstream with pellet boiler): 100%						
	Heating emission sub-system	Radiators: 100%						
	Cooling system type	Unknown: 100%						
	Daily operating time of the cooling system *	t_C	h	-	-	-	-	-
	Cooling emission sub-system	Unknown: 100%						
	DHW system type	District heating: 100%						
	DHW generator	Heat exchanger of district heating: 100%						
*These values are derived from UNI EN ISO standards; ** U-values of the upper and lower slabs face unconditioned spaces (i.e., attic, basement, etc.); ***Roof type in the envelopes refers to the slab towards unconditioned space (i.e., attic)								

Region:	Piemonte			Archetype code: RES_APPBLOCK_1931- 1940_E_PIE
Building category:	Residential buildings – Apartment blocks			
Period of construction:	1931-1940			
Climatic zone:	E	Number of records:	16	

Numerical variables – GEOMETRY



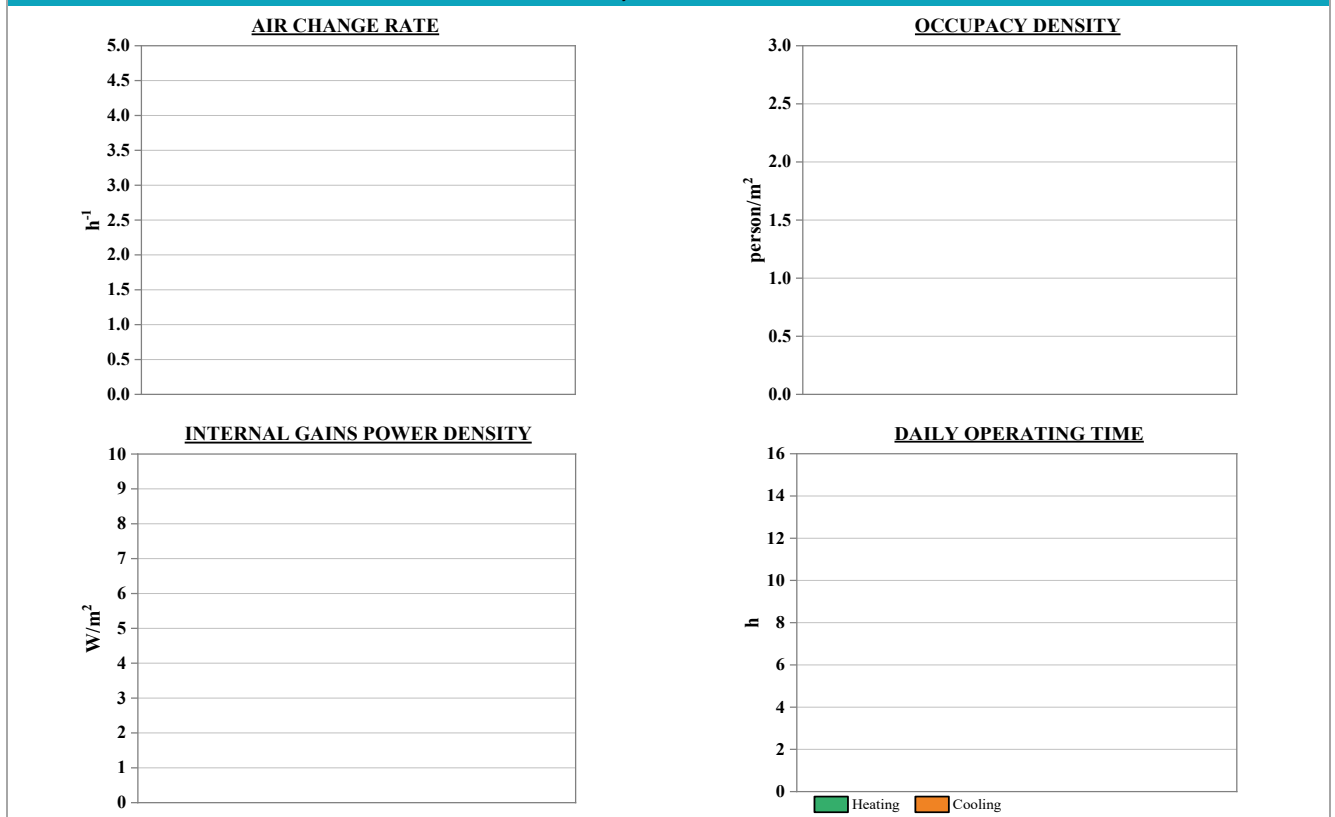
Numerical variables – ENVELOPE



Region:	Piemonte	Archetype code: RES_APPBLOCK_1931- 1940_E_PIE
Building category:	Residential buildings – Apartment blocks	
Period of construction:	1931-1940	
Climatic zone:	E	
Number of records:		16

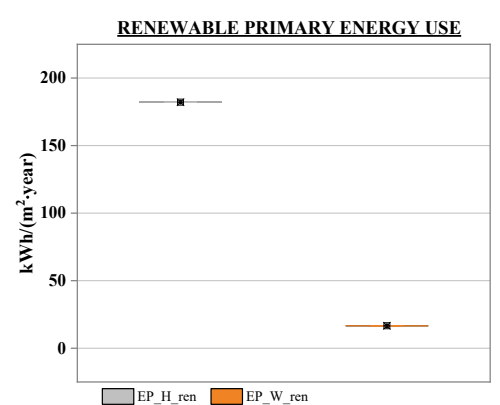
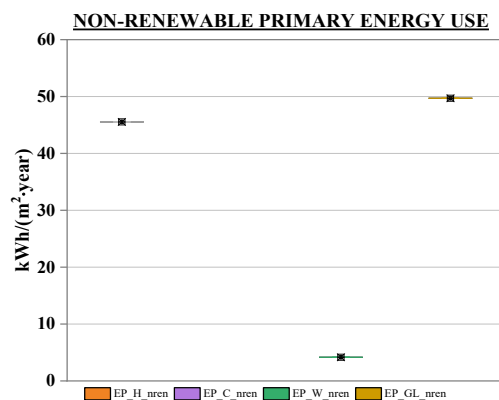
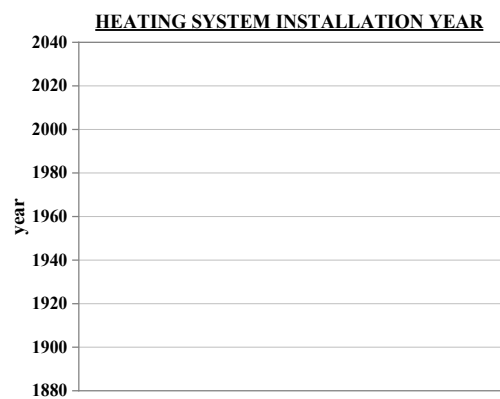
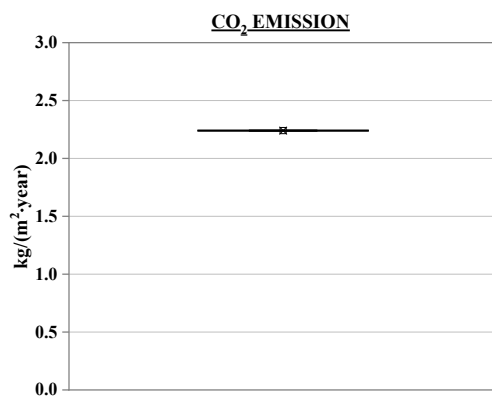
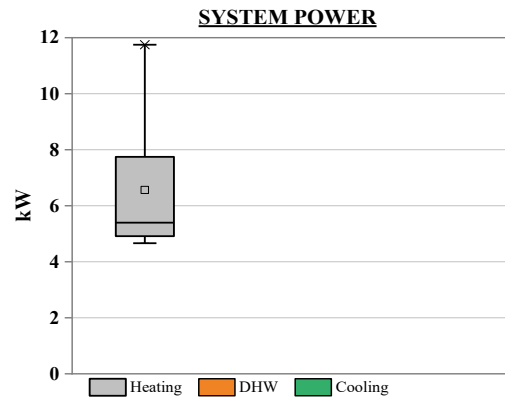
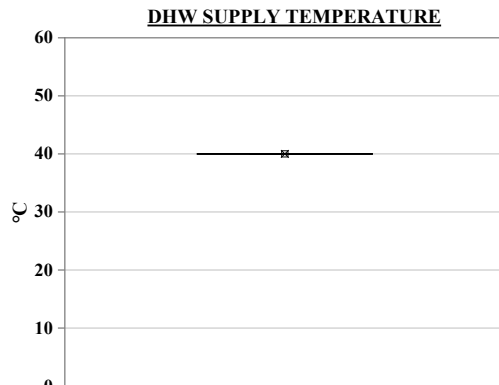
ADDITIONAL DATA								
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
THERMAL SYSTEMS	Heating efficiency or <i>COP</i>	$\eta_{H,gen}$ or $COP_{H,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total heating power	$P_{H,gen}$	kW	6.56	3.00	5.01	5.40	6.85
	Cooling efficiency or <i>EER</i>	$\eta_{C,gen}$ or $EER_{C,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total cooling power	$P_{C,gen}$	kW	-	-	-	-	-
	Temperature of DHW	θ_w	°C	40.0	0.0	40.0	40.0	40.0
	DHW system power	$P_{W,gen}$	kW	-	-	-	-	-
* This value refers to the building scale. Distinction between apartment and building scale is only necessary in the "Residential" category.								

Numerical variables – GAINS, VENTILATION and SYSTEMS USAGE



Region:	Piemonte	Archetype code: RES_APPBLOCK_1931- 1940_E_PIE
Building category:	Residential buildings – Apartment blocks	
Period of construction:	1931-1940	
Climatic zone:	E	
Number of records:		16

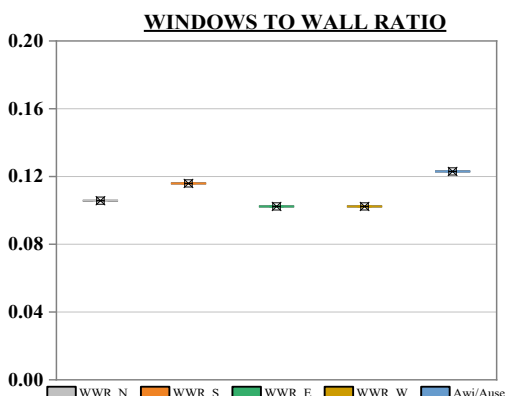
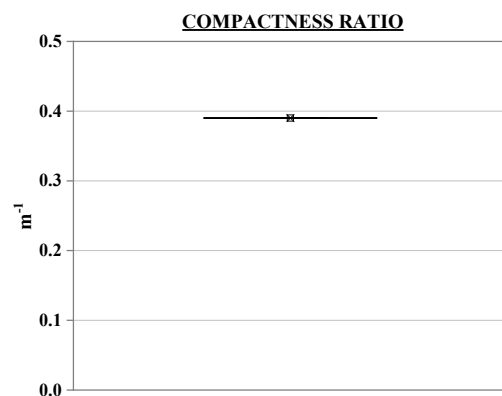
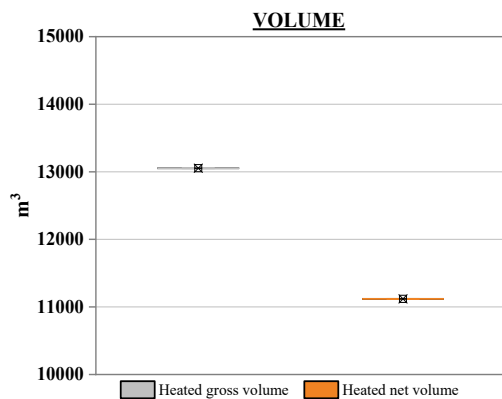
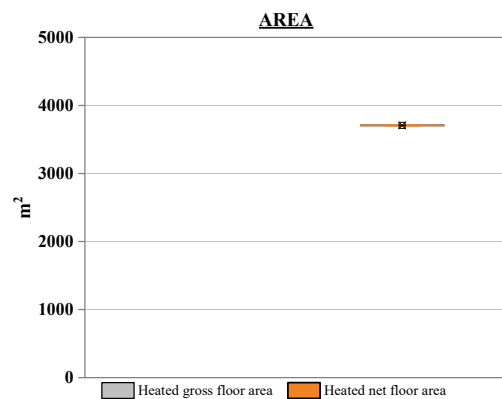
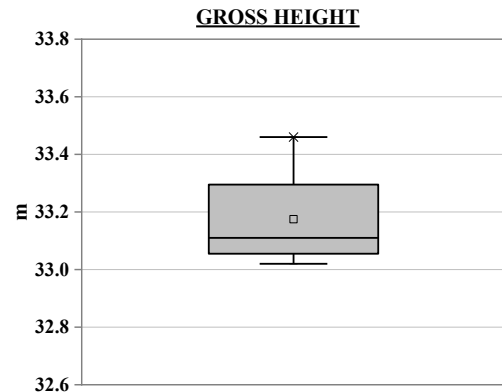
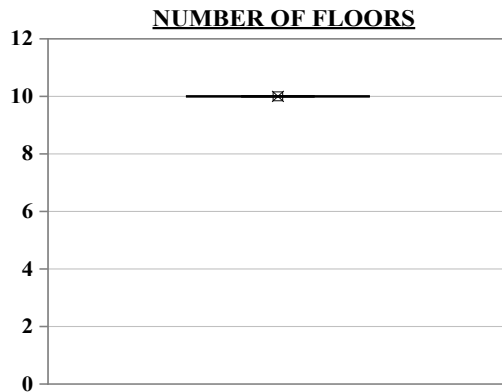
Additional data: other numerical variables that are not included in the archetype



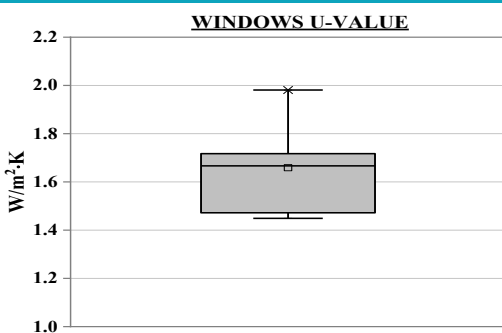
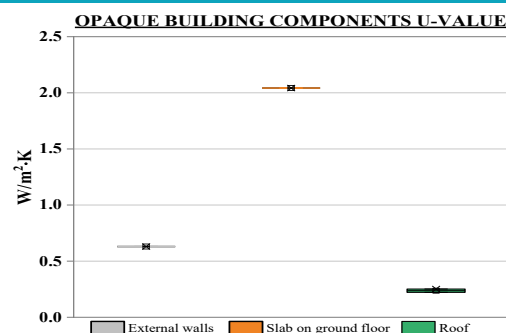
Region:	Piemonte						Archetype code: RES_APPBLOCK_1951-1960_E_PIE	
Building category:	Residential buildings – Apartment blocks							
Period of construction:	1951-1960							
Climatic zone:	E	Number of records:		4				
Description (the codes associated with walls and slabs refer to the structures described in UNI/TR 11552:2014): External walls: Hollow brick masonry with air gap (cod. MCO04/03). Roof slabs: Pitched reinforced brick-concrete roof (cod. CIN04) of Flat roof with reinforced brick-concrete floor (cod. COP04).							Data sources: Energy audit: 90%; Municipal database: 10%	
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
BUILDING GEOMETRY	Number of floors	n_f	-	10.00	0.00	10.00	10.00	10.00
	Gross height	H_g	m	33.18	0.20	33.07	33.11	33.21
	Footprint area	$A_{\text{footprint}}$	m ²	-	-	-	-	-
	Heated gross floor area	$A_{H,g}$	m ²	-	-	-	-	-
	Heated net floor area	$A_{H,n}$	m ²	3706.30	0.00	3706.30	3706.30	3706.30
	Heated gross volume	$V_{H,g}$	m ³	13053.77	0.00	13053.77	13053.77	13053.77
	Heated net volume	$V_{H,n}$	m ³	1111.90	0.00	1111.90	1111.90	1111.90
	Compactness ratio	$A_{\text{env}}/V_{H,g}$	m ⁻¹	0.39	0.00	0.39	0.39	0.39
	WWR – North orientation	WWR_N	-	0.11	0.00	0.11	0.11	0.11
	WWR – South orientation	WWR_S	-	0.12	0.00	0.12	0.12	0.12
	WWR – East orientation	WWR_E	-	0.10	0.00	0.10	0.10	0.10
	WWR – West orientation	WWR_W	-	0.10	0.00	0.10	0.10	0.10
	Window to useful floor area ratio	A_{wi}/A_{use}	-	0.12	0.00	0.12	0.12	0.12
ENVELOPE	Roof type ***	Reinforced brick-concrete slab: 100%						
	U-value of the roof **	$U_{fi,up}$	W/(m ² ·K)	0.24	0.02	0.23	0.24	0.24
	External walls type	Concrete wall: 100%						
	U-value of the wall	U_{wl}	W/(m ² ·K)	0.63	0.00	0.63	0.63	0.63
	Slab on ground floor type	Concrete floor: 100%						
	U-value of the floor **	$U_{fi,lw}$	W/(m ² ·K)	2.04	0.00	2.04	2.04	2.04
	Windows type	Double glazing, PVC frame: 100%						
	U-value of the windows	U_W	W/(m ² ·K)	1.66	0.19	1.52	1.67	1.71
GAINS and VENTILATION	Shading system type	Curtain and shutter: 100%						
	Occupancy density *	O_C	person/m ²	UNI EN 16798-1 - Table A.19				
	Lighting power density *	W_L	W/m ²	UNI EN 16798-1 - A.8.3				
	Equipment power density *	W_A	W/m ²	UNI EN 16798-1 - A.8.3				
	Type of ventilation	Natural: 100%						
	Air exchange rate *	n	h ⁻¹	-	-	--	-	-
THERMAL SYSTEMS	Heating system type	Centralized: 100%						
	Heating generator	Traditional boiler: 100%						
	Daily operating time of the heating system *	t_H	h	14	0	14	14	14
	Energy carrier	Natural gas: 100%						
	Heating emission sub-system	Radiators: 100%						
	Cooling system type	Absent: 100%						
	Daily operating time of the cooling system *	t_C	h	-	-	-	-	-
	Cooling emission sub-system	Absent: 100%						
	DHW system type	Autonomous, detached from heating: 40%; Centralized, coupled with heating: 30%; Absent: 20%; Unknown: 10%						
	DHW generator	Natural gas boiler and solar thermal: 100%						
	*These values are derived from UNI EN ISO standards; ** U-values of the upper and lower slabs face unconditioned spaces (i.e., attic, basement, etc.); ***Roof type in the envelopes refers to the slab towards unconditioned space (i.e., attic)							

Region:	Piemonte	Archetype code: RES_APPBLOCK_1951- 1960_E_PIE
Building category:	Residential buildings – Apartment blocks	
Period of construction:	1951-1960	
Climatic zone:	E	
Number of records:		4

Numerical variables – GEOMETRY

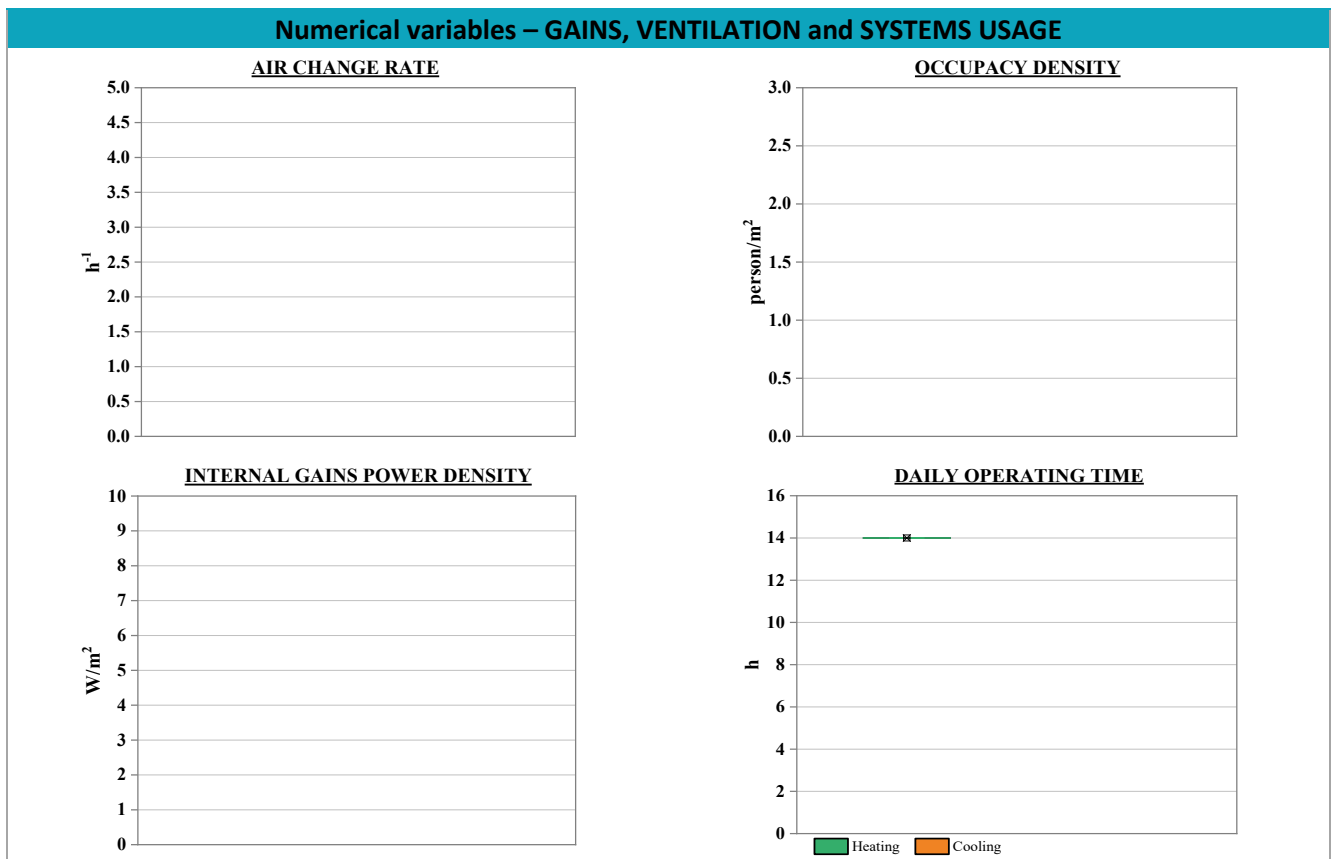


Numerical variables – ENVELOPE



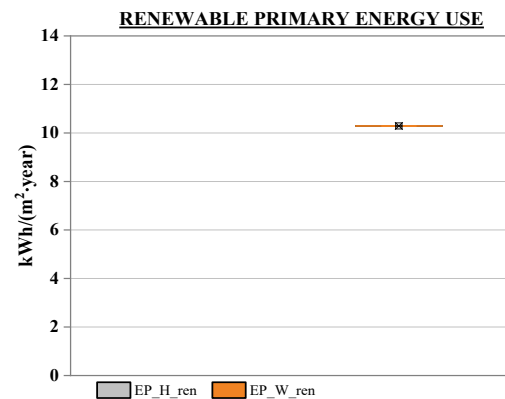
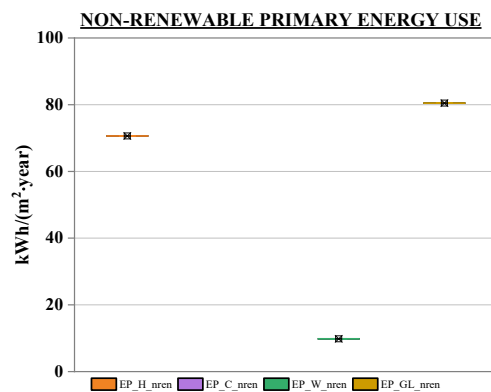
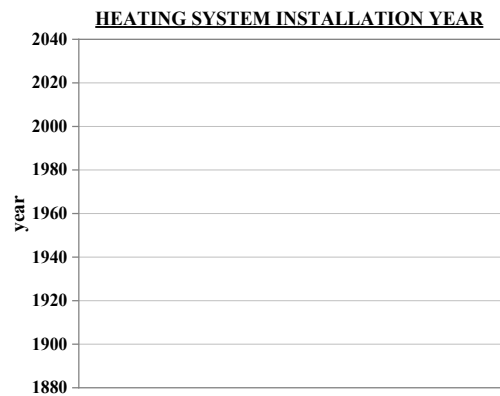
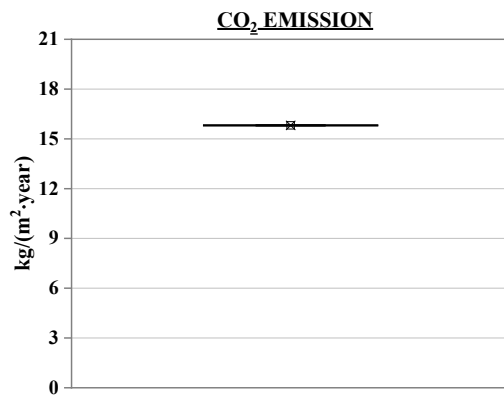
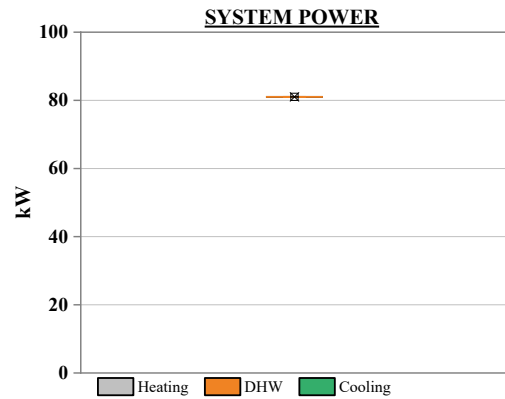
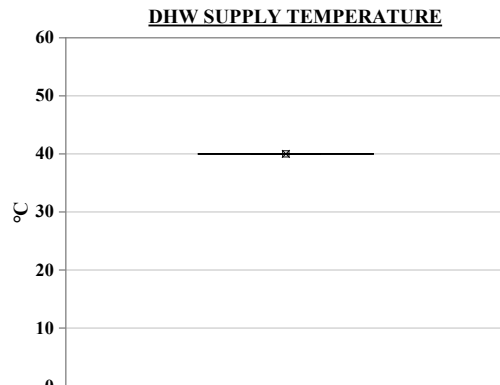
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Building category:	Residential buildings – Apartment blocks	
Period of construction:	1951-1960	
Climatic zone:	E	
Number of records:		4

ADDITIONAL DATA								
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
THERMAL SYSTEMS	Heating efficiency or <i>COP</i>	$\eta_{H,gen}$ or $COP_{H,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total heating power	$P_{H,gen}$	kW	-	-	-	-	-
	Cooling efficiency or <i>EER</i>	$\eta_{C,gen}$ or $EER_{C,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total cooling power	$P_{C,gen}$	kW	-	-	-	-	-
	Temperature of DHW	θ_w	°C	40.0	0.0	40.0	40.0	40.0
	DHW system power	$P_{W,gen}$	kW	-	-	-	-	-
* This value refers to the building scale. Distinction between apartment and building scale is only necessary in the “Residential” category.								



Region:	Piemonte	Archetype code: RES_APPBLOCK_1951- 1960_E_PIE
Building category:	Residential buildings – Apartment blocks	
Period of construction:	1951-1960	
Climatic zone:	E	
Number of records:		4

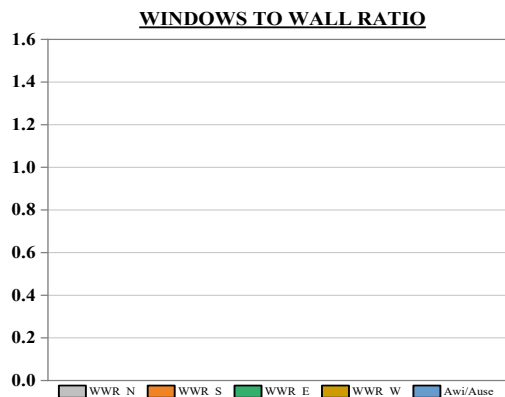
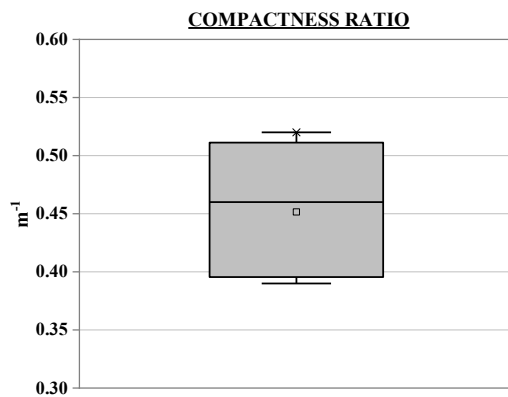
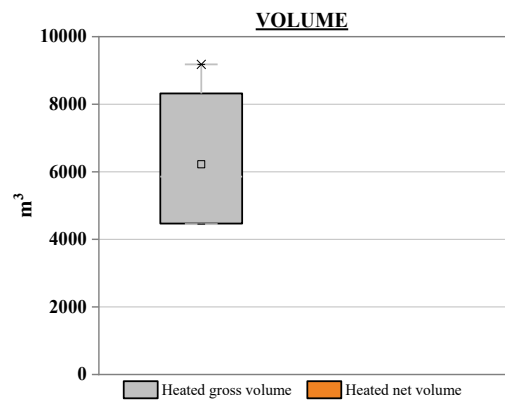
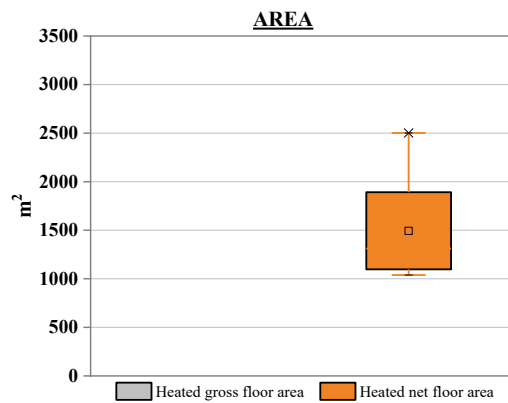
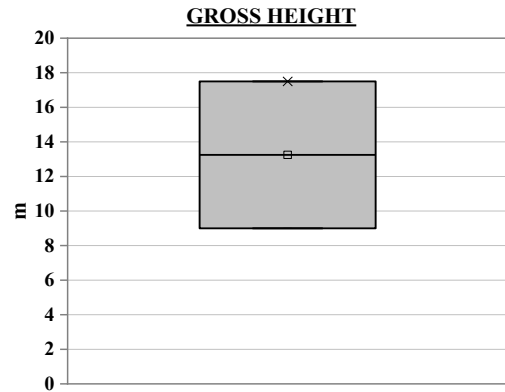
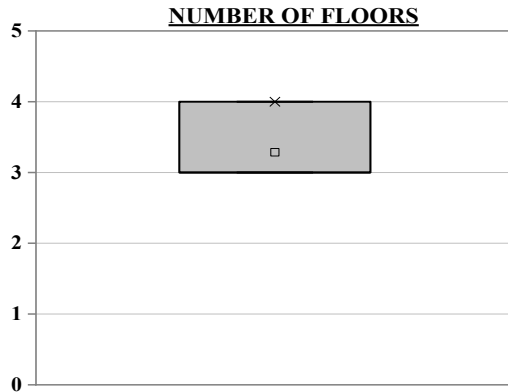
Additional data: other numerical variables that are not included in the archetype



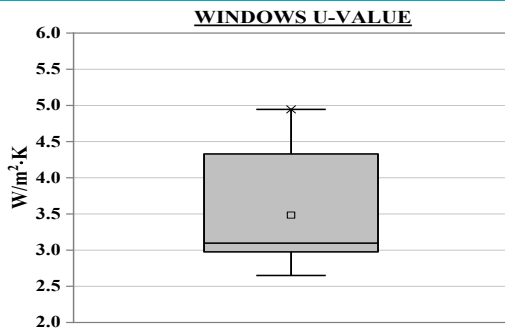
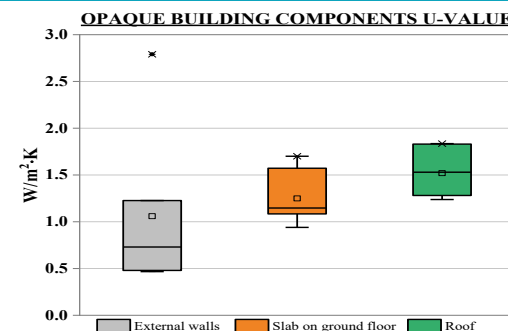
Region:	Piemonte						Archetype code: RES_APPBLOCK_1960-1988_E_PIE	
Building category:	Residential buildings – Apartment blocks							
Period of construction:	1960-1988							
Climatic zone:	E	Number of records:				7		
Description (the codes associated with walls and slabs refer to the structures described in UNI/TR 11552:2014): External walls: Solid brick masonry with cavity or insulation (cod. MCV03) or Hollow brick masonry (cod. MCV02). Roof slabs: Pitched wooden roof with insulation (cod. CIN01) or Flat reinforced brick-concrete roof with insulation (cod. COP03).							Data sources: Energy audit: 66%; CENED database (APE): 24%; Municipal database: 10%	
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
BUILDING GEOMETRY	Number of floors	n_f	-	4.00	0.49	3.00	3.00	4.00
	Gross height	H_g	m	13.00	5.66	11.00	13.00	15.00
	Footprint area	$A_{\text{footprint}}$	m ²	729.62	265.31	515.14	694.28	873.75
	Heated gross floor area	$A_{H,g}$	m ²	-	-	-	-	-
	Heated net floor area	$A_{H,n}$	m ²	1493.27	523.20	1193.68	1311.49	1606.96
	Heated gross volume	$V_{H,g}$	m ³	6221.99	1923.03	4552.23	5857.20	7480.78
	Heated net volume	$V_{H,n}$	m ³	-	-	-	-	-
	Compactness ratio	$A_{\text{env}}/V_{H,g}$	m ⁻¹	0.45	0.06	0.40	0.46	0.50
	WWR – North orientation	WWR_N	-	-	-	-	-	-
	WWR – South orientation	WWR_S	-	-	-	-	-	-
	WWR – East orientation	WWR_E	-	-	-	-	-	-
	WWR – West orientation	WWR_W	-	-	-	-	-	-
	Window to useful floor area ratio	A_{wi}/A_{use}	-	-	-	-	-	-
ENVELOPE	Roof type ***	Reinforced brick-concrete slab: 57%; Brick-concrete slab: 29%; Unknown: 14%						
	U-value of the roof **	$U_{fi,up}$	W/(m ² ·K)	1.52	0,24	1.34	1.53	1.68
	External walls type	Hollow brick masonry, medium insulation: 43%; Hollow brick masonry, low insulation: 29%; Solid brick masonry: 14%; Unknown: 14%						
	U-value of the wall	U_{wl}	W/(m ² ·K)	1.06	0.83	0.49	0.73	1.23
	Slab on ground floor type	Reinforced brick-concrete slab: 72%; Brick-concrete slab: 14%; Unknown: 14%						
	U-value of the floor **	$U_{fi,lw}$	W/(m ² ·K)	1.25	0.28	1.12	1.15	1.37
	Windows type	Double glazing, aluminum frame with thermal break: 71%; Double glazing, aluminum frame, no thermal break: 29%						
	U-value of the windows	U_W	W/(m ² ·K)	3.48	0.84	2.98	3.10	3.87
	Shading system type	Shutter: 50%; Roller blinds: 13%; Curtains: 13%; Unknown: 24%						
GAINS and VENTILATION	Occupancy density *	O_C	person/m ²	UNI EN 16798-1 - Table A.19				
	Lighting power density *	W_L	W/m ²	UNI EN 16798-1 - A.8.3				
	Equipment power density *	W_A	W/m ²	UNI EN 16798-1 - A.8.3				
	Type of ventilation	Natural: 76%; Mechanical: 24%						
	Air exchange rate *	n	h ⁻¹	-	-	--	-	-
THERMAL SYSTEMS	Heating system type	Centralized: 100%						
	Heating generator	Condensing boiler: 76%; Traditional boiler: 29%						
	Daily operating time of the heating system *	t_H	h	14	0	14	14	14
	Energy carrier	Natural gas: 100%						
	Heating emission sub-system	Radiators: 88%; Fan coil: 12%						
	Cooling system type	Air-cooled chiller: 43%; Water-cooled chiller: 29%; Absent: 28%						
	Daily operating time of the cooling system *	t_C	h	-	-	-	-	-
	Cooling emission sub-system	Multisplit: 57%; Fan coil: 15%; Absent: 28%						
	DHW system type	Centralized, coupled with heating: 100%						
	DHW generator	Natural gas boiler: 100%						
	*These values are derived from UNI EN ISO standards; ** U-values of the upper and lower slabs face unconditioned spaces (i.e., attic, basement, etc.); ***Roof type in the envelopes refers to the slab towards unconditioned space (i.e., attic)							

Region:	Piemonte	Archetype code: RES_APPBLOCK_1960- 1988_E_PIE
Building category:	Residential buildings – Apartment blocks	
Period of construction:	1960-1988	
Climatic zone:	E	
Number of records:		7

Numerical variables – GEOMETRY

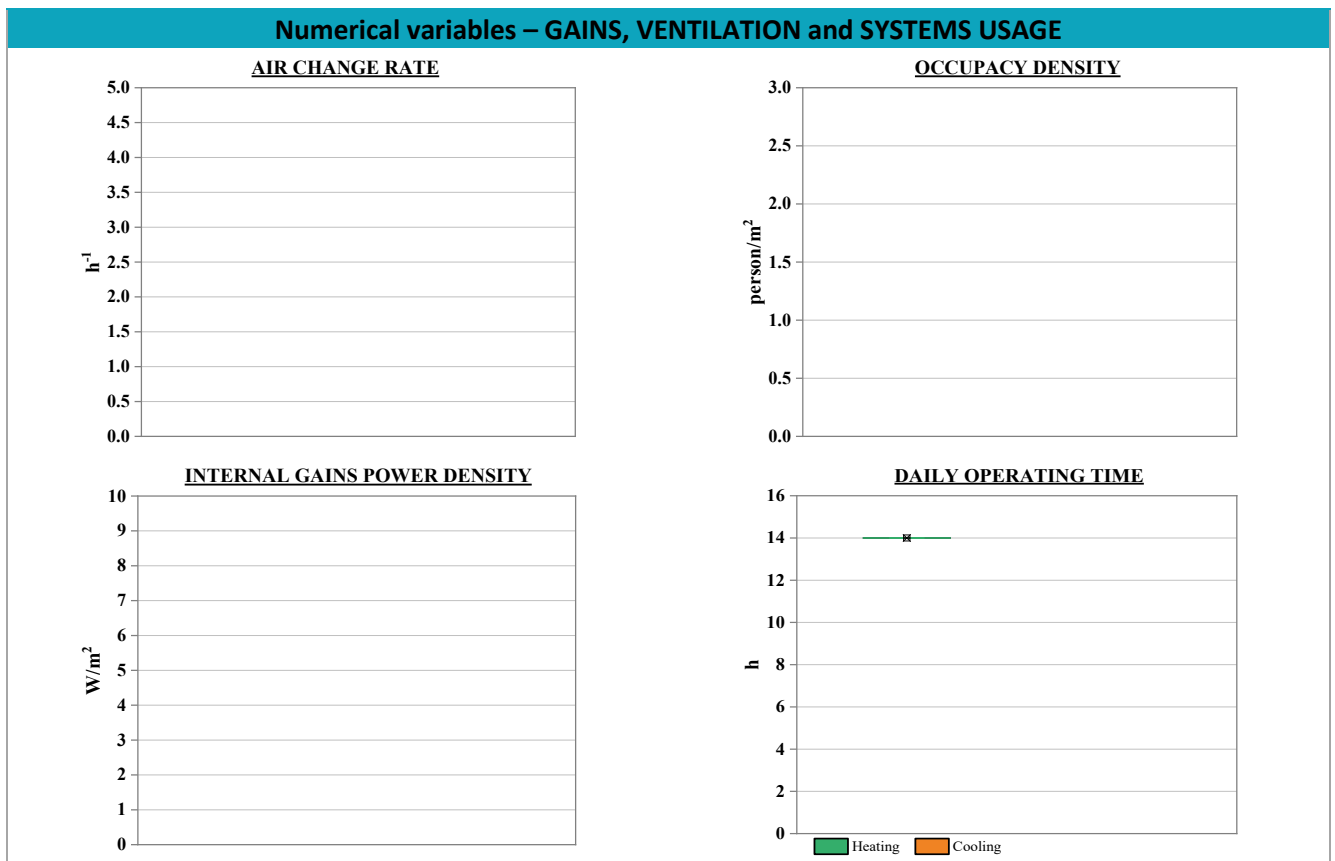


Numerical variables – ENVELOPE



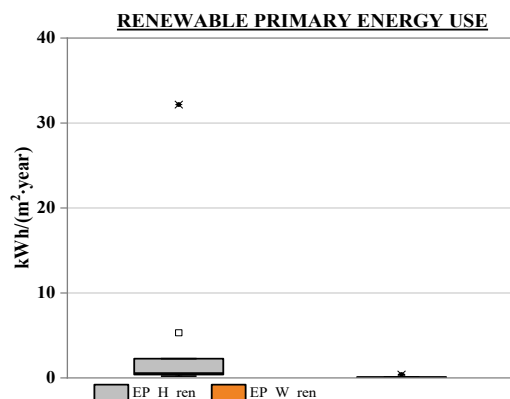
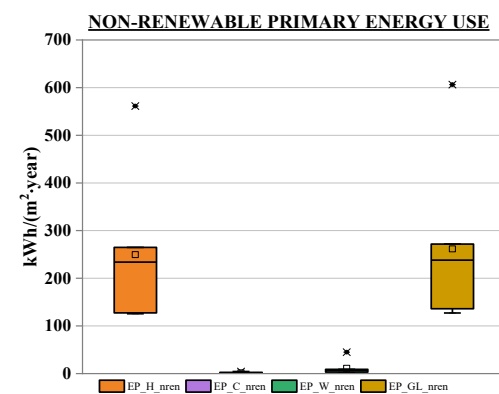
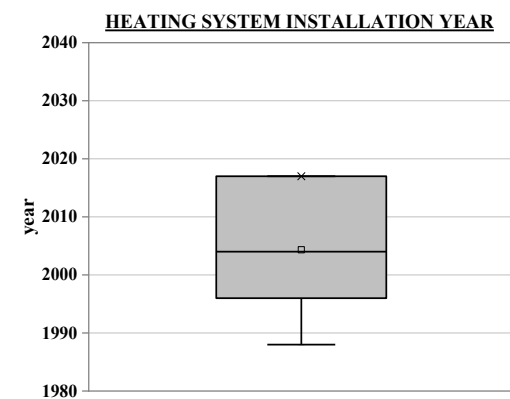
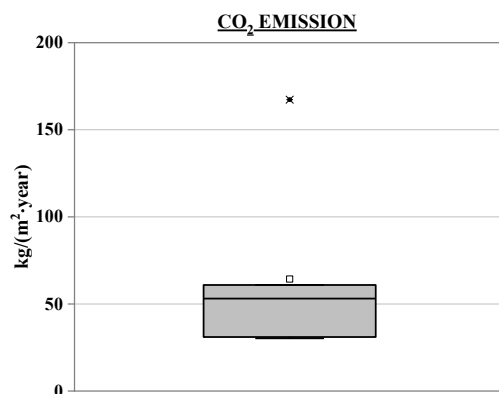
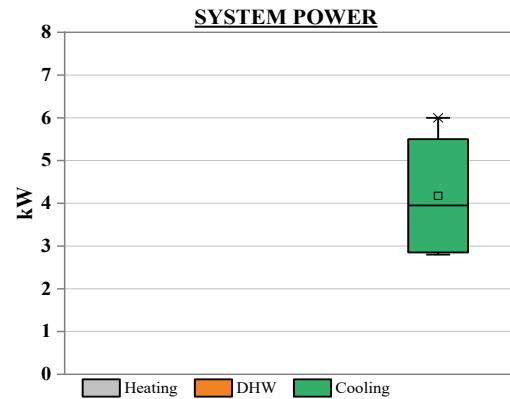
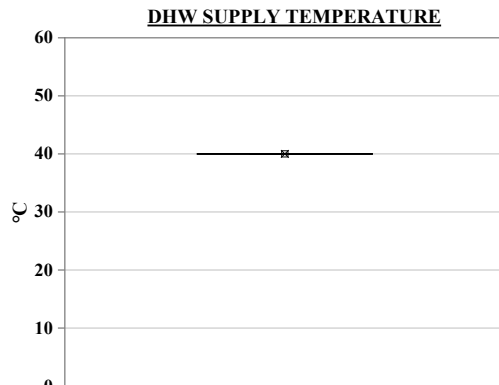
Region:	Piemonte	Archetype code: RES_APPBLOCK_1960- 1988_E_PIE
Building category:	Residential buildings – Apartment blocks	
Period of construction:	1960-1988	
Climatic zone:	E	
Number of records:		7

ADDITIONAL DATA								
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
THERMAL SYSTEMS	Heating efficiency or <i>COP</i>	$\eta_{H,gen}$ or $COP_{H,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total heating power	$P_{H,gen}$	kW	-	-	-	-	-
	Cooling efficiency or <i>EER</i>	$\eta_{C,gen}$ or $EER_{C,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total cooling power	$P_{C,gen}$	kW	3.38	1.08	2.80	2.85	3.43
	Temperature of DHW	θ_w	°C	40.0	0.0	40.0	40.0	40.0
	DHW system power	$P_{W,gen}$	kW	-	-	-	-	-
* This value refers to the building scale. Distinction between apartment and building scale is only necessary in the “Residential” category.								



Region:	Piemonte	Archetype code: RES_APPBLOCK_1960- 1988_E_PIE
Building category:	Residential buildings – Apartment blocks	
Period of construction:	1960-1988	
Climatic zone:	E	
Number of records:		7

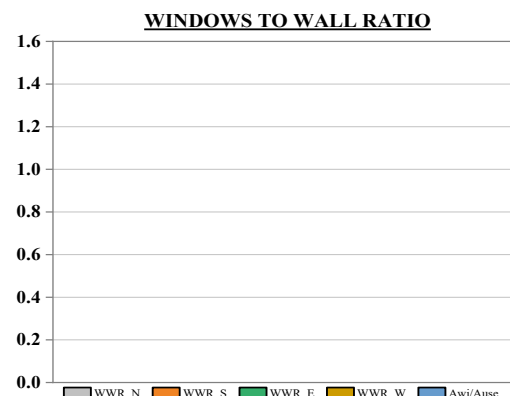
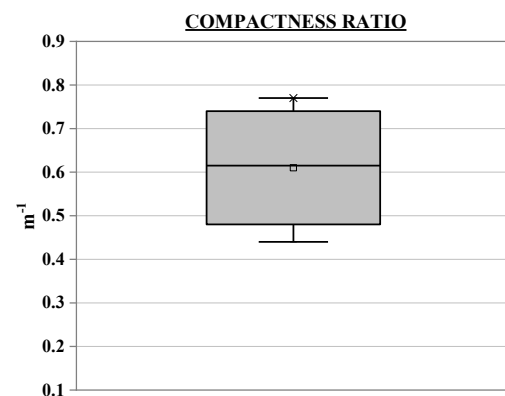
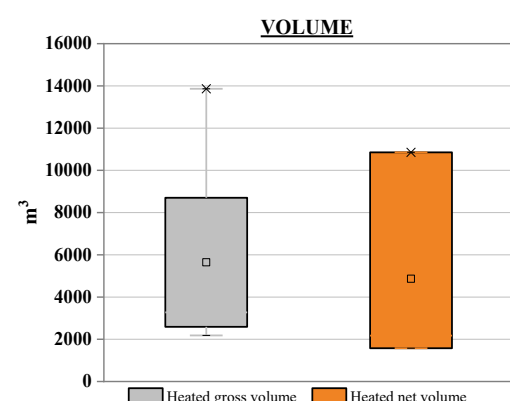
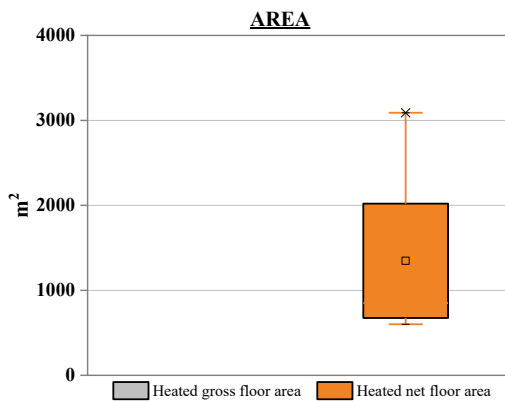
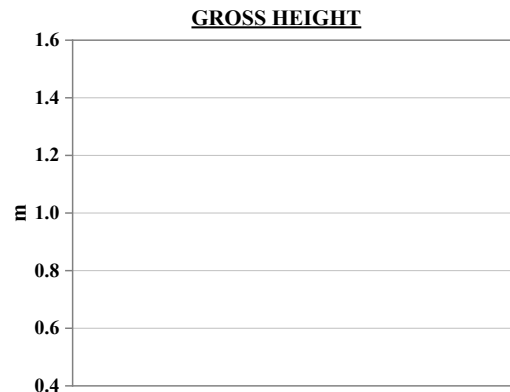
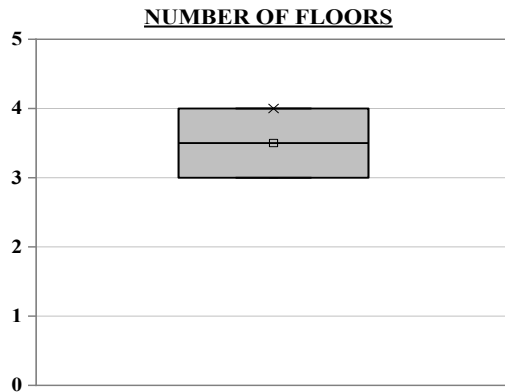
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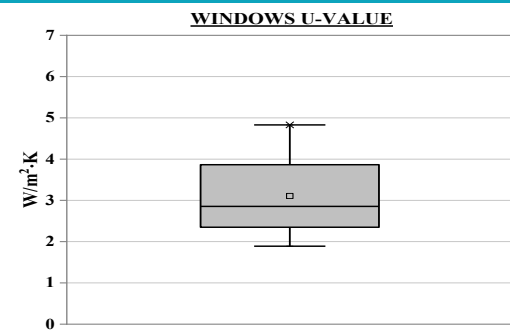
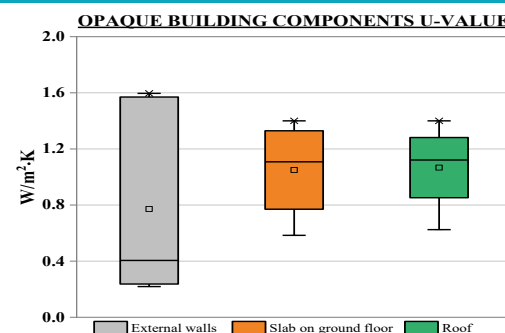
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Building category:	Residential buildings – Apartment blocks							
Period of construction:	> 1995							
Climatic zone:	E	Number of records:		4				
Description (the codes associated with walls and slabs refer to the structures described in UNI/TR 11552:2014): External walls: Hollow brick masonry with air gap (cod. MCV01). Roof slabs: Pitched reinforced brick-concrete roof with insulation (cod. CIN03) or Flat reinforced brick-concrete roof with insulation (cod. COP03).							Data sources: Energy audit: 68%; CENED database (APE): 29%; Municipal database: 3%	
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
BUILDING GEOMETRY	Number of floors	n_f	-	4.00	0.58	3.00	4.00	4.00
	Gross height	H_g	m	-	-	-	-	-
	Footprint area	$A_{\text{footprint}}$	m ²	1207.46	718.65	901.19	1386.00	1603.00
	Heated gross floor area	$A_{H,g}$	m ²	-	-	-	-	-
	Heated net floor area	$A_{H;n}$	m ²	1347.62	1170.27	711.90	850.05	1485.76
	Heated gross volume	$V_{H,g}$	m ³	5646.23	5505.28	2795.69	3271.31	6121.85
	Heated net volume	$V_{H;n}$	m ³	4866.36	5191.95	1873.74	2172.07	6511.84
	Compactness ratio	$A_{\text{env}}/V_{H,g}$	m ⁻¹	0.61	0.16	0.50	0.62	0.73
	WWR – North orientation	WWR_N	-	-	-	-	-	-
	WWR – South orientation	WWR_S	-	-	-	-	-	-
	WWR – East orientation	WWR_E	-	-	-	-	-	-
	WWR – West orientation	WWR_W	-	-	-	-	-	-
	Window to useful floor area ratio	A_{wi}/A_{use}	-	-	-	-	-	-
ENVELOPE	Roof type ***	Reinforced brick-concrete slab: 50%; Brick-concrete slab: 25%; Unknown: 25%						
	U-value of the roof **	$U_{fi,up}$	W/(m ² ·K)	1.07	0.32	0.97	1.12	1.22
	External walls type	Hollow brick masonry, high insulation: 40%; Hollow brick masonry: 20%; Concrete wall: 20%; Unknown: 20%						
	U-value of the wall	U_{wl}	W/(m ² ·K)	0.77	0.63	0.26	0.41	1.33
	Slab on ground floor type	Reinforced brick-concrete slab: 25%; Brick-concrete slab: 25%; Concrete floor: 25%; Unknown: 25%						
	U-value of the floor **	$U_{fi,lw}$	W/(m ² ·K)	1.05	0.36	0.86	1.11	1.29
	Windows type	Double glazing, aluminum frame with thermal break: 75%; Unknown: 25%						
	U-value of the windows	U_W	W/(m ² ·K)	3.11	1.24	2.58	2.85	3.38
GAINS and VENTILATION	Shading system type	Shutter: 50%; Curtains: 34%; Unknown: 16%						
	Occupancy density *	O_C	person/m ²	UNI EN 16798-1 - Table A.19				
	Lighting power density *	W_L	W/m ²	UNI EN 16798-1 - A.8.3				
	Equipment power density *	W_A	W/m ²	UNI EN 16798-1 - A.8.3				
	Type of ventilation	Natural: 100%						
THERMAL SYSTEMS	Air exchange rate *	n	h ⁻¹	-	-	--	-	-
	Heating system type	Centralized: 50%; Autonomous: 50%						
	Heating generator	Condensing boiler: 40%; Boiler (unknown type): 40%; Air-sourced heat pump: 20%						
	Daily operating time of the heating system *	t_H	h	14	0	14	14	14
	Energy carrier	Natural gas: 80%; Electricity: 20%						
	Heating emission sub-system	Radiators: 67%; Fan coil: 33%						
	Cooling system type	Absent: 100%						
	Daily operating time of the cooling system *	t_C	h	-	-	-	-	-
	Cooling emission sub-system	Absent: 100%						
	DHW system type	Autonomous, coupled with heating: 75%; Centralized, coupled with heating: 25%						
	DHW generator	Natural gas boiler: 60%; Electric boiler: 40%						
*These values are derived from UNI EN ISO standards; ** U-values of the upper and lower slabs face unconditioned spaces (i.e., attic, basement, etc.); ***Roof type in the envelopes refers to the slab towards unconditioned space (i.e., attic)								

Region:	Piemonte			Archetype code: RES_APPBLOCK_1995- _E_PIE
Building category:	Residential buildings – Apartment blocks			
Period of construction:	> 1995			
Climatic zone:	E	Number of records:	4	

Numerical variables – GEOMETRY



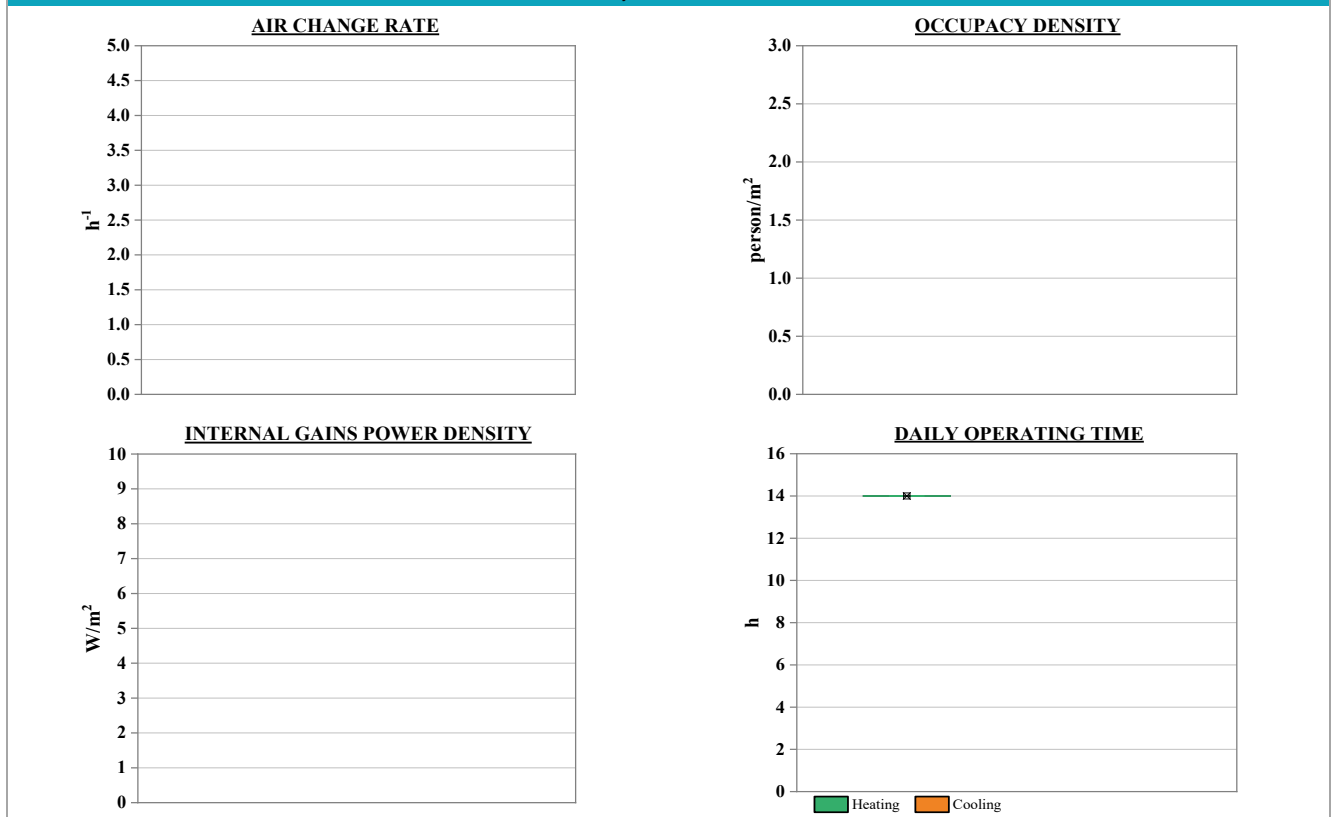
Numerical variables – ENVELOPE



Region:	Piemonte	Archetype code: RES_APPBLOCK_1955- _E_PIE
Building category:	Residential buildings – Apartment blocks	
Period of construction:	> 1995	
Climatic zone:	E	
Number of records:		4

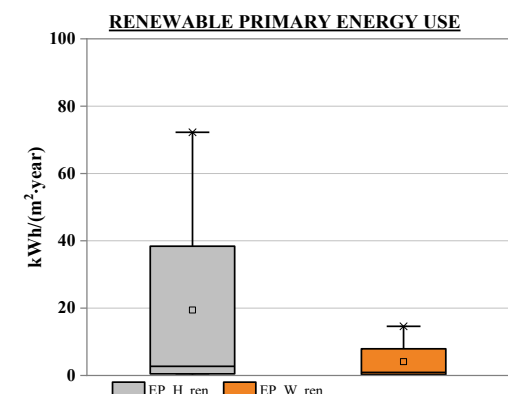
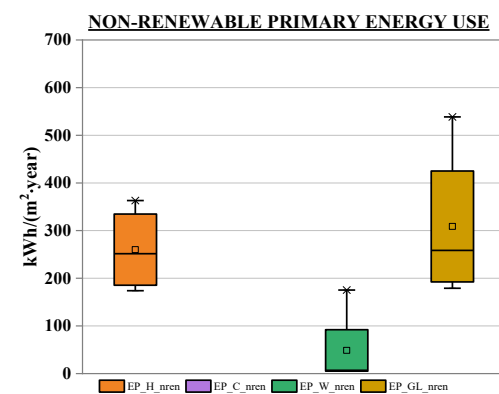
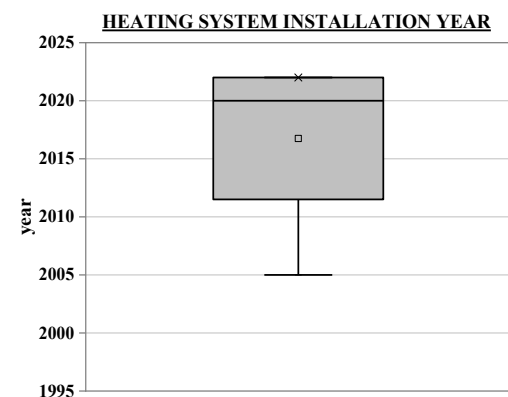
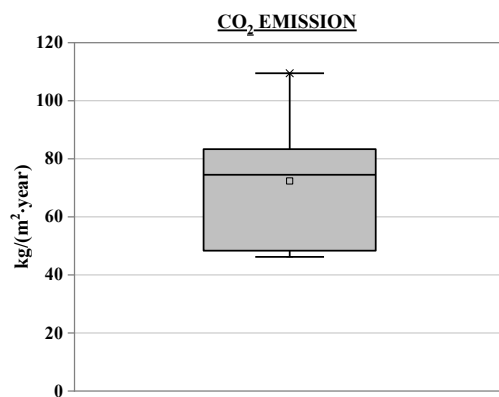
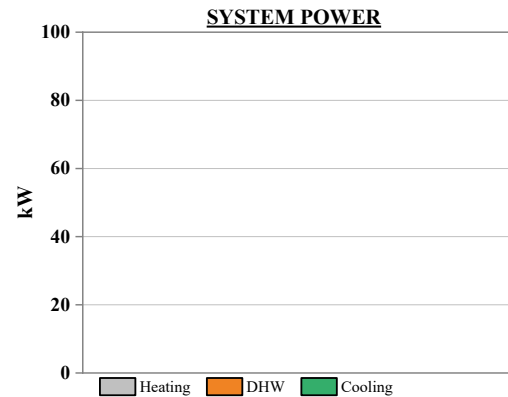
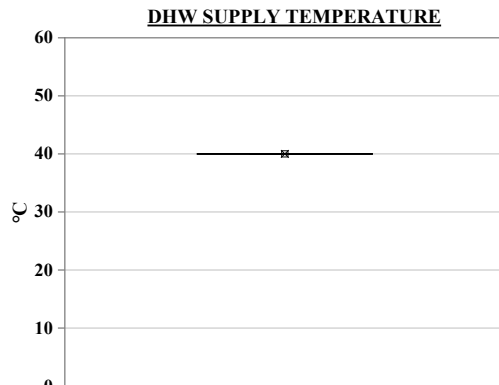
ADDITIONAL DATA								
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
THERMAL SYSTEMS	Heating efficiency or <i>COP</i>	$\eta_{H,gen}$ or $COP_{H,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total heating power	$P_{H,gen}$	kW	-	-	-	-	-
	Cooling efficiency or <i>EER</i>	$\eta_{C,gen}$ or $EER_{C,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total cooling power	$P_{C,gen}$	kW	-	-	-	-	-
	Temperature of DHW	θ_w	°C	40.0	0.0	40.0	40.0	40.0
	DHW system power	$P_{W,gen}$	kW	-	-	-	-	-
* This value refers to the building scale. Distinction between apartment and building scale is only necessary in the “Residential” category.								

Numerical variables – GAINS, VENTILATION and SYSTEMS USAGE



Region:	Piemonte	Archetype code: RES_APPBLOCK_1995- _E_PIE
Building category:	Residential buildings – Apartment blocks	
Period of construction:	> 1995	
Climatic zone:	E	
Number of records:		4

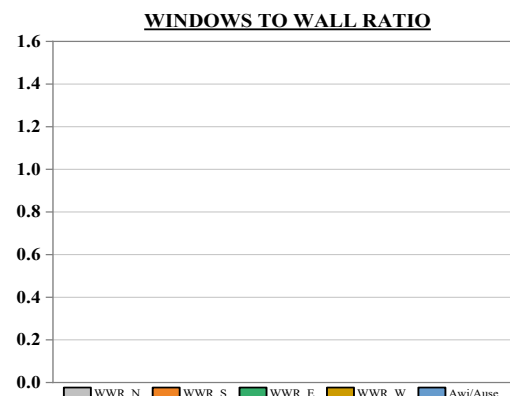
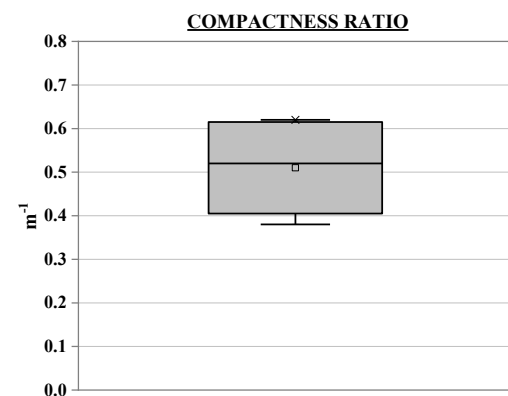
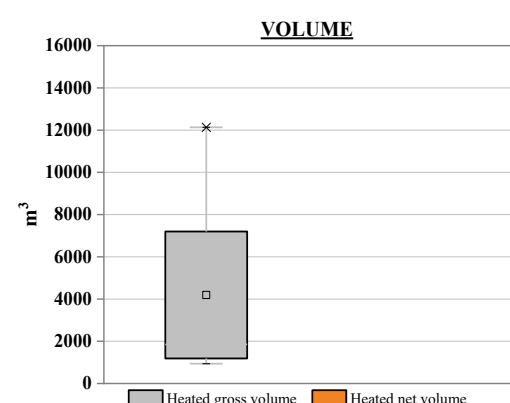
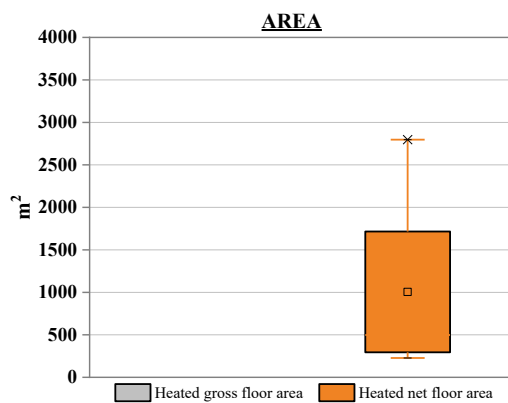
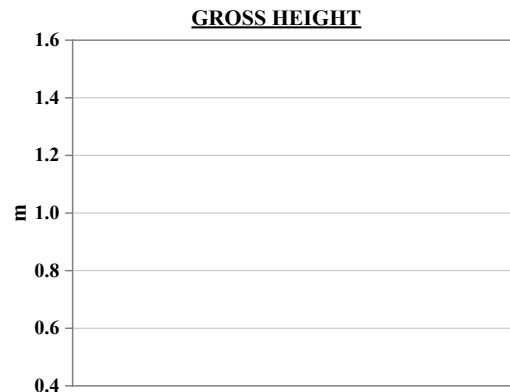
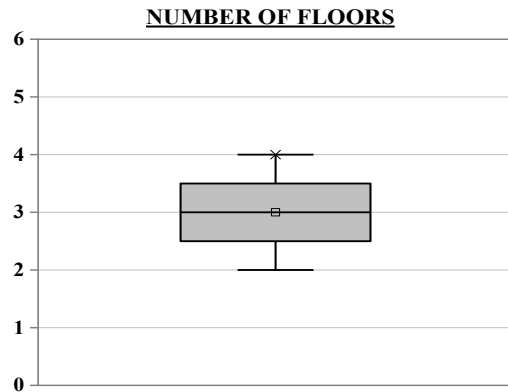
Additional data: other numerical variables that are not included in the archetype



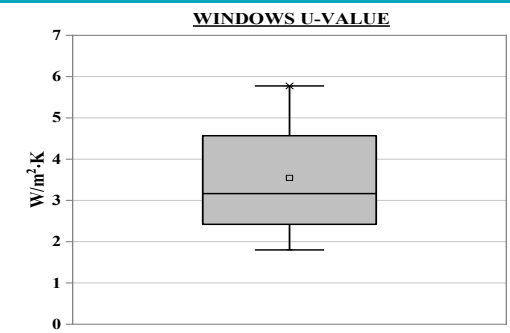
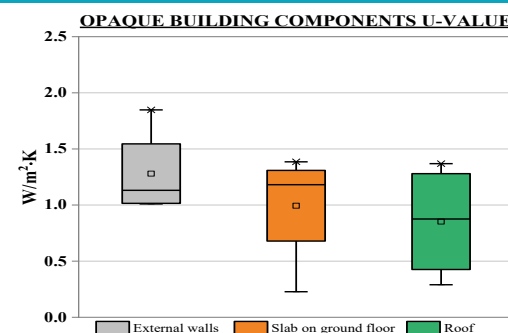
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Building category:	Residential buildings – Entire building							
Period of construction:	1960-1991							
Climatic zone:	F	Number of records:				4		
Description (the codes associated with walls and slabs refer to the structures described in UNI/TR 11552:2014): External walls: Hollow brick masonry (cod. MCV02). Roof slabs: Pitched wooden roof with insulation (cod. CIN01) or Flat reinforced brick-concrete roof with insulation (cod. COP03).							Data sources: Energy audit: 66%; CENED database (APE): 24%; Municipal database: 10%	
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
BUILDING GEOMETRY	Number of floors	n_f	-	3.00	0.82	3.00	3.00	4.00
	Gross height	H_g	m	-	-	-	-	-
	Footprint area	$A_{\text{footprint}}$	m ²	338.95	232.09	193.44	242.81	388.32
	Heated gross floor area	$A_{H,g}$	m ²	-	-	-	-	-
	Heated net floor area	$A_{H;n}$	m ²	1005.04	1206.56	327.93	498.01	1175.12
	Heated gross volume	$V_{H,g}$	m ³	4193.11	5322.66	1313.57	1851.21	4730.75
	Heated net volume	$V_{H;n}$	m ³	-	-	-	-	-
	Compactness ratio	$A_{\text{env}}/V_{H,g}$	m ⁻¹	0.51	0.12	0.42	0.52	0.61
	WWR – North orientation	WWR_N	-	-	-	-	-	-
	WWR – South orientation	WWR_S	-	-	-	-	-	-
	WWR – East orientation	WWR_E	-	-	-	-	-	-
	WWR – West orientation	WWR_W	-	-	-	-	-	-
	Window to useful floor area ratio	A_{wI}/A_{use}	-	-	-	-	-	-
ENVELOPE	Roof type ***	Reinforced brick-concrete slab: 50%; Reinforced brick-concrete slab with medium insulation: 25%; Brick-concrete slab: 25%						
	U-value of the roof **	$U_{fI;up}$	W/(m ² ·K)	0.85	0.51	0.49	0.88	1.23
	External walls type	Hollow brick masonry: 50%; High density stone masonry (dry density from 2000 kg/m ³): 25%; Unknown: 25%						
	U-value of the wall	U_{wI}	W/(m ² ·K)	1.28	0.39	1.02	1.13	1.39
	Slab on ground floor type	Reinforced brick-concrete slab: 25%; Ventilated crawl space: 25%; Brick-concrete slab: 25%; Unknown: 25%						
	U-value of the floor **	$U_{fI;lw}$	W/(m ² ·K)	0.99	0.52	0.90	1.18	1.27
	Windows type	Double glazing, aluminum frame with thermal break: 40%; Double glazing, wooden frame: 20%; Single glazing, wooden frame: 20%; Other: 20%						
	U-value of the windows	U_W	W/(m ² ·K)	3.55	1.62	2.42	3.17	4.57
	Shading system type	Shutter: 50%; Curtains: 25%; No shading: 25%						
GAINS and VENTILATION	Occupancy density *	O_C	person/m ²	UNI EN 16798-1 - Table A.19				
	Lighting power density *	W_L	W/m ²	UNI EN 16798-1 - A.8.3				
	Equipment power density *	W_A	W/m ²	UNI EN 16798-1 - A.8.3				
	Type of ventilation	Natural: 100%						
	Air exchange rate *	n	h ⁻¹	-	-	--	-	-
THERMAL SYSTEMS	Heating system type	Centralized: 75%; Autonomous: 25%						
	Heating generator	Traditional boiler: 50%; Condensing boiler: 25%; Heat exchanger of district heating: 25%						
	Daily operating time of the heating system *	t_H	h	14	0	14	14	14
	Energy carrier	Natural gas: 50%; District heating: 25%; LPG: 25%						
	Heating emission sub-system	Radiators: 71%; Fan coil: 29%						
	Cooling system type	Absent: 100%						
	Daily operating time of the cooling system *	t_C	h	-	-	-	-	-
	Cooling emission sub-system	Absent: 100%						
	DHW system type	Autonomous, detached with heating: 75%; Centralized, coupled with heating: 25%						
	DHW generator	Natural gas boiler: 50%; Electric boiler: 30%; LPG: 20%						
	*These values are derived from UNI EN ISO standards; ** U-values of the upper and lower slabs face unconditioned spaces (i.e., attic, basement, etc.); ***Roof type in the envelopes refers to the slab towards unconditioned space (i.e., attic)							

Region:	Piemonte	Archetype code: RES_BLDGS_1960- 1991_F_PIE
Building category:	Residential buildings – Entire building	
Period of construction:	1960-1991	
Climatic zone:	F	
Number of records:		4

Numerical variables – GEOMETRY



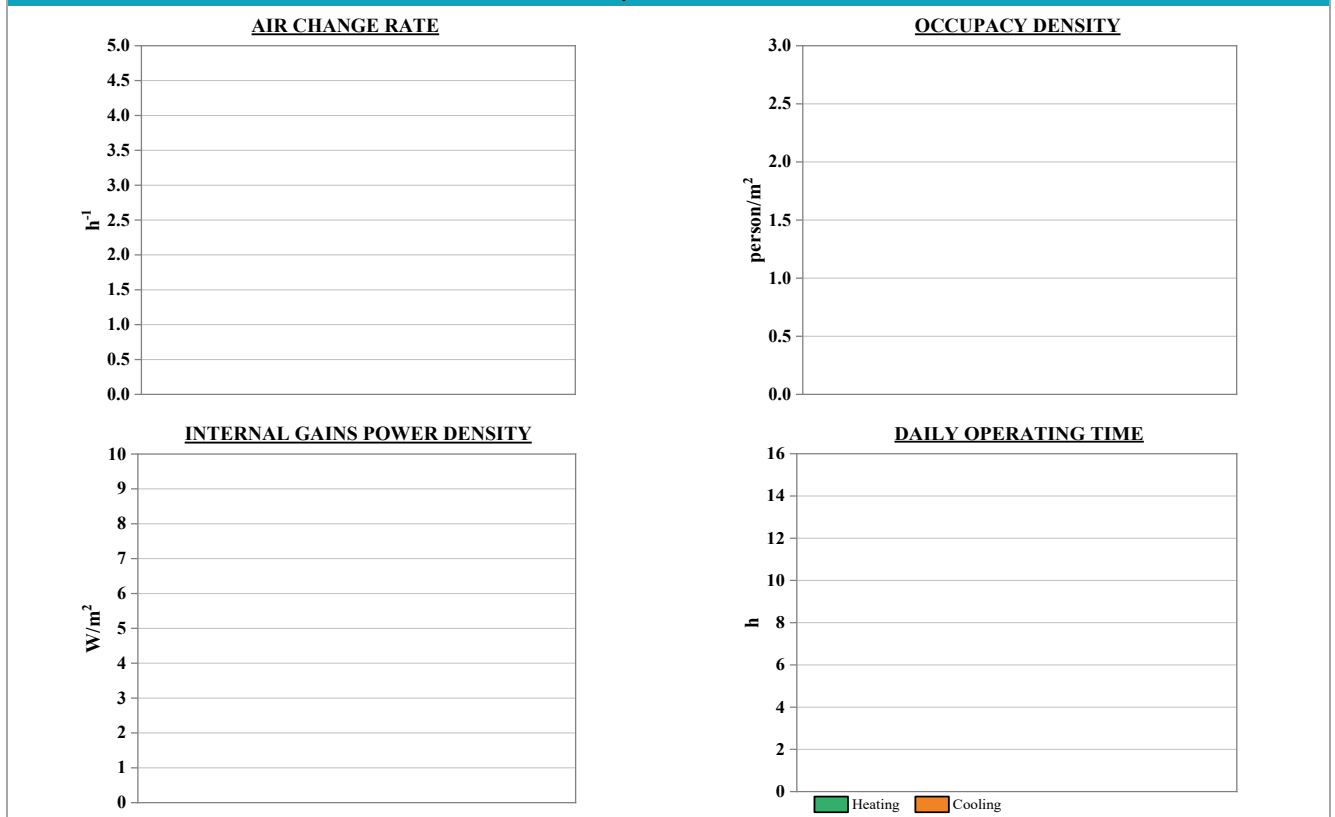
Numerical variables – ENVELOPE



Region:	Piemonte	Archetype code: RES_BLDGS_1960- 1991_F_PIE
Building category:	Residential buildings – Entire building	
Period of construction:	1960-1991	
Climatic zone:	F	
Number of records:		4

ADDITIONAL DATA								
	Data	Symbol	Unit of measure	Mean value	Standard deviation	Q1 (first quartile)	Median value	Q3 (third quartile)
THERMAL SYSTEMS	Heating efficiency or <i>COP</i>	$\eta_{H,gen}$ or $COP_{H,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total heating power	$P_{H,gen}$	kW	-	-	-	-	-
	Cooling efficiency or <i>EER</i>	$\eta_{C,gen}$ or $EER_{C,gen}$	-	This value has to be retrieved from suitable datasheets				
	Total cooling power	$P_{C,gen}$	kW	-	-	-	-	-
	Temperature of DHW	θ_w	°C	40.0	0.0	40.0	40.0	40.0
	DHW system power	$P_{W,gen}$	kW	-	-	-	-	-
* This value refers to the building scale. Distinction between apartment and building scale is only necessary in the “Residential” category.								

Numerical variables – GAINS, VENTILATION and SYSTEMS USAGE



Region:	Piemonte	Archetype code: RES_BLDGS_1960- 1991_F_PIE
Building category:	Residential buildings – Entire building	
Period of construction:	1960-1991	
Climatic zone:	F	
Number of records:		4

Additional data: other numerical variables that are not included in the archetype

