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Variability in Heating Demand Predictions: A Comparative Study of PHPP and Mc001-2022 in Existing Residential Buildings

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Abstract: The construction industry is a key driver of environmental change due to its extensive use of resources and high emissions, thus significantly burdening global efforts towards sustainable development targets. A large portion of the environmental footprint of buildings results from the energy required to sustain indoor comfort levels. Thus, enhancing the energy efficiency of existing buildings becomes critical in reducing their environmental impact. This study explores the impact of thermal performance improvements on the heating demand, employing numerical modeling and two energy performance methodologies, PHPP and Mc001-2022, across various climatic datasets and case studies in Romania. The results show substantial variability in heating demand predictions: Mc001-2022 predicts up to 27.2% higher continuous heating demands and 21.0% higher intermittent demands compared to PHPP in one case study. In the second case study, the differences range from 8.1% higher to 6.9% lower for continuous heating and from 3.3% higher to 9.9% lower for intermittent heating, depending on the scenario. These findings underscore the importance of the methodological choice and localized climatic data in heating demand assessments, highlighting the need for a tailored, context-specific approach to energy performance assessment, integrating multiple energy efficiency measures suited to the unique characteristics of each building.

Keywords: thermal performance; heating demand; building modeling; Passive House Planning Package (PHPP); Methodology for Calculating Heating Demand (Mc001); comparative study

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1. Introduction

1.1. Context of Building Energy Performance

The negative impact of global human activity on the natural environment is well documented and continues to escalate. The relentless consumption of nonrenewable resources, coupled with emissions to air, water, and soil, places significant pressure on the Earth’s ecosystems and jeopardizes the prospects for sustainable development for future generations. Paradoxically, despite a marked increase in awareness regarding the necessity of integrating sustainability principles into all economic activities, the overall environmental burden has continued to grow [1,2]. Despite increased societal awareness and efforts, this trend underscores the complexity and challenges in achieving meaningful environmental progress.

One of the most significant negative impacts on the future development of humankind is the current rate of natural resource consumption. The global consumption rates exceed the Earth’s capacity to renew its raw material stocks by 70% [3,4]. Another critical environmental issue is the extent to which our daily activities influence the global temperature value. Currently, global warming is considered the foremost and most pressing issue concerning the environmental dimension of sustainable development. According to the Intergovernmental Panel on Climate Change (IPCC), in its Sixth Assessment Report, the global surface temperature in 2020 was 1.1 °C higher than preindustrial levels [5]. According to the IPCC report, the average annual greenhouse gas (GHG) emissions recorded between 2010 and 2019 surpassed those of previous decades. However, the growth rate of these emissions in the last decade was 1.3% per year, which is lower than the 2.1% per year recorded during 2000–2009.

Despite increased awareness of the adverse effects of GHGs on global warming in recent years, specific economic sectors continue to struggle in identifying and implementing practical solutions to enhance their environmental performance. In the European Union (EU), energy production and consumption account for approximately 75% of the total GHG emissions. Within this context, the construction sector is responsible for nearly 40% of the EU's total energy consumption [6–12]. Additionally, an analysis of sector-specific activities reveals that the built environment contributes to 36% of the EU's GHG emissions [10,11,13,14]. Given these statistics, the construction industry is rightly identified as a critical sector in mitigating the overall negative environmental impacts at the EU level. This sector plays a significant role in achieving the EU's declared objective of becoming climate-neutral by 2050 [6,7].

To achieve the objectives of the Green Deal, the European Union's strategic framework for the significant reduction of the adverse global effects of climate change, it is essential to fully understand the impact of existing and future building stocks on GHG emissions. In Europe, the built-up area is estimated to encompass approximately 25 billion square meters, with about 10 billion square meters completed before 1960 and over 15 billion square meters by 1990. Further analysis indicates that eight out of ten European buildings were constructed before 1990 [15]. Considering the energy efficiency standards mandated by current building codes, 75% of the existing built environment is entirely energy-inefficient [14,15]. Additionally, since design and execution standards enforcing energy efficiency were adopted post-1970, it can be concluded that infrastructure built before this period fails to meet the expected minimum energy performance levels [15]. An evaluation of the standardized usage durations of buildings reveals that approximately 85% of the current building stock in the European Union, representing about 220 million units, was constructed before 2001. Despite advanced physical wear as per current technical regulations, almost the entire existing stock is projected to still be in use by 2050 [12].

In addition to the high energy consumption encountered in buildings, which partially originates from the extraction and manufacture of construction materials, buildings consume significant amounts of energy during their operational phase for heating, cooling, domestic hot water production, mechanical ventilation and artificial lighting. This operational energy consumption is driven by standards that ensure residents' comfort and health safety conditions. In 2021, 6.9% of the EU population faced significant challenges in maintaining adequate indoor temperatures during the cold season due to high energy costs [16]. Therefore, beyond the fact that high energy consumption in buildings generates GHG emissions, contributing to global climate change, it also becomes increasingly expensive for occupants. Consequently, measures to renovate the existing building stock are essential. Currently, the renovation rate of the existing building stock across EU member states ranges between 0.4% and 1.2% per year [7]. However, the rate of deep energy renovations—capable of reducing energy consumption by more than 60%—is only 0.2%, with areas lacking any renovated buildings [13]. Furthermore, 75% of existing buildings have extremely inefficient thermal envelopes, placing significant pressure on energy consumption and increasing GHG emissions [13,15].

Therefore, the construction sector plays an essential role in the European Commission's roadmaps to achieve a climate-neutral continent by 2050 [7,13,17]. A vital objective to be met by 2030 is the reduction of greenhouse gas emissions by 55%, a goal that is achievable if the energy consumption for heating and cooling in the residential building sector is reduced by 18% [13,17]. Given that European households consume 64.4% of their energy for space heating [18], it is imperative for professionals in building energetics to develop and implement advanced solutions to significantly enhance the energy performance of built infrastructure [19–22].

Achieving these ambitious goals requires not only the deployment of innovative technologies and materials but also the refinement of the methodologies used to evaluate and predict building energy performance. The accuracy of thermal performance calculations is crucial in guiding effective energy efficiency measures, particularly for space heating, which constitutes the largest share of energy consumption in residential buildings. Therefore, understanding and addressing the scientific challenges involved in predicting the heating demand is key to ensuring that energy savings targets are met. This leads to the core of our study, which focuses on a comparison of the results obtained using two methodologies, namely the Passive House Planning Package (PHPP) [23] and the Methodology for Calculating the Energy Performance of Buildings (Mc001-2022) [24], to calculate the heating demand in buildings.

1.2. Heating Demand Calculation Approaches: ISO 52016 vs. PHPP

Calculating the heating demand, also known as the energy demand for heating, is a critical aspect of energy-efficient building design, influencing both the operational energy consumption and the overall sustainability of buildings. Two widely recognized methodologies for the calculation of the heating demand are the ISO 52016 standard [25] and the PHPP, a commercial quasi-steady-state calculation tool that was developed by the Passive House Institute [23]. While ISO 52016 provides detailed hourly and monthly calculation methods suitable for dynamic simulations, the PHPP employs steady-state calculations tailored specifically to Passive House standards. This tool follows ISO Standard 13790:2008 and performs monthly calculations of energy losses and gains using distinct fixed set point temperatures for winter and summer energy requirements [26,27].

The ISO 52016-1 standard provides a comprehensive methodology for the calculation of buildings' heating and cooling energy needs. It includes both an hourly calculation method and a monthly calculation method, allowing for detailed dynamic simulations as well as simplified assessments depending on the specific requirements of the analysis. The hourly method, in particular, accounts for the influence of hourly and daily variations in weather, operational schedules, and user interactions, making it suitable for detailed thermal performance evaluations [25,28–30].

The application of ISO 52016-1 in assessing the energy demand for the heating of the building envelope has been found to be efficient in several studies. Dijk [31] and Degerfeld [32] both highlight the advanced and improved hourly method of ISO 52016-1, which is better suited to deal with dynamic effects and provides increased accuracy. The standard's effectiveness is also demonstrated in its application to assess buildings' cost-optimal energy performance levels in Italy [33]. However, some variations have been observed in the heating energy needs calculated by ISO 52016-1 compared to its predecessor, ISO 13790. These variations are mainly attributed to the use of different surface heat transfer coefficients and modeling extra thermal radiation to the sky [34]. Despite these variations, the overall efficiency of ISO 52016-1 in assessing the energy demand for the heating of the building envelope is evident.

The key features of the PHPP include the use of steady-state methods to estimate the energy demand, which focuses on simplicity and reliability for Passive House design. It provides detailed calculations of the heating and cooling demand, as well as other energy performance metrics, ensuring that buildings meet the stringent Passive House criteria. Additionally, the PHPP is designed to be user-friendly, with clear guidelines and comprehensive documentation to support designers in achieving high energy performance standards [35–38].

The accuracy of the PHPP in calculating the energy demand for heating has been explored in several studies. Chen [39] and Siegele [40] found the PHPP to have acceptable precision, with the latter emphasizing the importance of a calibrated temperature for accurate results. Kang [41] further improved the reliability and robustness of the PHPP through a bottom-up approach. Mahboob [42] and Yu [43] demonstrated the tool's effectiveness in assessing the energy-saving potential and comparing the thermal performance. However, Šteffek [44] highlighted the impact of different computational methods on the tool's accuracy, suggesting the need for further research. Mitchell and Natarajan [45] highlighted that normalizing the measured space heating energy data by adjusting for variations in internal and external temperatures enhances the accuracy of comparisons with building models. This normalization can be achieved using the PHPP and the Standard Assessment Procedure (SAP), which is the UK Government's methodology for the measurement of the energy performance of dwellings, without needing site-specific assessments. Similarly, Johnston et al. [46] show that the Passive House (PH) standards reliably achieve the predicted energy savings with minimal performance gaps. This reliability is attributed to stringent quality assurance and strict adherence to design standards, leading to significantly reduced space heating energy consumption compared to conventional buildings.

Comparative studies between ISO 52016 and the PHPP highlight several key differences and similarities, emphasizing their advantages in different contexts. Regarding accuracy in calculations, ISO 52016's hourly method allows for more detailed and dynamic simulations compared to the steady-state approach of the PHPP. This aspect can lead to more accurate energy demand predictions under varying conditions. Nevertheless, regarding usability, the PHPP is often praised for its simplicity and ease of use, making it accessible for designers focused on Passive House standards [39,41]. In contrast, ISO 52016, particularly the hourly method, requires more detailed input data and can be more complex to implement [29].

1.3. The National Methodology for the Calculation of the Energy Performance of Buildings

In light of the recent update to the national methodology for the calculation of the energy performance of buildings, the Mc001-2022 has adopted the monthly calculation approach from ISO 52016. The Mc001-2022 [24] is a comprehensive calculation framework used in Romania to assess the energy performance of buildings. This methodology is detailed in the national regulation and aligns with European directives on energy efficiency [47].

The Mc001-2022 methodology includes several key components and calculation procedures, starting with calculating the thermal transmittance (U-value) of building envelope components, including walls, roofs, floors, windows, and doors. Additionally, thermal bridges are considered, with specific guidelines accounting for linear and point thermal bridges in the overall heat transfer calculations. The energy needs for heating and cooling are determined based on the thermal performance of the building envelope and the efficiency of the heating, ventilation, and air conditioning (HVAC) systems. The methodology uses monthly or hourly climatic data to accurately estimate the heating and cooling demand, considering external temperatures, solar radiation, wind speeds, and other relevant climatic factors. Specific boundary conditions are set for the internal and external temperatures, internal heat gains, and ventilation rates to ensure a standardized approach to calculating energy performance. Although the Mc001-2022 primarily uses a monthly calculation approach, it can incorporate hourly data for more detailed simulations, especially for dynamic thermal performance assessments [24].

Despite the fact that ISO 52016-1 uses detailed climatic data, including hourly variations, to provide an accurate estimation of heating and cooling needs [25], the Mc001-2022 utilizes comparable climatic data but tailors them to Romanian climatic conditions [48], ensuring that the calculations reflect the local environmental factors accurately. ISO 52016-1 is designed for broad application across various climates and building types, whereas the Mc001-2022 explicitly addresses the Romanian context, ensuring compliance with national regulations and standards.

1.4. The Scientific Problem

To explore the thermal performance calculation of buildings, one needs to explore the various methodological approaches and frameworks proposed and tested in the academic literature. These approaches address energy sufficiency and simulation methodologies and deal with challenges such as the energy performance gap, calibration, and modeling complexity, as highlighted by multiple studies.

Considering the discussions among specialists in the field of energy-efficient building design, various perspectives have emerged regarding the most accurate calculation method that closely reflects real-world phenomena when discussing the heating demand of a building. The heating demand is a significant indicator in achieving near-zero energy building (nZEB) levels [47], as it directly influences the overall energy efficiency and sustainability of a building.

In this study, the focus is specifically on calculating the heating demand using distinct methodologies, namely the PHPP and Mc001-2022, which is based on the ISO 52016 standard, to better understand their reliability and applicability to existing residential buildings. This is particularly relevant when considering the broader context of how building energy performance is assessed and modeled in scientific research.

For instance, the work of Mendes et al. [49] provides a comprehensive overview of different thermal performance evaluation methods. They emphasize the importance of model calibration and validation, which aligns closely with our work's focus on accurately predicting the heating demand. By systematically reviewing the methodologies used globally, Mendes et al. underscore the limitations of simulation models if calibration is overlooked. Our study similarly highlights this concern, particularly when comparing the outcomes of the PHPP and Mc001-2022 across various scenarios. It is crucial that methodologies consider standard climatic conditions and the variances introduced by real-world operational factors to minimize discrepancies between the predicted and actual performance.

Similarly, the research conducted by Kramer et al. [50] discusses the challenges of balancing complexity with accuracy in building energy simulations. While our work focuses on specific heating demand prediction, the discussion surrounding simplified models is relevant because it raises questions about the trade-offs between comprehensive, detailed modeling and more streamlined approaches. Simplified models might struggle to capture the full range of variables that influence the heating demand, especially when dealing with the nuances of building envelope performance under different climate conditions. We consider this when discussing the differences between the PHPP and Mc001-2022 models, as each model may capture different aspects of thermal behavior and insulation performance.

Moreover, as discussed in the paper by Oliveira Panão [51], the concept of energy sufficiency ties directly to the minimization of energy use through efficiency measures and control of the overall energy demand. This approach resonates with our study's objective of evaluating heating demand predictions under different insulation and thermal performance scenarios. Although the focus is on the heating demand of buildings, rather than the total energy use, energy sufficiency remains crucial in framing the broader impact of our findings on energy consumption patterns in the residential sector.

Mitchell and Natarajan [52] demonstrate that Passive House buildings, due to their stringent standards, show minimal performance gaps between the predicted and actual space heating demand. This conclusion is particularly noteworthy compared to our study, where we evaluate similar low-energy standards but observe significant variability between predictions from the PHPP and Mc001-2022. The Passive House standard's success in the UK highlights the potential to minimize performance gaps through rigorous design and quality assurance processes, reinforcing the importance of precision in the methodologies that we apply.

Finally, a crucial method to enhance the accuracy of these calculations and improve energy efficiency is the "fabric-first" approach, which prioritizes the thermal performance of the building envelope before considering mechanical systems [53]. This strategy is vital in reducing the heating demand, as it enhances the thermal performance airtightness and minimizes thermal bridging, thereby significantly lowering the heat loss and the overall energy required for space heating. This approach, along with mechanical ventilation and heat recovery, solar thermal collectors, and hot water tanks, is a key strategy in reducing the energy demand in green residential architecture [54].

Building upon the existing body of literature, this paper focuses on a detailed comparison of methodologies, specifically the PHPP [23] and Mc001-2022 [24], as applied to predicting the heat demand in residential buildings undergoing thermal rehabilitation. By examining these methodologies through numerical simulations, the study aims to enhance the understanding of how each method performs in real-world scenarios, rather than addressing a broad research gap. The analysis provides practical insights to improve energy performance assessments in the residential building sector, underscoring the importance of context-specific adjustments in modeling practices. The comparison of the PHPP and Mc001-2022 across various scenarios emphasizes the need for increased accuracy and tailored adjustments, particularly in how the heat demand is calculated for different building types and stages of rehabilitation. Ultimately, the paper seeks to offer actionable guidance to practitioners, aiming to improve the reliability of heat demand predictions and ensure more accurate assessments of the energy efficiency in buildings.

2. Materials and Methods

2.1. Research Framework

A comprehensive framework has been developed to provide a clear understanding of the methodology employed in this study, outlining each step of the research process. This framework, illustrated in Figure 1, guides the reader through the critical stages of the research, from the selection of case study buildings to the conclusions and recommendations. Each step involves critical processes, including assessing thermal rehabilitation measures, detailed thermal bridge analysis, and calculating the heat demand using two distinct methodologies, the PHPP and Mc001/2022. This structured approach ensures a systematic evaluation of building energy performance, allowing for a thorough comparison of the results across different thermal rehabilitation scenarios. The flowchart below summarizes the research framework and the interconnected stages of this analysis.

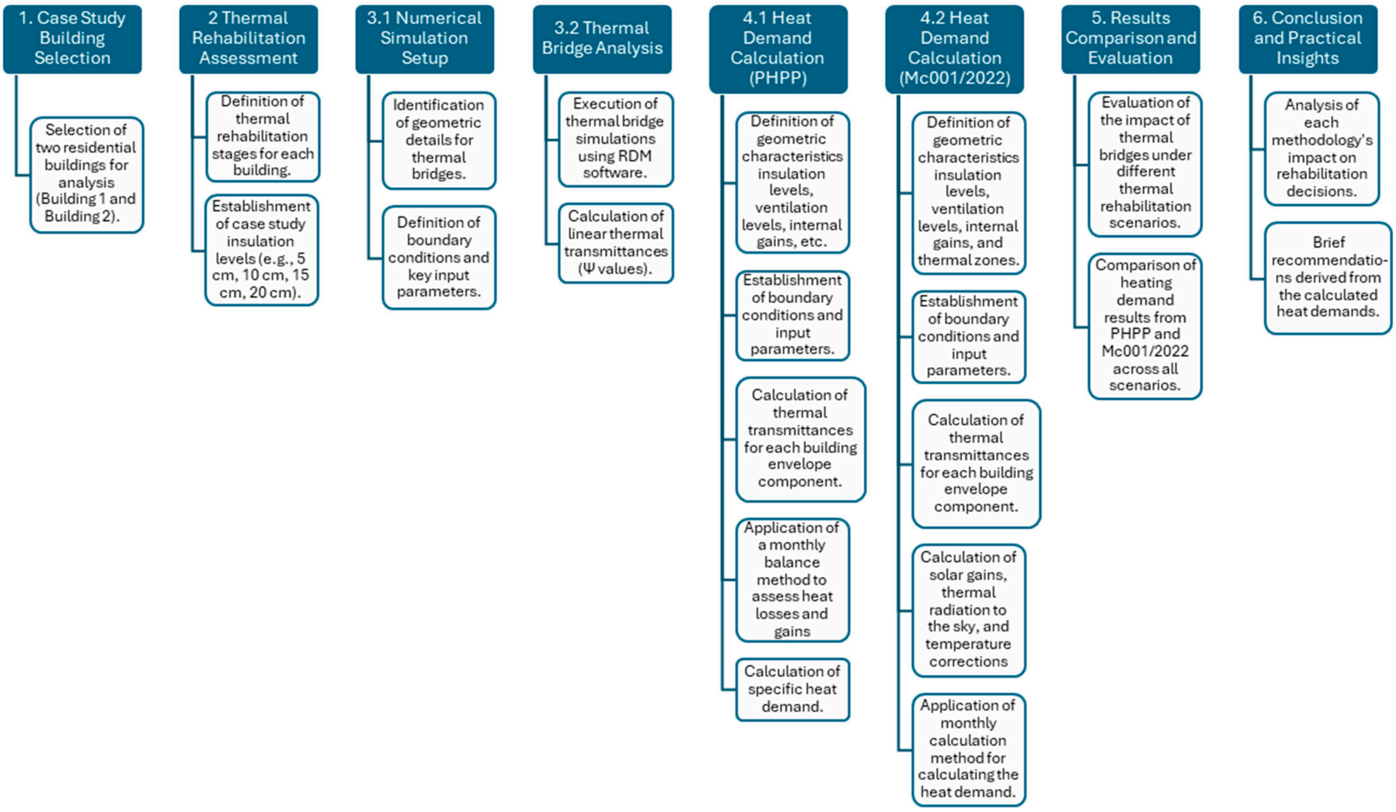
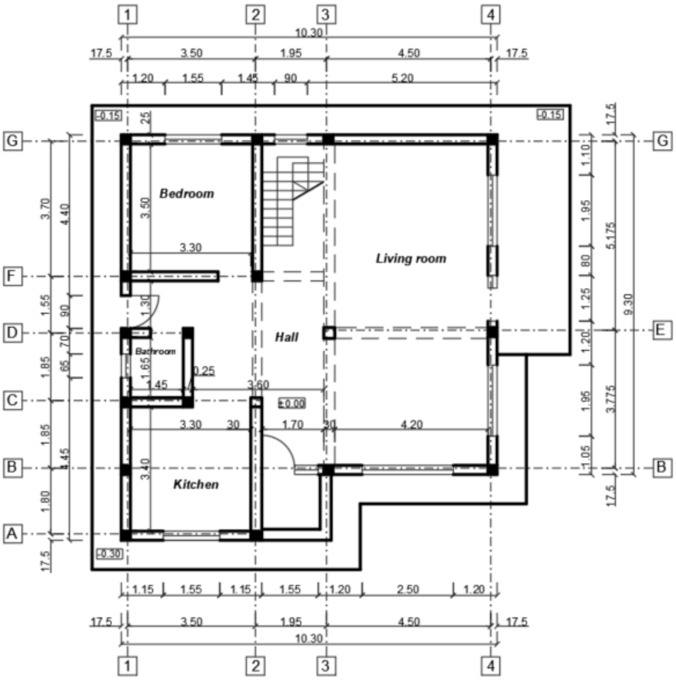


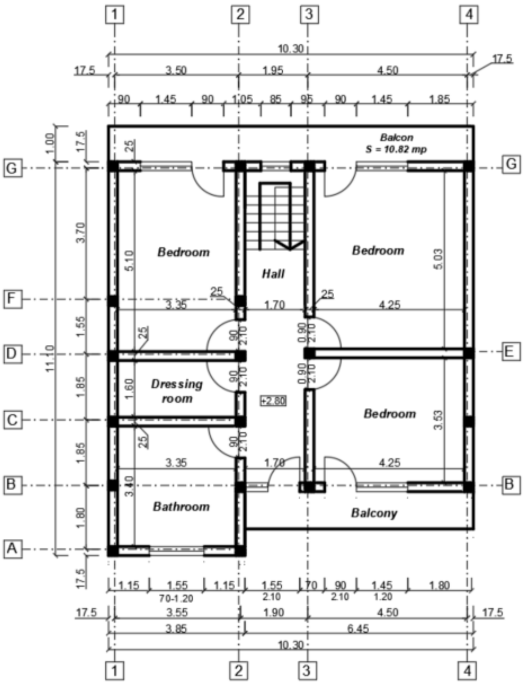
Figure 1. Research flow chart.

2.2. Description of Case Study Buildings

Within the framework of this research study, two residential buildings, each having a height regime of two floors (i.e., a ground floor and a first floor) and built in 2008 in Iași County, Romania, were analyzed (see Figures 2 and 3). The analysis primarily focused on assessing the heat demand of these buildings, considering various stages of thermal rehabilitation to evaluate the impact on their overall thermal performance patterns.

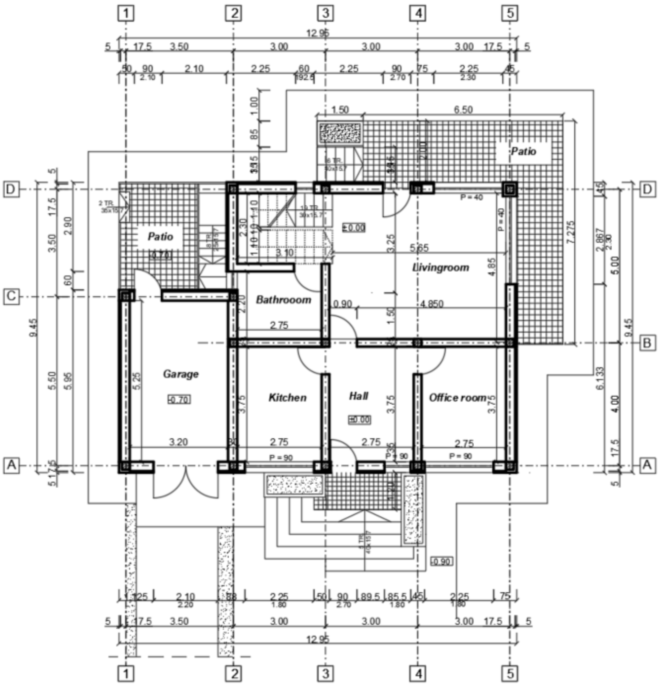


Ground floor plan

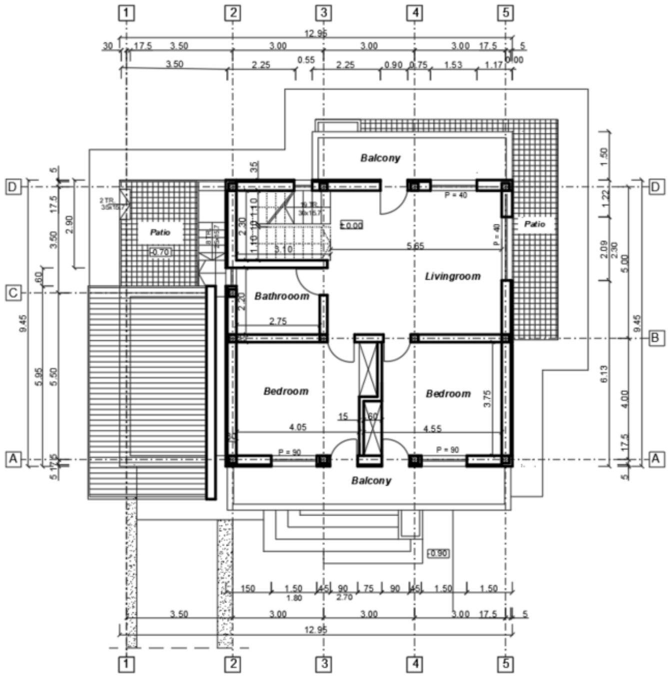


First floor plan

Figure 2. Building layouts—Case Study No. 1.



Ground floor plan



First floor plan

Figure 3. Building layouts—Case Study No. 2.

In order to facilitate the calculation of the heating demand, it is essential to consider the geometrical characteristics of the two buildings under study. Table 1 provides these details, which were used in the computation process. The thermal envelope area (m^2) refers to the total surface area of all building components that separate the conditioned indoor environment from the unconditioned outdoor environment, including walls, roofs, floors, windows, and doors. This metric is crucial in understanding the heat loss or gain through the building envelope. The heated interior volume (m^3) indicates the total volume of the indoor space that is actively heated, which affects the building's heating load and the amount of energy required to maintain a comfortable indoor climate. The heated indoor floor area (m^2) represents the total floor area of all spaces within the building that are actively heated, providing insights into the distribution and effectiveness of the heating system [24,55]. These parameters are essential in assessing the thermal performance of the buildings under study.

Table 1. Geometrical characteristics of the considered building.

Characteristic	Case Study No. 1	Case Study No. 2
Thermal envelope area (m^2)	383.23	447.46
Heated interior volume (m^3)	436.68	393.92
Heated indoor floor area (m^2)	162.97	145.80

The thermal envelopes of the buildings are defined by the following components: the slabs on the ground, the external walls, the roof structure, and the external openings (i.e., windows and doors). The layers defining the opaque construction details and their corresponding thicknesses are provided in Table 2. These data were used to determine the thermal performance of each building envelope component, represented by the thermal transmittance U ($W/(m^2{\cdot}K)$) values for each assessed envelope element.

Table 2. Materials and thicknesses of building envelope components.

Building Envelope Element	Layer (Material)	Case Study No. 1	Case Study No. 2
		Thickness (mm)	Thickness (mm)
Exterior walls	Interior plaster	10	10
	Ceramic bricks	250	300
	Expanded polystyrene	50	100
	Exterior plaster	5	5
Roof	Metal roof tiles	0.6	0.6
	Polypropylene foil	0.4	0.4
	Timber boards	25	25
	Rockwool	150	100
	Plasterboard	12.5	12.5
	Interior plaster	10	10
Slab on ground	Floor tiles	10	10
	Adhesive	5	5
	Reinforced concrete slab	100	100
	Extruded polystyrene	-	100
	Polyethylene foil	0.2	0.2
	Gravel	100	100
	Soil *	7000	7000

* According to the Romanian thermotechnical design norm C107/5-2005, when determining the thermal performance of building envelope components in contact with the ground, two soil layers with a combined thickness of 7 m must be considered to represent the local ground conditions accurately and to determine the overall thermal transfer coefficient of the floor [56]. This requirement is essential to accurately evaluate the thermal transfer between the building and the ground, as the soil layer significantly influences the thermal transfer coefficient and, consequently, the building's energy performance. The properties of the materials considered in the simulations are presented in Table 3.

In the case studies of the numerical simulations of the VTB 4, HTB 5, and HTB 6 thermal bridges, the equivalent thermal conductivity for the window frame and the glazing unit was determined. These values were derived in direct accordance with the solutions implemented in the building and their corresponding thermal transmittance.

Table 3. Thermophysical properties of materials.

Material	**ρ (kg/m^3)**	**λ (W/(m·K))**	**c (J/(kg·K))**
Interior plaster	1700	0.87	840
Ceramic bricks	1700	0.75	870
Reinforced concrete	2500	1.74	840
Expanded polystyrene	20	0.044	1460
Extruded polystyrene	20	0.035	1460
Exterior plaster	1700	0.87	840
Rockwool	40	0.035	1030
Timber	450	0.13	1700
Plasterboard	790	0.21	1000
Gravel	1800	0.7	840
Soil—first layer	1800	3	1110
Soil—second layer	1800	4	1110

The thermal bridges identified within the building envelope were defined following the guidelines provided by the Romanian building norm C107-2005 [55]. The identified thermal bridges are presented in Table 4, where "V" denotes thermal bridges identified along a vertical length, and "H" denotes thermal bridges identified along a horizontal length. This classification helps to distinguish the orientation and specific locations of the thermal bridges within the building envelope, ensuring a comprehensive analysis of their impacts on the thermal performance.

Table 4. Classification and details of the assessed linear thermal bridges.

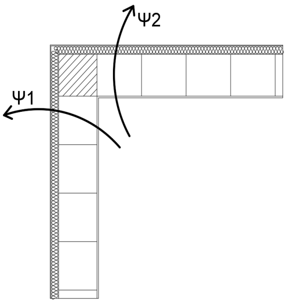
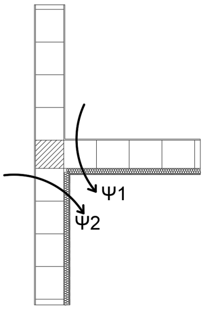
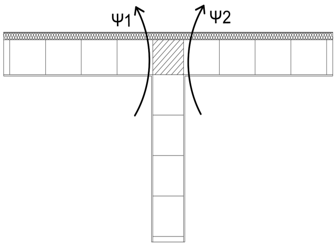
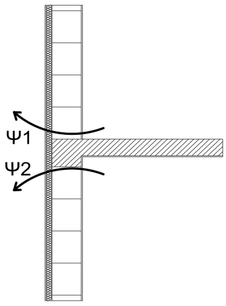
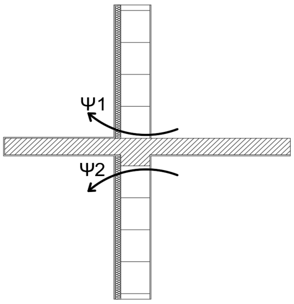
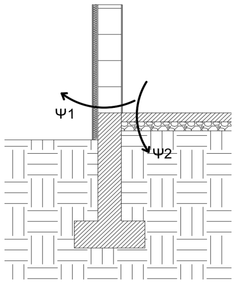
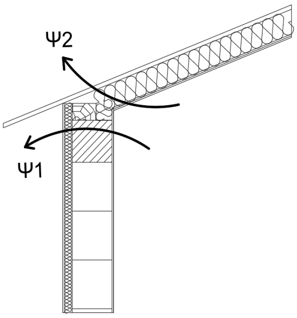
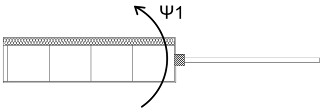
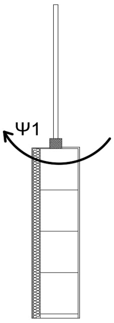
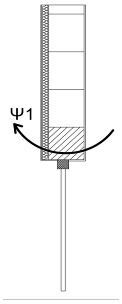
Exterior corner wall (VTB 1) 	Interior corner exterior wall (VTB 2) 	Exterior to interior wall junction (VTB 3) 
Exterior wall to reinforced concrete slab junction (HTB 1) 	Exterior wall to balcony junction (HTB 2) 	Exterior wall to ground reinforced concrete slab junction (HTB 3) 

Table 4. *Cont.*

Exterior wall to roof junction (HTB 4)  	Exterior wall to joinery vertical junction (VTB 4)  	Exterior wall to joinery horizontal junction (HTB 5) 
	Exterior wall to joinery horizontal junction—lintel (HTB 6)  	

2.3. Numerical Simulation Methods and Boundary Conditions for Thermal Bridge Analysis

To evaluate the impacts of the linear thermal bridges detailed in Table 4, the authors conducted a series of finite element method (FEM) numerical simulations using the specialized software RDM version 7.04 [57]. These simulations were performed under the stipulations of the Romanian building norm C107-2005 [52] and the European standard EN ISO 10211 [58]. Further, the calculations employed Equation (1) to determine the linear heat transfer coefficient Ψ (W/(m·K)), ensuring compliance with national and international design norms for thermal performance assessment:

$$\psi = L_{2D} - \sum_{j=1}^{N_j} U_j \cdot l_j \tag{1}$$

where L_{2D} is the thermal coupling coefficient obtained from a 2D calculation of the component separating the two environments being considered W/(m·K); U_j is the thermal transmittance of the 1D component, j, separating the two environments being considered W/(m^2·K); l_j is the length over which the value U_j applies (m).

The boundary conditions for the modeling and simulation were established based on the Romanian design legislation, which specifies the following values: an exterior temperature Te of −18 °C (specific for Iași, classified in the 3rd climatic zone); an indoor temperature Ti of 20 °C; and a soil temperature at a depth of 7 meters Tp of 9 °C [24,56,59]. For the calculation of the considered linear thermal bridges, the values specified by the Romanian design norm [24,55] were as follows:

- R_{Si} = 0.125 (m^2·K/W)—for the exterior wall, the intermediary reinforced concrete slab, and the roof;
- R_{Si} = 0.167 (m^2·K/W)—for the slab on the ground;
- R_{Se} = 0.042 (m^2·K/W)—for all building envelope components in contact with the exterior environment;

- R_{Se} = 0 ($m^2 \cdot K/W$)—for the building envelope components in contact with the ground (i.e., HTB 3 thermal bridge case).

2.4. Overview of Heating Demand Calculations

2.4.1. PHPP Approach

To assess the heating demand of the buildings, the authors utilized the PHPP version 9.6 along with the DesignPH tool. The PHPP is an Excel-based tool used to determine buildings' heating demands and overall energy performance. DesignPH, an extension of the PHPP, provides a 3D data entry interface to optimize the thermal performance of buildings. The tool considers various parameters, including the building's geometry, insulation levels, window types, ventilation system, and internal heat gains, to calculate the heat demand. The PHPP performs a monthly balance method, considering the thermal envelope's heat losses and gains, solar gains, and internal heat sources. It calculates the specific heat demand by assessing the difference between the heat losses and gains, ensuring that the building maintains comfortable indoor temperatures [60]. The expression used to calculate the specific heat demand is the following:

$$Q_H = (Q_T + Q_V) \cdot f_{red} - \eta_{Gw} \cdot (Q_S + Q_I) \tag{2}$$

where Q_H is the annual heating demand, in kWh/($m^2 \cdot$yr); Q_T is the transmission losses, in kWh /($m^{2 \cdot}$a); Q_V is the heat losses of ventilation, in kWh/($m^2 \cdot$yr); Q_S is the solar heat gains, in kWh/($m^{2 \cdot}$yr); Q_I is the internal heat gains, in kWh/($m^2 \cdot$yr); η_{Gw} is the free heat utilization factor, defined as the proportion of free heat that can be utilized for space heating.

The results help to optimize the design features to meet the Passive House standards for low energy consumption.

The tool treats the indoor environment of the building as a unified space and considers the temperature evenly distributed throughout the building [27,39]. The convective heat transfer coefficient (HTC) for walls and windows is assumed to be constant. The tool implements a simplified thermal model for windows and walls, utilizing a fixed HTC to calculate the transmission losses. The thermal mass is modeled as a single node within the thermal zone. Internal gains, such as those from occupancy, lighting, and appliances, are treated as constant average values. Shading coefficients are input as fixed values for the summer and winter seasons. The calculation timestep is standardized to one-hour and one-month intervals [25,27].

The PHPP derives its exterior boundary climatic data from multiple reliable sources to ensure proper energy balance calculations. The PHPP uses local climate data specific to each project location, which are incorporated into the tool to reflect the actual environmental conditions that the building will face. These data are often sourced from local meteorological stations and standardized climate datasets provided by national or international agencies [60].

2.4.2. Mc001 Approach

In order to determine the energy demand for heating according to the Mc001-2022 [24], a monthly calculation method is applied for both sensible and latent heat in the heating and cooling scenarios. This method includes two main categories: the basic energy demand and the specific system energy demand. The basic energy demand calculation does not account for the influence of building systems but includes heat recovery from ventilation. The specific system energy demand calculation considers the impacts of systems, such as the recoverable thermal losses, set temperature corrections, and system operation duration, potentially requiring iterative calculations due to system-specific characteristics. The calculations also consider the monthly energy exchange across the building envelope, defined by one or more thermal zones (ztc), solar gains, radiation to the sky, and the energy derived from internal sources of heat and moisture (internal gains).

For each thermal zone and month (m), the total energy is evaluated for heating and cooling, corresponding to the required indoor comfort for each season separately.

Considering that the paper focuses on the heat demand for heating, the emphasis will be placed on the associated expressions used to calculate the monthly energy requirement for heating as defined by the Mc001-2022 methodology [24]. The calculation of the necessary values for heating, $Q_{H;ht;ztc}$ (kWh), includes the following.

$$Q_{H;ht;ztc;m} = Q_{H;tr;ztc;m} + Q_{H;ve;ztc;m} \tag{3}$$

where $Q_{H;tr;ztc;m}$ is the heat transferred by transmission for heating, in kWh; $Q_{H;ve;ztc;m}$ is the heat transferred by ventilation for heating, in kWh.

$$Q_{H;tr;ztc;m} = \left[H_{H;tr;ztc;m} \cdot (\theta_{int;calc;H;ztc;m} - \theta_{e;a;m}) + H_{gr;an;ztc;m} \cdot (\theta_{int;calc;H;ztc;m} - \theta_{e;a;an})\right] \cdot \Delta t_m \tag{4}$$

where $H_{H;tr;ztc;m}$ is the global heat transfer coefficient by transmission for heating and cooling for all building elements except those in contact with the ground, in W/K; $\theta_{int;calc;H;ztc;m}$ is the set temperature in the zone for heating, in °C; $\theta_{e;a;m}$ is the average monthly exterior temperature, in °C; $H_{gr;an;ztc;m}$ is the heat transfer coefficient to the ground for building elements in contact with the ground (floors on ground, above technical basement, and basement), depending on the annual temperature difference, in W/K; $\theta_{e;a;an}$ is the annual average exterior temperature, in °C; Δt_m is the duration of a month (m), in hours.

$$Q_{H;ve;ztc;m} = \left[H_{H;ve;ztc;m} \cdot (\theta_{int;calc;H;ztc} - \theta_{e;a;m})\right] \cdot \Delta t_m \tag{5}$$

where $H_{H;ve;ztc;m}$ is the global heat transfer coefficient by ventilation for heating/cooling, in W/K.

The total thermal gains for heating, $Q_{H;gn;ztc;m}$ in kWh, are calculated using the following equation:

$$Q_{H;gn;ztc;m} = Q_{H;int;ztc;m} + Q_{H;sol;ztc;m} \tag{6}$$

where, for each conditioned ztc and each month, $Q_{H;int;ztc;m}$ is the sum of internal gains for heating, in kWh; $Q_{H;sol;ztc;m}$ is the sum of solar gains for heating, in kWh.

For the examined cases, the internal heat gains were considered as typical values of the monthly average internal heat fluxes given "by default" according to EN 15316-1 [61] for residential buildings (single-family units), respectively, 2.4 W/m^2. The solar gains, $Q_{sol;dir;zt}$, in kWh, are calculated considering opaque and transparent elements:

$$Q_{H;sol;dir;zt;m} = \sum_k Q_{H;sol;wi;k} + \sum_k Q_{H;sol;op;k} \tag{7}$$

where, for each conditioned ztc and each month, $Q_{H;sol;wi;k;m}$ is the monthly solar gains through the transparent element k, in kWh; $Q_{H;sol;op;k,m}$ is the monthly solar gains through the opaque element k, in kWh.

The energy transferred through the transparent element (wi), in kWh, is given by the equation

$$Q_{H;sol;wi;m} = g_{gl;wi;H;m} \cdot A_{wi} \cdot \left(1 - F_{fr;wi}\right) \cdot F_{sh;obst;wi;m} \cdot H_{sol;wi;m} - Q_{sky;wi;m} \tag{8}$$

where $g_{gl;wi;H;m}$ is the monthly average coefficient of total solar energy transmission, A_{wi} is the area of the transparent element (wi), in m^2; $F_{fr,wi}$ is the frame area fraction of the window; in the absence of specific data, $F_{fr,wi} = 0.25$; $F_{sh;obst;wi;m}$ is the shading factor for external obstacles; $H_{sol;wi;m}$ is the intensity of monthly solar radiation on a surface inclined at angle β_{wi} to the horizontal and with an orientation angle γ_{wi}, in kWh/m^2; $Q_{sky;wi;m}$ is the additional monthly heat flux due to thermal radiation to the sky, in kWh.

The energy derived from solar gains through the opaque envelope element (k) for heating, $Q_{H;sol,k;m}$, in kWh, for a month (m), is calculated using the equation

$$Q_{H;sol;op;k;m} = \alpha_{sr;k} \cdot R_{se;k} \cdot U_{c;op;k} \cdot A_{c;k} \cdot F_{sh;obst;k;m} \cdot H_{sol;k;m} - Q_{sky;k;m} \tag{9}$$

where α_{sol} = 0.6 for intermediate colors, and α_{sol} = 0.9 for dark colors; $R_{se;k}$ is the external surface thermal resistance, with the external surface heat transfer coefficients h_{ce} and h_{re}; $U_{c;op;k}$ is the thermal transmittance, in W/(m^2·K); $A_{c;k}$ is the projected area, in m^2; and the other notations are defined in the previous formulas (replacing the index wi with the index k).

For the monthly calculation of the energy requirements, an additional flux, $Q_{sky;m}$, emitted to the sky by each element (k) of the building envelope, is determined. Thus, for month (m), the flux in kWh is calculated in a simplified manner using the relationship from the standard ISO 52016-1 [25]:

$$Q_{sky;k;m} = F_{sky;k} \cdot R_{se;k} \cdot U_{c;k} \cdot A_{c;k} \cdot h_{lr;e;k} \cdot \Delta\theta_{sky;m} \cdot \Delta t_m \tag{10}$$

where $F_{sky;k}$ is the shape factor between the element (k) and the sky; for horizontal surfaces without shading, $F_{sky;k}$ = 1; for vertical surfaces without shading, $F_{sky;k}$ = 0.5; $h_{lr;e;k}$ is the external heat transfer coefficient for long-wave radiation, in W/(m^2·K); $\Delta\theta_{sky;m}$ is the average difference between the apparent temperature of the sky and the air temperature; for the conditions in Romania, $\Delta\theta_{sky;m}$ can be considered as 11 K, in K.

In the monthly method, the effects of the non-stationary heat transfer regime are considered by introducing the utilization factor of gains for heating and the utilization factor of heat transfer for cooling. The utilization factor of gains for heating, $\eta_{H,gn}$, is a function of the thermal balance ratio, γ_H, and a parameter, a_H, which depends on the building's inertia.

$$\gamma_{H;ztc;m} = \frac{Q_{H;gn;ztc;m}}{Q_{H;ht;ztc;m}} \tag{11}$$

where $\gamma_{H;ztc;m}$ is the dimensionless thermal balance ratio for heating mode.

The dimensionless parameter $a_{H;ztc;m}$ is calculated with the equation

$$a_{H;ztc;m} = a_{H;0} + \frac{\tau_{H;ztc;m}}{\tau_{H;0}} \tag{12}$$

where $a_{H;0}$ is the reference parameter ($a_{H;0}$ = 1); $\tau_{H;ztc;m}$ is the time constant of the zone for heating, in hours; $\tau_{H;0}$ is the reference time constant ($\tau_{H;0}$ = 15), in hours.

The time constant of a conditioned zone (ztc), in hours, characterizes the internal thermal inertia of the conditioned zone. Calculations for heating and cooling can differ from month to month depending on the variations in the parameters that determine them, particularly H_{tr} and H_{ve}. This is calculated with the following expression:

$$\tau_{H;ztc;m} = \frac{C_{m;eff;ztc}/3600}{H_{H;tr;ztc;m} + H_{gr;an;ztc;m} + H_{H;ve;ztc;m}} \tag{13}$$

where $C_{m;eff;ztc}$ is the effective internal thermal capacity of the zone in J/K; the rest of the terms are defined above.

To calculate the monthly energy requirement for heating/cooling, a distinction is made between months with and month without long periods of unoccupancy. For the studied cases, the monthly energy requirement for heating, $Q_{H;nd;ztc;m}$, in kWh, is calculated if $\gamma_{H;ztc;m} > 0$ and ≤ 2.0, according to the following expression:

$$Q_{H;nd;ztc;m} = Q_{H;ht;ztc;m} - \eta_{H;gn;ztc;m} \cdot Q_{H;gn;ztc;m} \tag{14}$$

As previously mentioned, the boundary conditions defined by the exterior temperature's monthly average values, the solar radiation intensities, and the average difference between the apparent sky temperature and air temperature are taken as defined by the national design norms [24,48,55,56].

3. Results

3.1. Linear Heat Transfer Coefficient Results

The results in terms of the thermal transmittance values for each assessed building envelope component are provided in Table 5. As previously mentioned, several thermal bridges were investigated, and the resulting values for the linear thermal transmittance coefficient Ψ are detailed in Table 6. In connection with the conditions observed at the building site, the emphasis was placed on optimizing the thermal performance of the external walls by varying the existing constructive detail in terms of increasing the thermal insulation thickness in 5 cm increments from case scenario A to case scenario D, for each of the assessed buildings.

Table 5. Thermal transmittance of the building envelope elements.

Building Envelope Element		**Case Scenario**	**Thermal Transmittance U [W/m^2·K]**	
			Case Study No. 1	**Case Study No. 2**
Exterior walls	5 cm	A	0.61	0.58
	10 cm	B	0.36	0.35
	15 cm	C	0.25	0.25
	20 cm	D	0.20	0.19
Slab on ground		all case scenarios	0.34	0.17
Roof		all case scenarios	0.21	0.37
Windows		all case scenarios	1.11	1.11

Table 6. Linear heat transfer coefficient results for the assessed thermal bridges.

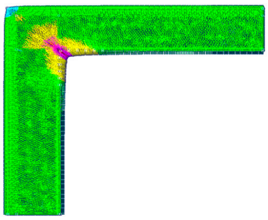
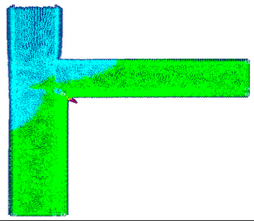
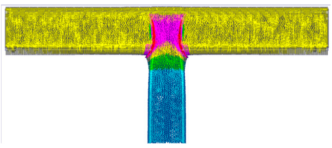
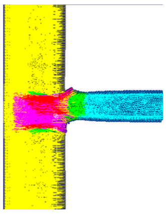
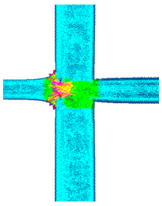
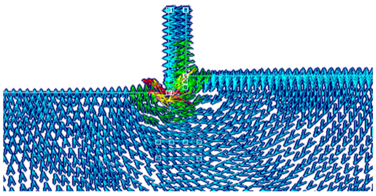
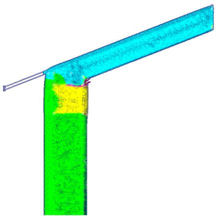
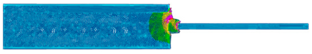
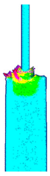
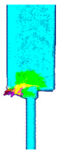
Linear Thermal Bridge	**Case Scenario**	**Linear Thermal Transmittance (W/(m·K))**		
			Case Study No. 1	**Case Study No. 2**
VTB 1 	A	Ψ_1	0.11	0.12
		Ψ_2	0.11	0.12
	B	Ψ_1	0.08	0.09
		Ψ_2	0.08	0.09
	C	Ψ_1	0.06	0.07
		Ψ_2	0.06	0.07
	D	Ψ_1	0.05	0.06
		Ψ_2	0.05	0.06
VTB 2 	A	Ψ_1	0.06	−0.17
		Ψ_2	−0.12	−0.05
	B	Ψ_1	−0.16	−0.12
		Ψ_2	−0.12	−0.05
	C	Ψ_1	−0.11	−0.09
		Ψ_2	−0.08	-0.05
	D	Ψ_1	−0.09	−0.08
		Ψ_2	−0.07	−0.05
VTB 3 	A	Ψ_1	0.006	−0.04
		Ψ_2	0.006	−0.04
	B	Ψ_1	0.002	−0.03
		Ψ_2	0.002	−0.03
	C	Ψ_1	−0.03	−0.03
		Ψ_2	−0.03	−0.03
	D	Ψ_1	−0.02	−0.02
		Ψ_2	−0.02	−0.02

Table 6. *Cont.*

Linear Thermal Bridge	Case Scenario	Linear Thermal Transmittance (W/(m·K))		
			Case Study No. 1	Case Study No. 2
HTB 1 	A	Ψ_1	−0.02	−0.10
		Ψ_2	0.04	−0.07
	B	Ψ_1	−0.01	−0.06
		Ψ_2	0.02	−0.05
	C	Ψ_1	−0.04	−0.05
		Ψ_2	−0.016	−0.04
	D	Ψ_1	−0.03	−0.04
		Ψ_2	−0.013	−0.03
HTB 2 	A	Ψ_1	0.24	0.06
		Ψ_2	0.33	0.26
	B	Ψ_1	0.17	0.10
		Ψ_2	0.32	0.25
	C	Ψ_1	0.12	0,11
		Ψ_2	0.18	0,23
	D	Ψ_1	0.12	0.11
		Ψ_2	0.17	0.21
HTB3 	A	Ψ_1	0.05	0.03
		Ψ_2	0.48	0.96
	B	Ψ_1	0.05	0.07
		Ψ_2	0.56	0.90
	C	Ψ_1	0.07	0.06
		Ψ_2	0.42	0.87
	D	Ψ_1	0.06	0.04
		Ψ_2	0.41	0.78
HTB4 	A	Ψ_1	0.06	0.16
		Ψ_2	0.04	−0.01
	B	Ψ_1	0.07	−0.09
		Ψ_2	0.03	−0.15
	C	Ψ_1	0.08	0.08
		Ψ_2	0.03	−0.01
	D	Ψ_1	0.08	0.09
		Ψ_2	0.03	−0.01
VTB4 	A	Ψ_1	0.27	0.10
	B	Ψ_1	0.20	0.17
	C	Ψ_1	0.23	0.20
	D	Ψ_1	0.24	0.22
HTB5 	A	Ψ_1	0.27	0.10
	B	Ψ_1	0.20	0.17
	C	Ψ_1	0.23	0.20
	D	Ψ_1	0.24	0.22
HTB6 	A	Ψ_1	0.49	0.27
	B	Ψ_1	0.37	0.34
	C	Ψ_1	0.41	0.37
	D	Ψ_1	0.42	0.39

The results presented in this section (see Figures 4 and 5) highlight the variations in the thermal transmittance coefficients for different thermal rehabilitation scenarios, explicitly analyzing the impact of increased insulation thicknesses on the thermal performance of building components. A detailed examination of these results and their implications in optimizing energy efficiency and minimizing heat loss through thermal bridges is provided in the subsequent analysis in Section 4.1.

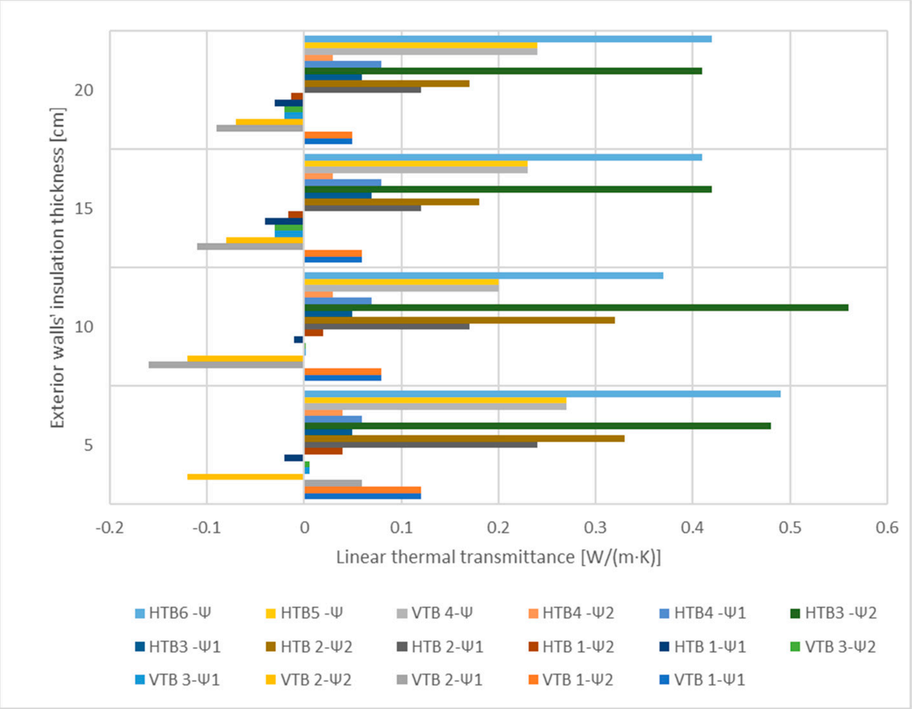


Figure 4. Influence of exterior wall insulation thickness on linear thermal transmittance for various thermal bridges in Case Study No. 1.

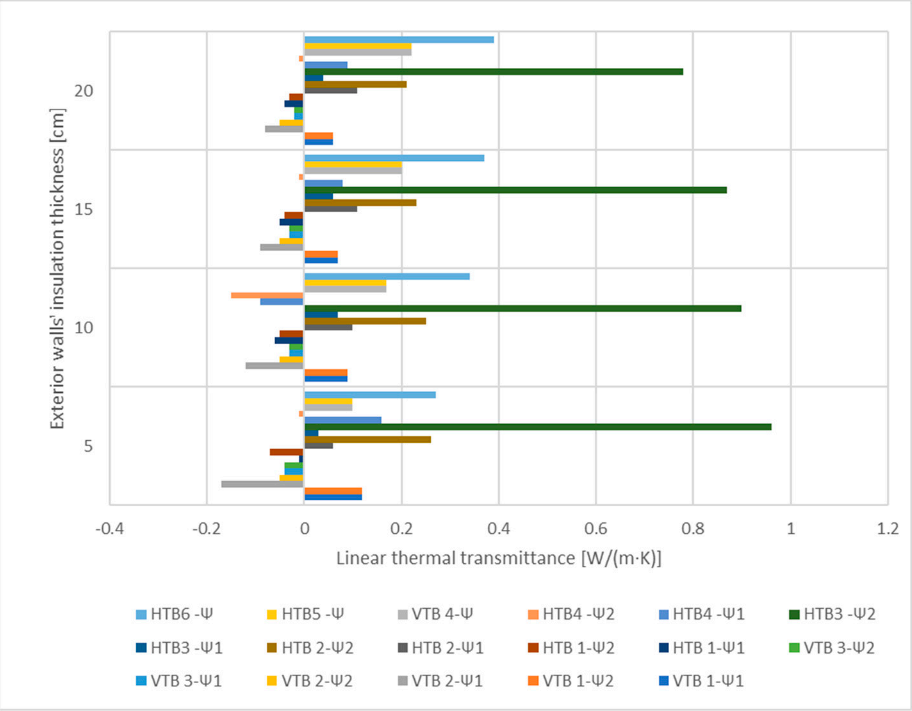


Figure 5. Influence of exterior wall insulation thickness on linear thermal transmittance for various thermal bridges in Case Study No 2.

3.2. Head Demand Calculation Results

3.2.1. PHPP Results

The heating demand results obtained using the PHPP for various scenarios are presented in Table 7. These results provide a baseline for comparison across different case studies. The data reveal a clear trend: as the thermal performance of the building envelope increases, the heating demand decreases significantly in both case studies. A more detailed breakdown of these findings is given in Section 4.2.1, where the PHPP results are analyzed in depth.

Table 7. Heating demand results from PHPP.

Case Scenario	**Heating Demand (kWh/m^2·Year)**	
	Case Study No. 1	**Case Study No. 2**
Scenario A	127.10	166.9
Scenario B	98.10	136.20
Scenario C	85.10	134
Scenario D	81.20	128.2

3.2.2. Mc001 Results

The Mc001-2022 calculations were performed under continuous and intermittent heating, incorporating interior temperature reductions, to assess the heating demand comprehensively. The continuous operation mode considers a constant set temperature for the entire period, ensuring that the heating system maintains a stable indoor environment. The methodology applies a correction factor for intermittent heating to account for periods when the set temperature is reduced [24]. This approach aligns with the procedures outlined in SR EN ISO 52016-1 [25]. By applying these correction factors, the Mc001-2022 methodology accurately represents the building's heating demand under realistic operating conditions, capturing the dynamic interactions between the heating system and user behavior.

In this analysis, calculations with Mc001-2022 are presented for two scenarios: the first scenario uses the external climate conditions as specified by the PHPP. In contrast, the second scenario employs the external climate conditions mandated by national design legislation. Therefore, Table 8 provides the heating demand results calculated using Mc001-2022 with PHPP climatic data.

Table 8. Heating demand results from Mc001-2022 using PHPP climatic data.

Case Scenario	**Heating Demand (kWh/m^2·Year)**			
	Case Study No. 1		**Case Study No. 2**	
	Continuous	**Intermittent**	**Continuous**	**Intermittent**
Scenario A	146.83	138.72	178.08	167.34
Scenario B	120.45	114.24	147.22	140.73
Scenario C	108.25	102.91	136.33	130.67
Scenario D	103.25	98.24	127.61	123.47

Following the analysis of the first scenario using the PHPP climatic data, the second scenario applies nationally imposed climatic conditions to the Mc001-2022 calculations. Therefore, Table 9 presents the heating demand results generated under these national climatic conditions, allowing for a comprehensive comparison between different climatic influences and their effects on the heating demand outcomes.

Table 9. Heating demand results from Mc001-2022 using nationally imposed climatic data.

Case Scenario	Heating Demand (kWh/m^2·Year)			
	Case Study No. 1		Case Study No. 2	
	Continuous	Intermittent	Continuous	Intermittent
Scenario A	147.83	139.76	168.78	158.11
Scenario B	120.44	114.30	138.00	132.27
Scenario C	107.65	102.64	127.36	122.70
Scenario D	102.47	98.05	119.36	115.52

To conclude this section, the results from both scenarios using Mc001-2022 demonstrate the variability in the heating demand predictions when different climatic data sources are applied. In the subsequent Section 4.2.2, a detailed comparative discussion will be presented, analyzing the differences between the Mc001-2022 and PHPP methodologies to understand better their reliability and implications for building energy performance assessments.

4. Discussion

4.1. Analysis of Resultant Linear Heat Transfer Coefficients

The resulting values, presented in Table 6, show that, in the case of the existing state of the considered buildings, almost all linear thermal bridges have a massive adverse effect in both considered case studies. The correlation between the thermal bridge type and the considered numerical simulation studies is presented in Figures 4 and 5.

The analysis of the Ψ-values obtained reveals significant variations depending on the type of thermal bridge and the thickness of the wall insulation. For instance, the exterior corner wall junctions (i.e., VTB1, VTB2, and VTB3) indicate a decrease in the Ψ-values as the insulation thickness increases. Specifically, for VTB1, the Ψ-value decreases from 0.11 W/(m·K) with 5 cm insulation to 0.05 W/(m·K) with 20 cm insulation. Thus, a reduction of 50% for the first case study building and 60% for the second case study building is identified compared to the initial case. This trend is consistent across other junction types, indicating that an increased insulation thickness effectively reduces thermal bridging.

For exterior wall-to-balcony junctions (i.e., HTB2), the Ψ-values are relatively high, reflecting the challenge of insulating these areas effectively. At 5 cm insulation, the Ψ-value is 0.33 W/(m·K), which reduces to 0.11 W/(m·K) at 20 cm insulation, indicating a 66% reduction in the thermal bridge's negative impact. The high initial Ψ-value indicates significant heat loss through the balcony junction, mitigated to some extent by increasing insulation. This finding aligns closely with the results from other studies in the literature. For instance, Zhang et al. [62] reported similar reductions in linear thermal transmittance of 63.1% to 72.3% when using thermal break elements such as thermal breaks and a thermal break–fiber glass-reinforced polymer across various insulation systems, underscoring the effectiveness of additional insulation, similar to the 66% reduction that we observed in the wall-to-balcony junctions

Moreover, the findings of Ge and Baba [63] emphasize the substantial energy losses that can result from unmitigated thermal bridges, particularly in balcony junctions, where the heat loss could lead to an increase in the heating demand by as much as 30%. At the same time, the study conducted by Pérez-Carramiñana et al. in [64] demonstrated that the external wall junctions and balcony connections that benefited from an increased insulation thickness led to a reduction in the Ψ-values. These findings mirror the results that we observed, particularly in the balcony junctions. Their results support the importance of addressing thermal bridges through optimized insulation, echoing the trends observed in our study.

Exterior wall-to-ground slab junctions (i.e., HTB3) also demonstrate a reduction in the Ψ-values with increased insulation, from 0.48 W/(m·K) at 5 cm to 0.21 W/(m·K) at 20 cm. These findings underscore the importance of addressing ground-related thermal bridges in improving the overall thermal performance. Similarly, in [65], the reduction in thermal transmittance at the exterior wall-to-ground slab junctions was a key focus, and the study reported substantial improvements with an increased insulation thickness, consistent with our findings, as previously mentioned.

As will be further observed, certain thermal bridges substantially impact the final heating demand. This issue is particularly evident at the window–wall junctions due to the lack of proper thermal insulation connection to the window frame, a detail commonly addressed in high-performance, energy-efficient buildings. As also observed by Šadauskienė et al. in [65], improper insulation in these areas is a known issue that significantly impacts the thermal performance of buildings. The study emphasizes that, without adequate thermal bridging solutions, even high-quality insulation applied to the rest of the building envelope may not yield the expected energy savings. One key point highlighted is that modern installation techniques, such as placing windows within the insulation layer and optimizing window fastener designs, can lead to substantial reductions in the Ψ-values—sometimes as much as 80% compared to traditional methods. This finding aligns with the trends identified in our analysis, where the absence of proper insulation connections at the window–wall junctions hindered improvements in the Ψ-values, even with an increased insulation thickness. Consequently, this also limits the potential reduction of the building energy consumption.

In conclusion, our study and the referenced literature stress the necessity of adequately addressing thermal bridge details to fully realize the benefits of energy-efficient retrofitting efforts, further reducing the building's heating demand and overall energy consumption.

4.2. Comprehensive Analysis of Heating Demand and Performance Discussion

A comparative analysis of the results obtained from both methodologies is conducted, examining the factors contributing to the discrepancies and similarities. The analysis focuses on the heating demand results derived from these tools and discusses their implications for building thermal performance. Further discussions also address the impact of boundary conditions, such as external temperature averages, solar radiation intensities, and the apparent sky temperature difference, on the accuracy and reliability of the heating demand assessments.

4.2.1. Interpretation of the Values Resulted by Using the PHPP Method

The heating demand results derived from the PHPP methodology, presented in Table 7, reaffirm a consistent pattern: as the thermal performance of the building envelope improves, the heating demand decreases significantly in both case studies. This trend illustrates the direct relationship between the quality of the insulation and the resulting reduction in energy required for heating. This pattern is most evident when examining the specific values across different scenarios.

For instance, in Scenario A, where the thermal performance is least optimized, the heating demand is the highest, at 127.10 kWh/m^2/year for Case Study No. 1 and 166.90 kWh/m^2/year for Case Study No. 2. This high demand reflects the insufficient thermal performance of the inadequate thermotechnical dimensioning of the constructive details of building envelope components.

As the insulation thickness increases in Scenario B, the heating demand drops significantly, with a reduction of approximately 22.8% for Case Study No. 1 and 18.4% for Case Study No. 2. This reduction demonstrates the positive impact of additional insulation on the building envelope's thermal performance and consequently on the energy efficiency of the building.

Further increases in the insulation thickness in Scenario C result in even lower heating demands, corresponding to reductions of approximately 33.1% and 19.7%, respectively, compared to Scenario A. This continued decline underscores the importance of enhanced insulation in reducing energy consumption. When comparing Scenario B to Scenario C, the additional insulation results in further reductions of 13.3% for Case Study No. 1 and 1.6% for Case Study No. 2.

Finally, in Scenario D, the heating demand reaches its lowest value, translating to reductions of approximately 36.2% for Case Study No. 1 and 23.2% for Case Study No. 2. These results highlight the substantial energy savings that can be achieved through significant improvements in the thermal performance of building envelope components.

When comparing Scenario C to Scenario D, there are further reductions in the heating demand of 4.6% for Case Study No. 1 and 4.3% for Case Study No. 2. While these percentages might seem modest, they can be better highlighted when considering the overall energy consumption for the heating of the building.

The incremental reduction from Scenario C to Scenario D is significant in maintaining low energy consumption levels, which is essential for buildings aiming to meet high energy performance standards. For instance, the additional insulation helps to minimize heat loss further, thereby reducing the overall energy demand for heating. This improvement contributes to achieving an A energy efficiency class rating and aligns with the stringent requirements for near-zero energy building (nZEB) levels [44,47], designed to minimize energy usage and promote sustainability. Moreover, the reductions in the heating demand facilitate a decrease in primary energy consumption, making it easier for residential buildings in climatic zone III to comply with nZEB standards. Considering that the third climatic zone is characterized by specific climatic conditions that can significantly influence the energy requirements, it is essential to ensure optimal insulation and minimize thermal bridges. These actions are critical steps in achieving the mentioned targets and enhancing the building's energy performance.

4.2.2. Mc001 vs. PHPP Results

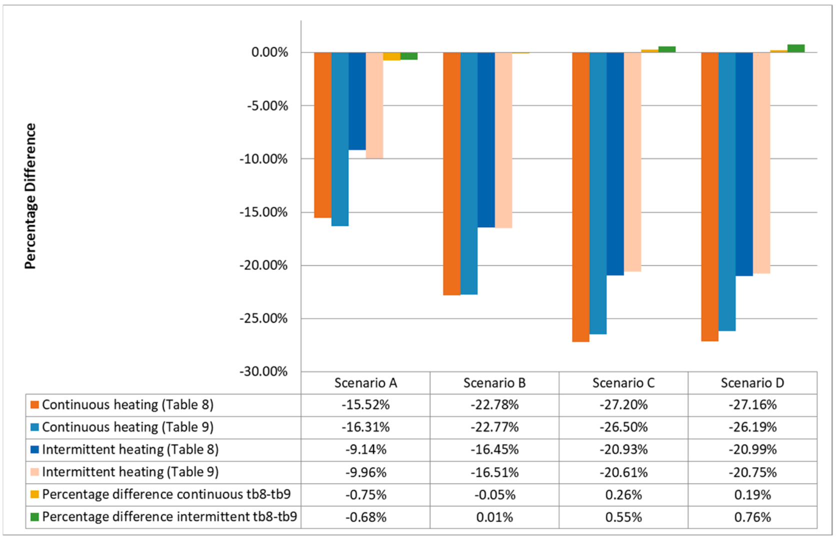
To comprehensively understand the impact of different calculation methodologies on the heating demand, comparing the results obtained from the PHPP and Mc001-2022 approaches is essential. Therefore, the results presented in Tables 8 and 9 are discussed in comparison with those obtained using the PHPP. This approach allows for an analysis of the consistency and reliability of the heating demand assessments across different methodologies and climatic data sources.

Following this, a detailed comparison is undertaken for Case Study No. 1 and Case Study No. 2, examining the discrepancies in the heating demand between the Mc001-2022 and PHPP methodologies for various scenarios, as presented in Tables 7 and 8.

The comparative analysis for Case Study No. 1 reveals the following (see Figure 6). In Scenario A, the Mc001-2022 methodology shows an increase in the heating demand compared to the PHPP, with a difference of approximately 15.5% for continuous heating and an increase of approximately 9.1% for intermittent heating. In Scenario B, continuous heating using Mc001-2022 is higher by approximately 22.8% compared to the PHPP, and the intermittent heating demand is approximately 16.4% higher. Scenario C indicates a 27.2% higher heating demand for continuous heating and a 21.0% higher demand for intermittent heating when using Mc001-2022 compared to the PHPP. Finally, in Scenario D, the Mc001-2022 methodology shows a 27.1% increase in the continuous heating demand and a 21.0% increase in the intermittent heating demand compared to the PHPP.

The differences indicate an interesting trend when comparing the Mc001-2022 results with the PHPP results for Case Study No. 2. In Scenario A, the intermittent heating demand is higher by 0.3% compared to the PHPP, suggesting a higher heating demand prediction when temperature setbacks are considered. Similarly, in Scenario B, the intermittent heating demand is higher, with an increase of 3.3%, while, in Scenarios C and D, a decrease of 2.5% and 3.7%, respectively, is seen compared to the PHPP results. For the continuous heating case, the differences also show a consistent increase for Scenarios A, B, and C, with values equal to 6.7%, 8.1%, and 1.7%, respectively, while, for Scenario D, a slight decrease of 0.5% compared to the PHPP is observed.

The continuous heating for Case Study No. 1 shows a significant increase compared to intermittent heating across all scenarios: Scenario A has a continuous heating demand that is 5.9% higher than that of intermittent heating, Scenario B shows a 5.4% higher demand, Scenario C indicates a 5.2% higher demand, and Scenario D reveals a 5.1% higher demand. Comparably, for Case Study No. 2, the continuous heating demand is consistently higher than the intermittent heating demand across all scenarios. The increases range from 3.4% in Scenario D to 6.4% in Scenario A. This indicates that maintaining a constant indoor temperature without setbacks (continuous heating) generally requires more energy than allowing temperature setbacks (intermittent heating).



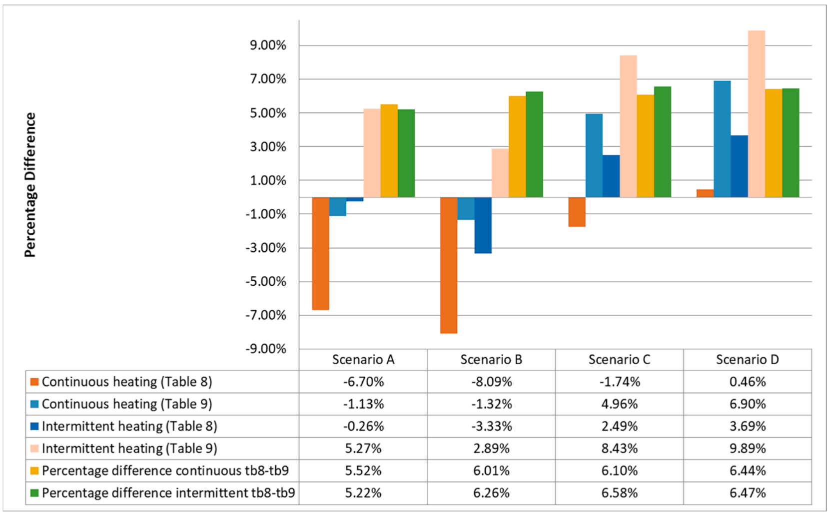
	Scenario A	Scenario B	Scenario C	Scenario D
🟧 Continuous heating (Table 8)	-15.52%	-22.78%	-27.20%	-27.16%
🟦 Continuous heating (Table 9)	-16.31%	-22.77%	-26.50%	-26.19%
🟦 Intermittent heating (Table 8)	-9.14%	-16.45%	-20.93%	-20.99%
🟧 Intermittent heating (Table 9)	-9.96%	-16.51%	-20.61%	-20.75%
🟨 Percentage difference continuous tb8-tb9	-0.75%	-0.05%	0.26%	0.19%
🟩 Percentage difference intermittent tb8-tb9	-0.68%	0.01%	0.55%	0.76%

Figure 6. Percentage differences in heating demand between PHPP and Mc001-2022 and between both cases of Mc001—Case Study No. 1.

In analyzing the heating demand results from Table 9 compared to Table 7, there are significant differences between the continuous and intermittent heating scenarios across both case studies (see Figure 7). For Case Study No. 1, the continuous heating demand shows an increase of 16.3% in Scenario A, identified as the minimum difference, and an increase of 26.2% in Scenario D, identified as the maximum difference, compared to the PHPP results. Similarly, the minimum increase for intermittent heating is 10.0% in Scenario A and the maximum is 20.7% in Scenario D.

For Case Study No. 2, the results differ. For continuous heating, the demand shows a maximum increase of 1.3% in Scenario B and a maximum decrease of 6.9% in Scenario D compared to the PHPP results. For intermittent heating, the demand shows a minimum decrease of 2.89% in Scenario B and a maximum decrease of 9.9% in Scenario D compared to the PHPP results. These findings highlight the variability in the heating demand predictions between the Mc001-2022 methodology and the PHPP across different scenarios and case studies.

For Case Study No. 1, when comparing continuous and intermittent heating, one can see that the values are higher within a percentage of 4.5% to 5.7%, similar to the results from Table 8. For Case Study No. 2, the same trend is identified, with increases ranging from 3.3% to 6.8%, thus supporting the earlier conclusion that continuous heating consistently results in a higher energy demand than intermittent heating, as mentioned in the literature [66–68]. Nevertheless, the differences between the two cases do not exceed 7% for both case studies.



	Scenario A	Scenario B	Scenario C	Scenario D
Continuous heating (Table 8)	-6.70%	-8.09%	-1.74%	0.46%
Continuous heating (Table 9)	-1.13%	-1.32%	4.96%	6.90%
Intermittent heating (Table 8)	-0.26%	-3.33%	2.49%	3.69%
Intermittent heating (Table 9)	5.27%	2.89%	8.43%	9.89%
Percentage difference continuous tb8-tb9	5.52%	6.01%	6.10%	6.44%
Percentage difference intermittent tb8-tb9	5.22%	6.26%	6.58%	6.47%

Figure 7. Percentage differences in heating demand between PHPP and Mc001-2022 and between both cases of Mc001—Case Study No. 2.

4.3. Final Discussion

The analysis of the heating demand results for Case Study No. 1 and Case Study No. 2 reveals distinct trends in how the Mc001-2022 and PHPP methodologies predict energy requirements (Figures 6 and 7). For Case Study No. 1, the continuous heating demands calculated with Mc001-2022 are consistently higher than those calculated with the PHPP, with increases ranging from 15.5% to 27.2%. Similarly, the intermittent heating demands are also higher, with increases ranging from 9.1% to 21.0%. These findings highlight the robustness of Mc001-2022 in capturing the complexities of continuous operation and intermittent heating scenarios for the analyzed building.

In contrast, Case Study No. 2 shows a different trend. For continuous heating, Mc001-2022 shows a maximum increase of 8.1% in Scenario B (Table 8) and a maximum decrease of 6.9% in Scenario D (Table 9) compared to the PHPP results. For intermittent heating, the demand shows a maximum increase of 3.3% in Scenario B (Table 8) and a maximum decrease of 9.9% in Scenario D (Table 9) compared to the PHPP results. These variations emphasize the sensitivity of heating demand predictions to different climatic data sources, case studies, and calculation methodologies.

The differing trends in the heating demand results between the two case study buildings indicate that no “one-size-fits-all” solution for energy performance assessment exists. The external boundary conditions play a crucial role in determining the heating demand. For Case Study No. 1, the climatic conditions used in the PHPP (Table 8) were closer to those mandated by the design legislation in Mc001-2022 (Table 9). However, the average difference between the apparent sky temperature and the air temperature and the solar radiation intensities used to obtain the results in Table 8 differed from those used in calculating the values in Table 9. Thus, this indicates that even slight variations in the climatic data can lead to significant differences in the heating demand predictions.

A range of studies have highlighted the same issue regarding the sensitivity of heating demand predictions to different climatic data sources. Mahdavi et al. [69] noted that different weather data sets can lead to significant fluctuations in the predicted heating and cooling energy demands of buildings. In contrast, standard climate indicators like the heating and cooling degree days can impact buildings’ heating and cooling loads. Maučec et al. [70] mentioned that one of the critical design parameters impacting the energy demand for the heating of timber buildings was the internal set-point temperature in moderate and cold climates. De Masi et al. [71] also highlighted that using different weather data sources resulted in significant deviations in the estimated energy consumption and energetic and environmental indexes, which can lead to inaccuracies in energy savings values and, consequently, affect retrofit approaches.

Another notable factor contributing to the differences in the results between Tables 7–9 is how the PHPP calculates the building's thermal capacity and applies set temperature corrections. The simplified method from the ISO 52016-1 standard [25], adopted in the Mc001-2022, allows users to select the value of the internal thermal capacity based on a range from very light to very massive for monthly calculations. This flexibility can lead to discrepancies between the two calculation methodologies, as the choice of the thermal capacity class significantly influences the heating demand outcomes.

Similar findings were identified in the literature, where Ferrari [72] mentioned that the thermal capacity of building components has a decisive contribution to energy savings in both winter and summer conditions, contrary to common belief. Thus, the materials defining the building envelope components are crucial in assessing buildings' real heat transfer process. Muñoz et al. [73] mentioned that the specific heat capacity of building materials is an essential factor, although it is commonly overlooked in building energy performance calculations. Varying the specific heat capacity of building materials can lead to significant energy savings, potentially up to 20%. Additionally, Simpson et al. [74] performed a sensitivity analysis on the heating of a typical UK dwelling. They found that the internal set-point temperature is a critical design parameter impacting the energy demand for heating, highlighting the importance of considering detailed thermal properties in retrofit design. Similar conclusions were also highlighted by Imam et al. [75], who noted that practitioners involved in energy modeling should agree on the importance of the model parameters in the design activity.

Comparing the results from Mc001-2022 using the PHPP climatic data from Table 8 and nationally validated climatic data from Table 9, it is not consistently shown that nationally validated data provide closer estimates of the PHPP values. For Case Study No. 1, the continuous and intermittent heating demands using the PHPP climatic data, as well as the nationally validated climatic data, are higher than the PHPP values. However, Case Study No. 2 has a mixture of increases and decreases, indicating that the impact of using different climatic data sources varies depending on the case study and scenario.

These insights underscore the importance of selecting appropriate methodologies and climatic data sources tailored to the specific characteristics and requirements of each building. While the Mc001-2022 may provide a more detailed analysis of the operational dynamics, the PHPP offers a dedicated framework for the evaluation of the overall energy efficiency, particularly for Passive House standards, as the literature mentions [41,46,76]. The findings suggest that the results from the PHPP do not always indicate lower heating demands compared to the Mc001-2022, highlighting the need for a careful and context-specific approach to energy performance assessment.

5. Conclusions

The construction sector significantly impacts European efforts to achieve sustainable development due to its high consumption of materials, nonrenewable energy, and emissions. The built environment has become a significant aggressor of the natural environment, mainly due to the current state of a substantial portion of the existing building stock, which is not energy-efficient. In the European Union, improving the energy efficiency of buildings is a crucial regulatory target to reduce the negative environmental impact. Therefore, this study focuses on an energy renovation solution in Romania, examining the impact of improving the thermal performance of two investigated buildings. Additionally, the study compares the heating demand predictions using two methodologies, the PHPP and Mc001-2022, across different climatic data sets and case studies.

The comparative study of two widely recognized methodologies, the PHPP and Mc001-2022, in predicting the heating demands for existing residential buildings reveals significant variability in the results, highlighting the importance of the methodological choice in energy performance assessments. Specifically, for Case Study No. 1, Mc001-2022 generally predicted 15.5% to 27.2% higher heating demands than the PHPP in continuous heating scenarios, whereas, for intermittent heating, Mc001-2022 predicted 9.1% to 21.0% higher heating demands. For Case Study No. 2, the differences were more varied, with Mc001-2022 predicting 8.1% higher to 6.9% lower demands in the continuous heating scenarios and 3.3% higher to 9.9% lower in the intermittent heating scenarios compared to the PHPP. This study indicates no consistent trend where one methodology always predicts higher or lower heating demands than the other. Thus, this suggests that Mc001-2022 might incorporate more detailed considerations of constant temperature maintenance and system interactions. Considering the variability associated with Case Study No. 2, it underscores the sensitivity of heating demand predictions to the external climatic conditions, the internal set-point temperatures, and the specific characteristics of each building.

This study also highlights the impact of different climatic data sources on heating demand predictions. While using nationally validated climatic data in Mc001-2022 did not always result in closer alignment with the PHPP values, it did emphasize the role of localized environmental conditions in determining energy performance. Furthermore, the differences in how the PHPP and Mc001-2022 handle thermal capacity and temperature corrections play a crucial role in the discrepancies observed. The flexibility allowed in Mc001-2022 regarding the selection of the internal thermal capacity can lead to significant differences in the heating demand outcomes, with discrepancies reaching up to 20%, as supported by similar findings in the literature.

These findings have important implications for engineers and building energy consultants seeking to optimize building retrofitting strategies and ensure compliance with energy efficiency regulations. The findings suggest that no universal solution in building energy modeling exists. The choice of methodology and climatic data must be tailored to the specific context and requirements of each building to ensure accurate and reliable heating demand predictions. This study underscores the necessity of a nuanced and context-specific approach to energy performance assessment, taking into account the unique characteristics and operational dynamics of each building.

In conclusion, this study contributes to the broader understanding of how different energy performance assessment methodologies respond to varying building characteristics and climatic conditions, offering both scientific insights and practical guidance for the enhancement of building energy efficiency. Moving forward, the results of this research can serve as a foundation for future theoretical studies and practical engineering applications aimed at refining energy assessment methodologies and optimizing building performance. Future research should extend the comparative analysis to various building types, climates, and rehabilitation scenarios. Moreover, while this study has focused on the heating demand, further investigations could integrate other energy performance factors, such as the cooling demand, renewable energy integration, and occupant behavior. The results from this study can serve as the basis for the refinement of energy performance assessment methodologies, the improvement of national calculation standards, and the advancement of best practices in building retrofitting strategies. The findings also offer valuable insights for engineering organizations and regulatory bodies aiming to enhance the accuracy and reliability of building energy simulations, ultimately contributing to more sustainable construction practices.

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