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The Effect of the Thermal Behavior of RT22HC Phase Change Material on Double-Skin Facades in Cold Climates

Pouya Mavaddati, Allahbakhsh Kavoosi *

Faculty of Engineering, School of Art and Architecture, Razi university, Kermanshah, Iran

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ABSTRACT

Given the high share of energy consumption in the building sector and the need to enhance thermal performance in cold climates, this study investigates the effect of the paraffin-based phase change material RT22HC on improving the thermal efficiency of a double-skin building facade. This material has a melting temperature in the range of 20–23°C (peak 22°C) and a latent heat storage capacity of about 190 kJ/kg, which enables storing and releasing heat at an approximately constant temperature. The aim of the study is to analyze the impact of removing thermal insulation and replacing it with an air cavity containing PCM on heating and cooling loads during cold periods in the city of Tabriz. Energy modeling was performed using DB software, and the heat transfer analysis was conducted with the Finite Difference algorithm. Three scenarios were examined: a base facade; a double-skin facade with PCM and thermal insulation; and a double-skin facade with PCM and an air cavity. The results showed that in the third case, the melting and solidification mechanism of RT22HC reduced heat flux and increased temperature stability; such that the annual sensible heat load decreased from 27276.61 kWh to 9985.8 kWh (equivalent to 63%). Moreover, indoor temperature fluctuations and mean radiant temperature differences decreased, improving thermal comfort conditions. Overall, the low thermal conductivity (0.2 W/m·K) and high heat capacity of PCM led to proposing this material as an effective substitute for conventional thermal insulations in DSF facades in cold climates.

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*Corresponding author: a.kavoosi@razi.ac.ir

1. Introduction

The building sector is one of the largest energy consumers in the world, accounting for approximately 30–40% of total energy produced and nearly 29% of total greenhouse gas emissions in CO2-equivalent terms [1] [2]. In developing countries such as Iran, energy intensity in this sector remains very high due to incomplete compliance with national building regulations, insufficient attention to climatic design principles, and weak utilization of modern construction technologies,. In cold regions, including the city of Tabriz, a large portion of the energy consumed is devoted to space heating, and heat loss through the building envelope plays a significant role. Studies show that more than 40% of buildings' energy consumption is related to the heat exchange through the external envelope [3]. Therefore, enhancing the thermal performance of walls and facades is a key strategy for reducing energy consumption and improving thermal sustainability.

Among passive systems in sustainable designs, DSF is considered one of the most efficient technologies for controlling heat exchange and optimizing energy use in buildings. This facade consists of two transparent layers and a middle cavity that functions as a thermal buffer and natural ventilation layer between the indoor and outdoor environments [4]. Airflow in the middle cavity is usually driven by wind pressure differences and the temperature difference between the inside and outside of the facade. The stack effect, arising from the density difference between the warm air inside the cavity and the cold outdoor air, causes the warm air to rise and exit from the top of the facade [5] [6]. In naturally ventilated buildings, DSF is usually designed on the southern elevation to allow maximum fresh airflow from the north and enhance natural ventilation [7]. The concept of the double-skin facade emerged in the early twentieth century, but its real development and expansion began in the 1990s [8]. This system is known for its benefits such as enhancing indoor air quality, enhancing thermal comfort without mechanical energy consumption, and reducing heating and cooling loads; however, it also presents challenges such as the high design and maintenance costs [9] [10], increased structural dead load, sound transmission through cavities, reduced usable interior space, and special fire safety requirements [11]. Moreover, comprehensive standards and guidelines for the DSF design and evaluation have yet to be fully established in many countries [12] [13]. Therefore, effective use of this system necessitates careful consideration of climatic conditions, material properties, and factors influencing heat transfer.

In recent years, integrating double-skin facade technology with PCM materials has emerged as a promising approach to enhancing the thermal performance of building envelopes. PCMs are thermal energy storage materials that, by changing the phase between solid and liquid, can absorb and release substantial latent heat at nearly constant temperature. This feature reduces indoor temperature fluctuations and improves thermal stability in living spaces [14]. Phase change materials are categorized into three main groups based on their chemical composition: organic, inorganic, and eutectic [15]. In terms of physical properties, these materials should have high heat capacity, chemical stability, no supercooling, and long service life over melting–freezing cycles [16]. In the present study, RT22HC manufactured by Rubitherm is used as PCM. This material is a pure paraffin with the melting temperature of about 22°C, which aligns with the thermal comfort range for indoor spaces. The physical properties of RT22HC include the latent heat of about 190 kJ/kg, specific heat capacity of 2 kJ/kg·K, thermal conductivity of 0.2 W/m·K, density of 0.7 to 0.76 kg/L, and maximum operating temperature of 50°C [17]. This material exhibits no supercooling and has high operational stability over phase change cycles. Given its melting temperature, RT22HC is a suitable option for the cold climate of Tabriz, as it stores solar heat during the day and releases it at night, thereby reducing temperature fluctuations.

Numerous studies have shown that employing PCM in various building components such as walls, roofs, and floors can effectively reduce temperature fluctuations and lower the thermal demand on HVAC systems [5] [18]. Moreover, a study [19] demonstrated that combining PCM with insulation can significantly enhance thermal performance. However, most prior research has focused on warm or temperate climates with the primary goal of reducing cooling loads, whereas in cold regions such as Tabriz, the main challenge is heat retention during long cold seasons.

In addition, most previous studies have not examined in sufficient detail the interior wall assembly, the execution method (wet versus dry), or the effects of removing thermal insulation and replacing it with a narrower air cavity. Eliminating the insulation layer and substituting an air cavity in a double-skin facade can alter the dynamic heat-transfer behavior and, when combined with PCM, enhance solar-energy absorption and delay heat transfer to the indoor space [8]. Prior research has also emphasized that, due to the lack of accurate climatic datasets and coherent design standards, many DSF findings are difficult to be generalized to real projects; likewise, the literature notes a shortage of comprehensive guidelines for DSF design and evaluation [13].

Accordingly, the present study numerically evaluates the thermal performance of a PCM-integrated double-skin facade using RT22HC in residential buildings in the cold climate of Tabriz. Three main scenarios are considered:

1. single-skin facade (baseline);
2. double-skin facade with PCM and thermal insulation;
3. Double-skin facade with PCM and an air cavity instead of insulation.

Analyses are performed using DB software and a Finite Difference algorithm to capture heat-transfer behavior. The findings provide a scientific basis for optimizing the residential facade design in the cold regions of Iran and to contribute to reducing energy consumption and enhancing buildings' thermal sustainability.

In order to explain the position of the results of this study in comparison with those of previous studies and to assess the validity of the baseline model in terms of geometric scale and implementation specifications, a qualitative comparison with common features in previous studies is presented. Compared to previous research on combining double-skin facades and phase change materials, one of the fundamental distinctions of this study lies in the geometric and implementation characteristics of the base wall. In many previous studies, the reference walls have had significant thicknesses, usually more than 20 cm and in some cases up to about 60 or even 70 cm, which inherently increase the overall thermal resistance of the envelope and reduce heat transfer. In contrast, the base wall used in this study has a thickness of less than 20 cm and is therefore closer to the implementation conditions common in conventional residential buildings. Despite this initial reduction in wall thickness, the results obtained in the final scenario indicate a reduction of more than 60% in the sensible heating load compared to the baseline model. While most previous studies have reported improvements of around 40–50%, even using thicker walls and more complex structural details, this suggests that the improvement in thermal performance in the present study arises from the active role of PCM and its interaction with the interstitial space of the double-skin facade, rather than from the increased wall mass or thickness.

On the other hand, another important difference between this study and previous research is the modeling scale. A significant part of previous research has been conducted on experimental chambers with limited dimensions (such as 3 × 3 × 3 m), which, although useful for conceptual studies, cannot be directly generalized to real residential spaces. In this study, the analyses were conducted on the actual spaces of a residential unit with conventional dimensions, allowing the evaluation of the thermal behavior of the envelope under real loads, operational schedules, and standard spatial arrangements. Accordingly, it can be concluded that the achievements of this study, in addition to a significant quantitative improvement in reducing the heating load, surpass those of many previous studies in terms of modeling scale and realism, providing a sound basis for generalizing the results to actual residential building designs. Despite the valuable achievements of previous studies, a close examination of these studies shows that some common assumptions in shell design, especially regarding the simultaneous use of PCM and thermal insulation in double-skin facades, remain largely unexamined.

In most previous studies, the investigation of double-skin facades and phase-change materials has been mainly carried out either separately or in combination with conventional thermal insulation layers. A significant part of these studies has focused on improving the thermal conductivity of PCM by adding reinforcing components, increasing the thickness of the insulation, or optimizing the technical details of advanced systems. As a result, the role of the direct interaction between the interior space and PCM in the absence of a thermal insulation layer, particularly in cold climates, has received less attention.

A review of the literature shows that in most studies related to double-skin facades equipped with PCM, the presence of a thermal insulation layer has been assumed as a standard design practice, and its complete elimination as a performance strategy has rarely been evaluated. This is significant because the presence of thermal insulation can restrict the direct heat exchange between the interior space and the phase-change material, thereby reducing the actual capacity of PCM to store and release latent energy. Focusing on this research gap, the present study specifically investigated the effect of completely removing thermal insulation and replacing it with a controlled air cavity in the interstitial space of a double-skin facade. The results demonstrate that this approach, contrary to initial expectations and common practice in building envelope designs, not only did not compromise thermal performance, but also led to enhanced thermal stability and a significant reduction in the heating load in cold climates by improving the effective heat exchange between PCM and the interior space. From this perspective, the main innovation of the present study lies in redefining the role of PCM from a complementary insulation layer to an active energy-regulating element in a double-skin facade without thermal insulation.

2. Methodology

In this study, with the aim of examining and optimizing the thermal performance of a PCM-integrated double-skin facade in high-rise residential buildings located in the cold city of Tabriz, a hybrid analytical-numerical approach has been employed. All stages including the climatic data collection, geometric modeling, definition of the thermal properties of materials, simulation execution, and data analysis were conducted in specific detail to provide full reproducibility for other researchers. First, the two-dimensional drawings and construction details of the case-study building were prepared in AutoCAD 2018. Then, the three-dimensional model and structural information were developed in Revit 2018 and exported to DesignBuilder 7.3.1.003 for energy simulation, which uses the EnergyPlus calculation engine for the energy analysis. The climatic data for Tabriz were extracted from a validated EPW file and analyzed using Climate Consultant 6 to determine temperature patterns, solar radiation, and prevailing wind direction. The baseline model comprised a south-oriented residential building with envelopes conforming to ASHRAE standards. In this model, the phase change material RT22HC was selected as the PCM. PCM was placed in the middle layer of the double-skin facade, and various scenarios were defined by changing the PCM thickness, the presence or absence of thermal insulation, and the air gap between the two skins. Specifically, the PCM layer was modeled without fins or thermal conductivity-enhancing elements. This decision was made to investigate the intrinsic thermal behavior of RT22HC material in a passive double-skin facade that is compatible with the operational conditions of residential buildings. In this approach, the relatively low thermal conductivity of PCM is considered as part of the design logic to provide a time delay in heat transfer, allowing for the gradual storage and release of energy, thereby increasing the temperature stability of the interior space. Thus, modeling the PCM without fins provides for an independent analysis of the thermal performance of this material under real operating conditions. For the sensitivity analysis, only one variable was changed at each step, while other boundary conditions including occupancy schedule, internal loads, ventilation rate, and solar radiation pattern were kept constant. All simulations were conducted over comparable time periods (the coldest week of the year, a cold month, a three-month cold period, and the annual cycle) to accurately evaluate the effect of each variable on the indoor air temperature, wall surface temperature, sensible heating load, and absorbed solar energy. The output data and results were analyzed using charts and numerical comparisons. To control simulation error, all models were examined under identical temporal and climatic conditions, and baseline parameters were kept constant across all scenarios. The accuracy of the model was assessed by comparing the inner and outer wall surface temperatures and by verifying consistency with the thermal behavior of real materials. To preserve reproducibility, all material specifications, climatic data, modeling parameters, and software settings were documented and are available to other researchers upon request. This study is limited to the cold climate of Tabriz, and its results may require the adjustment of input parameters for other climates. Moreover, the effects of smart ventilation systems, renewable energies, and dynamic thermal control were not examined at this stage. The study focused on the winter season and the heating behavior of the envelope; the analysis of summer behavior and cooling optimization is left to future research, although the results and analyses indicate that the cooling load also decreased.

3. Results and discussion

3.1. Validation of the Base model

To enable a precise analysis of the thermal performance of the PCM-integrated double-skin facade, a ten-story residential building with an approximate footprint of 344 m² (overall dimensions 16 × 21.5 m²) was selected as the baseline model. The building was designed according to typical construction practices for the cold climate of Tabriz, ensuring compatibility with local implementation realities, its rectangular plan, offering a favorable surface-to-volume ratio, facilitating effective control of the heat exchange and reducing energy losses. For the simulation, one south-facing floor of the building (Figure 1), with a usable area of 137.7 m², was chosen as the reference unit. This selection was made because the south facade directly affects the heat exchange and solar gains.

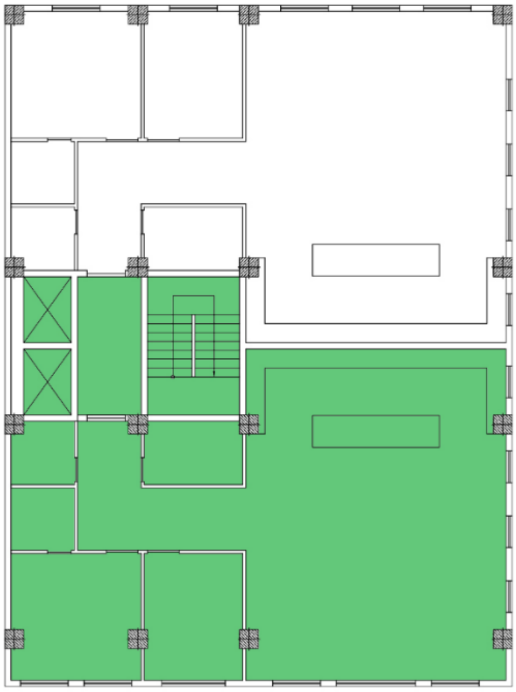

Figure 1. Current state type plan and base model building (author)

Given the functional nature of the double-skin facade and its reliance on solar radiation, this unit represents the most suitable location for evaluating the system performance due to solar radiation. Orientation provides the highest solar energy input during the cold season, allowing the effective activation of the thermal energy storage and release in the PCM layer. Accordingly, the results obtained from the middle-floor southern unit can be generalized to other southern units with similar boundary conditions, as these units exhibit similar radiation patterns, thermal wall behavior, and spatial context, because these units exhibit almost the same behavior. The units located above the parking floor and on the last floor, however, require independent investigations due to distinct boundary conditions. On the first floor, the floor is in contact with the parking space, considered an uncontrolled thermal environment, while on the top floor, the roof exchanges heat directly with outdoor air. These differences may affect heat transfer patterns and overall performance. This will be addressed in future studies.

The unit layouts, openings and envelope layer thicknesses were modeled in DesignBuilder to reflect real construction practice. Figure 2 illustrates the sections selected for thermal simulation.

Three scenarios were defined by varying the wall construction, layer sequence, and the presence or absence of thermal insulation and PCM:

- Scenario 1 (baseline): conventional single-skin wall without thermal insulation, in line with typical construction practices in Tabriz
- Scenario 2: double-skin facade with a combination of PCM and thermal insulation in the middle layer
- Scenario 3: the same as Scenario 2, but with the thermal insulation removed and replaced with an air gap

The differences among these scenarios lie in the placement and type of materials, as well as the PCM thickness, which directly affect the envelope’s thermal resistance and energy storage capacity. For the 2nd scenario, preliminary simulations were conducted to determine the optimal insulation thickness, PCM thickness, and cavity width before finalizing the design.

In order to determine the optimal thickness of the PCM layer, a numerical sensitivity analysis was conducted prior to finalizing the design scenarios. According to the technical specifications provided in the manufacturer’s catalog, a thickness of 2.5cm is recommended for building applications. However, to independently assess the thermal performance of this value under the specific climatic and geometric conditions of the present study, three different PCM thicknesses of 1, 2.5, and 4cm were examined in the middle cavity of the double-skin facade. In all cases, boundary conditions including the climatic data, cavity depth, types of internal and external transparent layers, and space utilization patterns were kept constant, allowing the exclusive evaluation of the effect of the PCM thickness on the thermal performance of the system. The primary comparison criterion was the total sensible heating load of the building during the cold period of the year.

The simulation results indicate that the PCM thickness of 1cm resulted in a total sensible heating load of 446.7 kWh. Increasing the thickness to 2.5cm reduced this value to 438.69 kWh, whereas a further increase to 4cm led to an increase in the heating load to 442.92 kWh. These findings demonstrate that the 2.5cm PCM thickness is the most effective option for reducing the building's heating demand among the investigated cases.

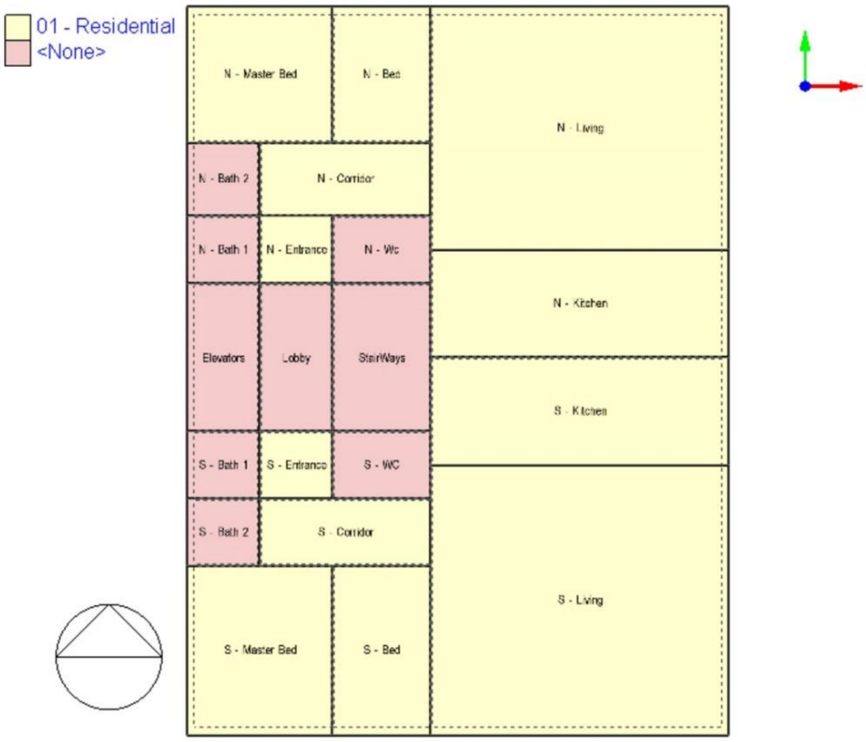

Figure 2. Simulated spaces; yellow spaces as controlled spaces and pink spaces as uncontrolled spaces (author)

The reduced efficiency observed at a thickness of 4cm can be attributed to the early saturation of the phase change material and the limited potential for the complete heat release during the diurnal cycle. Conversely, the PCM with the lower thickness of 1cm exhibited a weaker impact due to its limited latent heat storage capacity. These results suggest that the selection of an optimal PCM thickness should not be based solely on increasing thermal mass, but rather on achieving a balance between storage Capacity, effective charging and discharging behavior, and heat transfer conditions within the building envelope. Accordingly, the thickness of 2.5cm, while consistent with the manufacturer's technical recommendations, was selected as the optimal configuration for subsequent simulations in this study. Despite the optimization of the PCM thickness, the analysis of the initial simulation results indicated that the presence of a thermal insulation layer may restrict the effective heat transfer between the phase change material and the interior space. This limitation motivated the definition of corrective scenarios, including the reduction and eventual complete removal of the thermal insulation layer, which were systematically investigated in the subsequent stages of the research. The analysis results showed that a controlled reduction in the insulation thickness, when combined with the incorporation of PCM, can preserve adequate thermal performance while enhancing the dynamic thermal behavior of the façade. Accordingly, in Scenario 2, the optimized layer configurations obtained were adopted as the basis for the final simulation model, and the corresponding construction details and material properties are presented and discussed in the following sections.

3.1.1. Base model characteristics

The baseline specifications of the simulated building were systemically organized into four main categories to ensure that all technical parameters and energy-related inputs of the model are clearly defined and transparently traceable.

3.1.2. Hot water consumption

The daily DHW consumption was calculated based on the number of occupants (n) and the set temperature. The required thermal energy was determined from the following relationship:

Formula 1:

$$DHW = 50\ lit \times n\ Person / Area = 50 \times 4/190 \approx 1.05$$

3.1.3. Electrical equipment

Electrical equipment loads were set based on the actual usage patterns observed in residential buildings in accordance with Chapter 19 of the Iranian National Building Regulations, which has been developed with reference to ASHRAE standards, and were applied as average internal gains for each space.

Table 1.
Electrical equipment specifications in the Activity section (author)

Equipment type	Power consumption density (W/m²)	Radiant Fraction
Office Equipment	4	0.5

3.1.4. Openings and artificial light

Table 2.
Specifications of the building's light-transmitting wall (author)

Feature	value	Description
Glass type	Double-glazed window 13mm + 6mm air	-
Heat transfer coefficient	2.665	-
Frame heat transfer coefficient	2.5	PVC Frame
Overall heat transfer coefficient	2.785	Including air resistance of the inner and outer surfaces

Table 3.
Door specifications (author)

Door type	material	Heat transfer coefficient
Internal / entrance	Wooden	3.5

Table 4.
Specifications of the building's artificial lighting system (author)

Control	Status	Control type	Number of control steps
Lighting	Active	Step by step	2

3.1.5. Building shell details

The building envelope, including exterior walls, roof, floor, and windows, was defined and modeled in the simulation environment based on the thermal properties of materials commonly available in the Iranian construction market and widely used in local residential buildings.

Figure 3. Cross section of the foundation wall (author)

Table 5.
Materials used in the exterior wall of the building (author)

Layer (outer to inner)	d (cm)	λ (W/m.K)	R (m^2.K/W)
Exterior surface; exposed to the air outside the building			0.04
Brick facade	3	-	0.03
Cement-sand mortar	2	1.3	0.0154
Cement block	15	-	0.19
Gypsum and soil mortar	1.5	1.1	0.0136
Plasterboard	1.5	0.57	0.0263
Surface – Interior; Static air resistance of interior space			0.13
Thermal resistance of the entire wall			0.0445
Total wall thickness			23 cm

3.1.6. HVAC systems

The heating system was activated in all simulation scenarios and, in the baseline configuration, was assumed to operate in all conditioned spaces, excluding unconditioned areas. To ensure comparability among scenarios, a constant ventilation schedule and identical internal load profiles were applied, so that the observed differences in performance were attributable solely to variations in envelope characteristics. Climate boundary conditions were defined using the Tabriz EPW weather file, and the heating loads were evaluated over the cold season spanning December to February.

3.1.7. Resident's operating schedule

The occupancy and activity schedule were adopted from Appendix 5 of Chapter 19 of the Iranian National Building Regulations (pp. 194–195), which are developed in accordance with international standards, and were consistently applied across all simulation scenarios.

3.2. Second scenario: DSF with PCM and insulation

3.2.1. Design rationale and preliminary optimization

Prior to defining the final scenario, several preliminary numerical simulations were conducted to identify the optimal values for the thermal insulation thickness, PCM pack thickness, and width of the intermediate cavity between the two façade layers. The initial parametric analyses indicated that a controlled reduction in the thermal insulation thickness, combined with the enhanced PCM effectiveness leads to improved overall thermal performance. Accordingly, in Scenario 2, the optimized material properties and geometric parameters were selected as follows:

- Thermal insulation thickness: 3 cm
- PCM pack thickness: 2.5 cm
- Double-skin cavity width: 30 cm

These selections were made to achieve an optimal balance between the thermal resistance, latent energy storage capacity, and reduction of the sensible heating load.

3.2.2. Wall assembly and material properties

In Scenario 2, the wall assembly is composed of an external glazed facade, a ventilated intermediate cavity, a PCM layer, a reduced-thickness thermal insulation layer, and the interior wall construction. The PCM layer absorbs solar energy during daytime hours and gradually releases the stored heat during nighttime, thereby mitigating indoor temperature fluctuations and enhancing thermal stability.

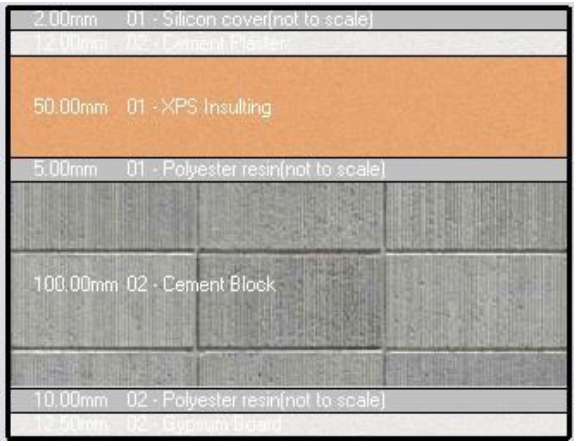

Figure 4. Optimal wall cross section (author)

Table 6.
Optimized wall details (author)

Layer (from outside to inside)	d (cm)	λ (W/m·K)	R (m²·K/W)
Facade paint (resistant coating)	0.2	0.35	0.0057
Cement facade cladding	1.2	1.3	0.0092
XPS thermal insulation	5	0.041	1.2195
Insulating polymer adhesive	0.5	0.2	0.025
Clay block	10	-	0.39
Special glue	1	0.2	0.05
Gypsum panel	1.25	0.25	0.05
Thermal resistance of the entire wall			1.7494
Total wall thickness			19.2 cm

3.2.3. Summary of design actions

In this scenario, the design interventions included the following measures: the optimization of openings, involving adjustments to the size and number of windows in the master bedroom and living room to enhance solar heat gains while minimizing heat losses; upgrading the external envelope, achieved by modifying the wall assembly from a wet construction system to a dry construction system and incorporating a PCM layer combined with the optimized thermal insulation, as well as redesigning the roof and inter-floor assemblies to reduce the overall heat transfer coefficient; the segmented box-type double-skin facade, in which independent facade modules were created in each section to increase localized heat storage capacity and enable separated thermal control.

Table 7.
Double-skin facade specifications (author)

Facade structure	Feature
Inside section	New optimal wall
Middle section	30 cm cavity without PCM
Outside section	Box-shaped double-skin facade with the interior wall cross-section as shown in Figures 4 and 5.

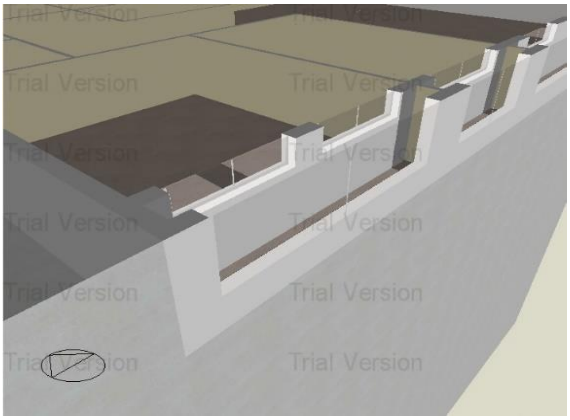

Figure 5. DSF designed for scenario2 (author)

3.2.4. Key observations

1- Reduction of the sensible heating load compared to the baseline model,

2- Improvement in the proportion of received and effectively utilized solar energy,

3- Positive impact of combining PCM with thermal insulation on enhancing the wall's effective thermal capacity and mitigating indoor temperature fluctuations.

3.3. Scenario 3: DSF with PCM and air cavity

3.3.1. Scenario design rationale

In the final stage of the design process, with the aim of further enhancing the PCM performance and evaluating its behavior under realistic cold-climate conditions, the effect of completely removing the thermal insulation layer from the interior wall was investigated. In the previous scenario, the insulation thickness had been reduced from 5 cm to 3 cm, however at this stage the thermal insulation was entirely removed and replaced with a controlled air gap. This structural modification was implemented to strengthen the heat exchange between the interior space and the PCM layer, thereby maximizing the material's capacity for daily heat storage and release. From an architectural and constructive perspective, the removal of the insulation layer, in addition to reducing the overall wall thickness and structural weight, lowers construction costs and reinforces the active role of PCM as a thermal energy-regulating element within the building envelope. In this scenario, natural ventilation is enabled in the model, but it is deactivated in the winter period in order to isolate and accurately assess the direct contribution of PCM to indoor thermal stability. The threshold temperature for the activation of natural ventilation in the simulation software is set at 24°C, and the system is automatically activated during the summer season in response to climatic conditions.

3.3.2. Layer composition and wall structure

In this scenario, the DSF wall consists of three main components:

- the outer skin,
- the intermediate cavity, incorporating the PCM layer positioned adjacent to the inner skin,
- the inner skin, implemented without thermal insulation and located at a defined distance from the outer akin.

The air gap between the two skins was set to 30 cm, and the PCM pack thickness was fixed at 2.5 cm. This air cavity replaces the removed thermal insulation layer and, by enabling the restricted convective heat transfer during the winter period, facilitates the transfer of stored thermal energy from the PCM layer to the interior space. The structural connections between the two facade layers were designed in a manner consistent with the previous scenario and implemented using a dry construction method, allowing for the accurate control, accessibility, and inspection of the internal layers.

Table 8.
Details of the final stage DSF (author)

Facade structure	Feature
Inside section	Alternative wall before with insulation removed and air gap replaced
Middle section	30 cm cavity (RT22HC phase change material packs are considered in this section and close to the inner wall)
Outside section	Double-skin facade in a box shape

3.3.3. Thermal and energy analysis

The simulation results showed that the complete removal of the thermal insulation layer, contrary to the initial expectation, led to measurable improvement in the PCM performance efficiency and a significant reduction in the building's sensible heating load. Compared to the scenario 2, this configuration allows more direct heat exchange between the interior space and the PCM layer, resulting in a reduced thermal time lag between energy absorption and release. By absorbing solar energy during daytime hours and gradually releasing the stored heat during the night, PCM effectively moderates indoor temperature fluctuations and reduces heating demand during long cold periods.

3.3.4. Facade design and energy distribution

In this scenario's double-skin facade design, the overall structural configuration remains comparable to that of the previous scenario, with the key difference being the replacement of the thermal insulation layer by a fixed air cavity. In addition to its thermal function, this cavity acts as a regulating intermediary layer, enhancing the thermal stability duration of the heat stored within the PCM layer. Under the cold-climate conditions of Tabriz, the air cavity facilitates the transfer of solar energy absorbed by the outer skin toward the interior space with a controlled time delay, thereby enhancing the double-skin facade's effectiveness in retaining heat during nighttime hours.

3.3.5. Key findings and comparative analysis

Based on the analysis of numerical simulation outputs and thermal performance indicators, the following results can be summarized for Scenario 3:

- The complete removal of the thermal insulation enhanced the direct heat exchange between the indoor space and the PCM layer, thereby increasing the effective latent heat storage capacity of the system.
- Despite the absence of thermal insulation, the heating load was further reduced compared with the same in Scenario 2, indicating the dominant and efficient role of PCM in regulating indoor thermal conditions.
- The improved dynamic response of PCM resulted in higher thermal stability, with daily indoor temperature fluctuations reduced by approximately 2–3 °C relative to Scenario 2.
- From an economic perspective, this scenario proved more cost-effective, as eliminating the insulation layer reduced construction costs and removed the need for additional insulating materials.

Overall, the results demonstrate that under the cold-climate conditions of Tabriz, removing the thermal insulation layer in a PCM-integrated double-skin facade not only did not degrade thermal performance, but by reinforcing the active energy-storage role of the phase change material led to a measurable improvement in overall thermal efficiency and indoor environmental stability.

3.4. Comparative performance analysis

At this stage, the comprehensive evaluation and comparative analysis of the three main scenarios were conducted based on the key outputs obtained from the DesignBuilder simulations, including the sensible heating load, received solar energy, and average thermal behavior of the southern unit. This comparative assessment not only clarifies the magnitude of the thermal performance improvement achieved in each scenario, but also illustrates the progressive impact of the applied design modifications from the baseline configuration to the final optimized model. In the baseline scenario, the building envelope consisted of conventional walls without thermal insulation, which resulted in a relatively high heating demand under the cold winter conditions of Tabriz. This behavior can be attributed to the excessive heat transfer through the envelope and the limited capacity of the facade to effectively absorb and store solar energy. In Scenario 2, the introduction of a double-skin facade combined with a PCM layer and 3 cm of thermal insulation led to a noticeable reduction in the sensible heating load. PCM contributed to the improved indoor thermal stability by storing solar energy during daytime hours and gradually releasing it during the night. Nevertheless, the simulation results indicated that the presence of the thermal insulation layer partially restricted direct heat exchange between the interior space and PCM, thereby limiting the full utilization of the material's latent heat storage potential. In Scenario 3, the complete removal of the thermal insulation and its replacement with a fixed air gap enabled more direct and effective heat transfer between the indoor environment and the PCM layer. This modification enhanced the system's thermal efficiency during the cold season, as PCM was able to absorb heat more effectively during periods with higher indoor temperature and release it during the cold nighttime, thereby improving temperature moderation. Quantitative results demonstrate that, under this configuration, the sensible heating load was reduced by more than 63% compared to the same in the baseline model, confirming the superior performance of the final scenario.

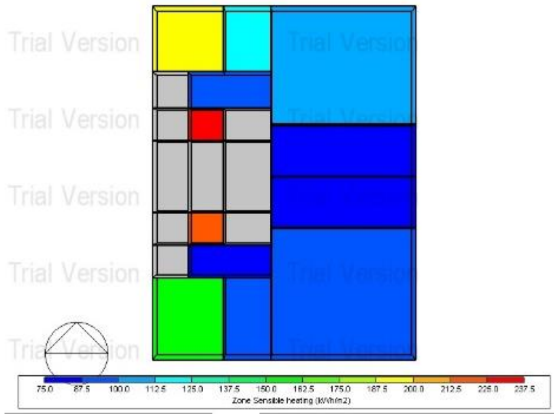

Figure 6. Thermal map of the base model in the 3 cold months of Tabriz (author)

Additionally, the analysis of the software-generated heat maps indicated that, in the final scenario, the heat distribution on the interior surface of the facade became significantly more uniform, and the temperature differences among south-facing rooms were minimized. This behavior reflects the stable thermal-regulating role of PCM and its effectiveness in balancing indoor temperatures while reducing localized thermal hotspots. Regarding the received solar energy, the final scenario demonstrated an increase of approximately 12–15% compared to the baseline model. This improvement can be attributed to the synergistic interaction between the cavity space and the reflective behavior of the inner surface of the outer facade, which enhanced the concentration of solar energy within the intermediate space and facilitated more effective transfer of heat to the PCM layer.

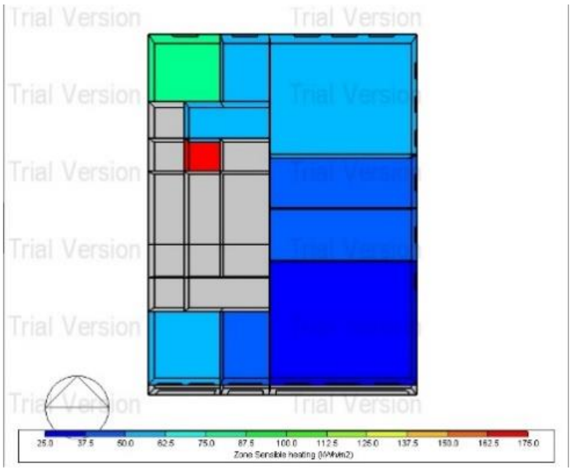

Figure 7. Thermal map of the final model in the 3 cold months of Tabriz (author)

The progressive design evolution from the baseline model to the final configuration reveals the following key trends:

- The application of a double-skin facade integrated with PCM represents the most effective strategy for reducing heating demand under the cold climatic conditions of Tabriz;
- The removal of thermal insulation in the presence of PCM not only did not degrade thermal performance, but instead led to further improvement;
- The incorporation of PCM significantly enhanced the heat storage capacity of the envelope and increased the thermal stability of indoor spaces.

Overall, the analytical outputs indicate that in climates comparable to Tabriz, employing a PCM-equipped double-skin facade with an air cavity in place of conventional thermal insulation can serve as a realistic and energy-efficient solution for reducing energy consumption and improving thermal comfort in residential buildings.

3.5. Discussion of findings

3.5.1. Overview of the simulation method

In this research, three distinct design scenarios were examined to evaluate the thermal performance of a residential building in the cold climate of Tabriz: Scenario 1, the baseline configuration; Scenario 2, a double-skin facade incorporating PCM in combination with thermal insulation within the intermediate layer; and Scenario 3, which is identical to Scenario 2 except that the thermal insulation is fully removed and replaced with an air gap. The objective of this comparative framework was to assess the influence of wall-layer composition and material configuration on the sensible heating load and solar energy received. Simulations were performed on four different temporal scales to capture both the short-term and long-term thermal behavior of the building. The resulting outputs are presented in the form of comparative tables and analytical charts to clearly illustrate the trends in heating-load reduction and solar-energy utilization across the examined scenarios.

3.5.1.1. Cold Week (16 – 22 Dec)

Table 9.
Comparison of Z.S.H and S.G values in a cold week (author)

Alternative	Z.S.H (KWH)	S.G (Wh/m^2)	Performance analysis
Base model	1214.29	126.7	-
2nd Scenario	438.69	80.29	63.9 % decrease in Z.S.H. ↓ radiation
3rd Scenario	431.39	80.29	64.5 % reduction in Z.S.H. ↓ radiation

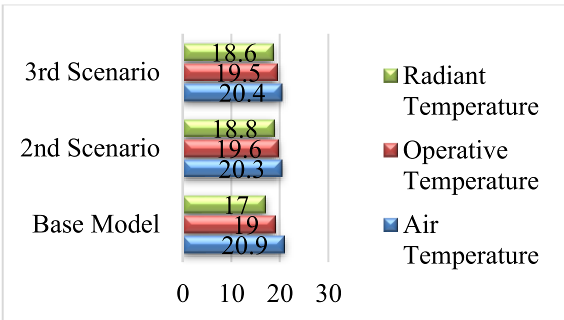

Chart 1. Comparative comparison of temperatures in a cold week (author)

3.5.1.2. Cold Months (22 Dec – 20 Jan)

Table 10.
Comparison of Z.S.H and S.G values in the coldest month (author)

Alternative	Z.S.H (KWH)	S.G (Wh/m^2)	Performance analysis
Base model	4659.21	550.58	-
2nd Scenario	1940.3	307.92	58.3 % decrease in Z.S.H. ↓ radiation
3rd Scenario	1911.27	307.92	59 % decrease in Z.S.H. ↓ radiation

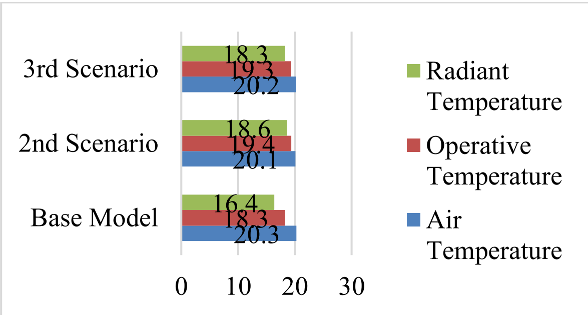

Chart 2. Comparative comparison of temperatures in the coldest month (author)

3.5.1.3. Three Cold Months (22 Nov – 18 Feb)

Table 11.
Comparison of Z.S.H and S.G values in the three cold months (author)

Alternative	Z.S.H (KWH)	S.G (Wh/m^2)	Performance analysis
Base model	12705.6	1649.69	-
2nd Scenario	5172.11	944.31	59.3 % decrease in Z.S.H. ↓ radiation
3rd Scenario	5084.51	944.31	60 % decrease in Z.S.H. ↓ radiation

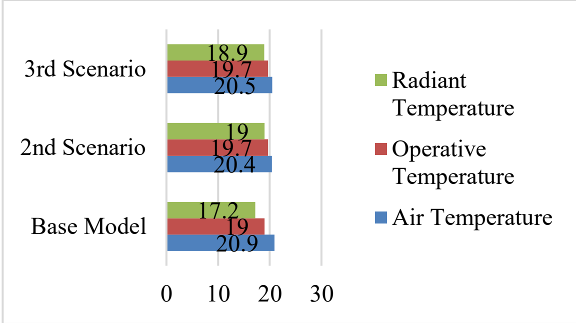

Chart 3. Comparative comparison of temperatures in the three cold months (author)

3.5.1.4. One Year (1 Jan – 31 Dec)

Table 12.
Comparison of Z.S.H and S.G values over the annual period (author)

Alternative	Z.S.H (KWH)	S.G (Wh/m^2)	Performance analysis
Base model	27276.61	5778.21	-
2nd Scenario	10210.93	2314.65	62.6 % decrease in Z.S.H. ↓ radiation
3rd Scenario	9985.8	2314.65	63.4 % decrease in Z.S.H. ↓ radiation

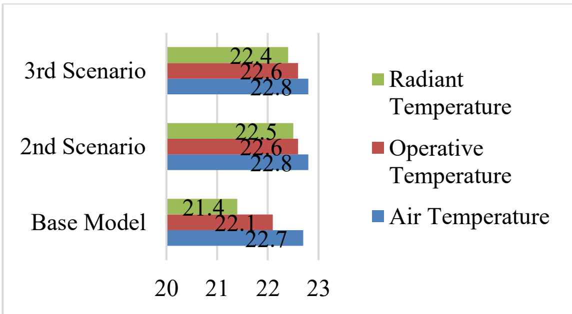

Chart 4. Comparative comparison of temperatures over the annual period (author)

3.5.2. Baseline model performance

In the baseline model, the total sensible heating demand of the building was estimated to be 2370.89 kWh, of which 1214.29 kWh was attributed to the southern unit. The total received solar energy for this unit was calculated as 126.7 kWh, corresponding to approximately 10.4% of its total heating load. This proportion is lower than the optimal expected range for a south-facing facade during the winter season (typically 15–30%) and therefore indicates a considerable potential for improvement through enhanced climatic and facade design strategies. The simulation outcomes for each evaluated time interval are summarized in comparative tables and illustrated in the associated charts, enabling a clear observation of variations in the sensible heating load and received solar energy across the different scenarios.

3.5.3. Comparative analysis of energy and thermal performance

For the purpose of comparing the performance of the defined scenarios, the simulation outputs were extracted and analyzed over multiple time spans, including weekly, monthly, seasonal, and annual periods. Before discussing the quantitative performance of each scenario, it is essential to clearly distinguish the thermal roles of the wall air cavity and the phase change material within the double-skin facade system, as this distinction provides a conceptual framework for interpreting the comparative results. Accordingly, this study analytically examines the independent and combined contributions of the “air cavity” and the “phase change material (PCM)” to the overall thermal behavior of the double-skin facade. The air cavity primarily functions as a passive thermal layer characterized by relatively low thermal conductivity and limited heat transfer capacity. Its main role is to moderate the rate of heat transfer and introduce a time delay in the heat exchange between the indoor and outdoor environments. While this mechanism is effective in reducing instantaneous heat loss, it is essentially static in nature and does not possess the ability to store or actively release thermal energy.

While this mechanism is effective in reducing instantaneous heat loss, it is essentially static in nature and does not possess the ability to store or actively release thermal energy. In contrast, the incorporation of PCM into the facade system introduces a dynamic thermal mechanism based on latent heat storage and release. The simulation results demonstrate that the marked improvement observed in the final scenario cannot be attributed solely to the presence of the air cavity. Rather, the enhanced performance results from the synergistic interaction between the air cavity and PCM, whereby the cavity regulates heat transfer rates and PCM acts as an active energy-regulating component. This interaction plays a decisive role in reducing the building’s sensible heating load and improving overall thermal efficiency.

In Scenario 2 (double-skin facade with PCM and thermal insulation), compared to the baseline model, a significant reduction in the heating load was observed. This improvement is attributed to the increased thermal storage capacity provided by the PCM layer, together with the reduced thickness of the thermal insulation, which enabled more effective heat exchange between the indoor space and PCM.

In Scenario 3 (double-skin facade with PCM and an air gap instead of insulation), the complete removal of the insulation layer and its replacement with an air cavity further enhanced the heat-exchange efficiency of PCM, resulting in an additional reduction in the sensible heating load. The results indicate that, in the absence of thermal insulation, PCM experiences more complete thermal charging and discharging cycles and therefore exhibits more optimal performance under the cold climatic conditions of Tabriz.

It should be emphasized that the complete elimination of thermal insulation in conventional single-layer or independent wall systems is generally not justifiable from either the thermal-performance or regulatorycompliance perspective. However, within the framework of the present study, the objective was not to evaluate an isolated wall system, but rather to investigate the integrated thermal behavior of the entire double-skin facade system and its interaction with the phase change material. The simulation results demonstrate that, under controlled and system-level conditions, removing the insulation layer can enhance the overall facade performance by strengthening the active thermal-regulating role of PCM and improving its effectiveness in stabilizing indoor temperatures. It should also be noted that the findings of this study are limited to the numerical simulations conducted within a software environment. Therefore, the proposed configuration should be regarded as a thermal optimization strategy, and its comprehensive evaluation under real implementation conditions —including safety and code-compliance analyses— should be pursued in future studies and practical applications. Nevertheless, the reliability of the simulation methodology and the validity of software-based thermal analyses are widely recognized in the scientific literature and supported by international research and practice.

3.5.4. Evaluation of the indoor temperature and thermal comfort

To examine the effect of the envelope design more precisely, the indoor air temperature was evaluated in four main spaces: the master bedroom, living room, kitchen, and second bedroom. To represent the building's overall thermal condition, the area-weighted average temperature was used as the primary indicator of the thermal comfort. The method for calculating this weighted average temperature is given by the following formula:

$$\frac{\sum(\mathrm{Ai} \times \mathrm{Tair,i})}{\sum(\mathrm{Ai})} = \mathrm{Tair} \qquad (2)$$

The results indicate that, in the improved scenarios, indoor temperature fluctuations were reduced, and the average indoor temperature remained within the comfort range of 20–23°C. This effect was most pronounced in Scenario 3, resulted from a more effective interaction between PCM and the heat flux between the interior and the exterior envelope.

3.5.5. Thermal and solar energy trends

The overall analysis showed a consistent decrease in the sensible heating load and an increase in the share of utilized solar energy from the baseline model to the improved scenarios. Scenario 2, which combined PCM with thermal insulation, successfully reduced part of the heat loss; however, Scenario 3, with the complete removal of the insulation and replacement with an air gap, demonstrated superior performance in balancing heat storage and heat transfer. Therefore, the double-skin facade equipped with PCM not only reduced the building's heating demand but also enhanced the indoor temperature stability and occupants' thermal comfort under cold-climate conditions of Tabriz.

4. Conclusion

The primary objective of this study was to numerically investigate and compare the thermal performance of three facade scenarios for high-rise residential buildings in Tabriz. The numerical simulations were conducted using DB software on a selected reference floor.

4.1. Analysis of Z.S.H and S.G

The comparison of simulation results demonstrates that the final scenario consistently outperforms the baseline model across all time periods:

- During the cold week, the sensible heating load decreased from 1214.29 kWh in the baseline to 431.39 kWh in the final scenario, representing a reduction of approximately 64.5%.
- Over the cold month, the load decreased from 4659.21 kWh to 1911.27 kWh, a 59% reduction.
- Over the cold quarter, the heating load fell from 12705.6 kWh to 5084.51 kWh, a reduction of 60%.
- Over the annual period, the load decreased from 27276.61 kWh to 9985.8 kWh, corresponding to a 63.4% reduction.

Although the total received solar radiation slightly decreased, the ratio of solar radiation to the sensible heating load increased in the final scenario, indicating a greater relative contribution of solar energy in offsetting heating demand.

4.2. Temporal performance trends

The results indicate that the greatest optimization occurs during the cold winter months, when the majority of the building's energy demand is for heating. The annual trend confirms a substantial reduction in the sensible heating load, even though cooling demand was not analyzed in this study.

4.3. Discussion and implications

A reduction of over 60% in the sensible heating load highlights the high potential of a double-skin facade integrating PCM with a modified inner wall. This improvement translates into the lower energy consumption, economic savings, and enhanced urban energy efficiency. Moreover, indoor temperature conditions became more stable, with reductions in the differences among the indoor air temperature, mean radiant temperature, and operative temperature, thereby improving the occupants' thermal comfort.

4.4. Key findings

- Reduction of the sensible heating load by 59–65% across all analyzed periods.
- Slight decrease in the received solar radiation, but a relative increase in its contribution to offsetting heating demand.
- Enhanced indoor thermal stability and reduced temperature differences.
- Overall conclusion: A double-skin facade with PCM significantly reduces the energy consumption and enhances the thermal comfort for occupants.

List of symbols

Category	Symbol / Abbreviation	definition
units	°C	Degree Celsius
	kWh	Kilowatt hour
	W/m^2	Watt per Square meter
	kJ/kg	Kilojoule per Kilogram
	kJ/kg°K	Kilojoule per Kilogram degree Kelvin
	W/m°K	Watt per meter degree Kelvin
	Kg/L	Kilogram per liter
Modeling & Software	DB	Design Builder
	EPW	Energy Plus Weather file
Technical Terms	PCM	Phase Change Material
	DHW	Domestic Hot Water
	DSF	Double-Skin Facade
	CO_2	Carbon Dioxide
Thermal Parameters	d (cm)	Thickness (centimeter)
	λ (W/m·K)	Thermal Conductivity
	R (m^2·K/W)	Thermal Resistance
	Z.S.H	Zone Sensible Heating
	S.G	Solar Gain

Mathematical Symbols	$\sum(A_i)$	Summation of Areas
	$A_i \times Tair$	Area weighted temperature

Author contributions

All authors participated in the ideation, research design, simulation execution, data analysis, and writing of the initial and final versions of the article. All authors have read and approved the final version of the article.

Data availability statement

The data used in this study, including simulation files and numerical results, are available from the authors upon request. No publicly published data was used in this study.

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Ethical considerations

This study was conducted in accordance with the principles of research ethics and did not involve any scientific misconduct, including data falsification, manipulation of results, or plagiarism. This study did not involve human or animal data and therefore did not require formal ethical approval.

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Conflict of Interest

The authors declare that there is no personal, financial, or organizational conflict of interests related to this study. Nor were any institutions involved in decisions related to the data analysis or publication of results.

References

[1] Yigit S, Ozorhon B. A (2018) simulation-based optimization method for designing energy efficient buildings. Energy and Buildings,Nov,1;178:216,27.https://doi.org/10.1016/j.enbuild.2018.08.045

[2] Wang W, Zmeureanu R, Rivard H. (2005) Applying multi-objective genetic algorithms in green building design optimization. Building and environment. Nov,1;40(11):1512,25.https://doi.org/10.1016/j.buildenv.2004.11.017

[3] Huang B, Wang Y, Lu W, Cheng M. (2022) Fabrication and energy efficiency of translucent concrete panel for building envelope,Energy,Jun,1;248:123635.https://doi.org/10.1016/j.energy.2022.123635

[4] Shameri MA, Alghoul MA, Sopian K, Zain MF, Elayeb O. (2011) Perspectives of double skin façade systems in buildings and energy saving. Renewable and sustainable energy reviews. Apr 1;15(3):1468,75.https://doi.org/10.1016/j.rser.2010.10.016

[5] De Gracia A, Cabeza LF. (2015) Phase change materials and thermal energy storage for buildings. Energy and Buildings.Sep,15;103:414.9.https://doi.org/10.1016/j.enbuild.2015.06.007

[6] De Gracia A, Castell A, Navarro L, Oró E, Cabeza LF. (2013) Numerical modelling of ventilated facades: A review. Renewable and Sustainable Energy Reviews,Jun.1;22:539.49.https://doi.org/10.1016/j.rser.2013.02.029

[7] Schulze T, Eicker U. (2013) Controlled natural ventilation for energy efficient buildings. Energy and buildings. Jan 1;56:221.32.https://doi.org/10.1016/j.enbuild.2012.07.044

[8] Pomponi F, Ip K, Piroozfar P. (2013) Assessment of double skin façade technologies for office refurbishments in the United Kingdom. InProceedings of the sustainable buildings–construction products & technologies Sep 20 (pp. 1098-1109). Verlag der Technischen Universität Graz.

[9] Poirazis H. (2008) Single and double skin glazed office buildings. Division of Energy and Building Design, Department of Architecture and Built Environment, Lund University, Sweeden

[10] Oesterle E, Lieb RD, Lutz M, Heusler W. (2001) Double-skin facades: integrated planning, building physics, construction, aerophysics, air-conditioning, economic viability. Munich

[11] Torres M, Alavedra P, Guzmán A, Cuerva E, Planas C, Clemente R, Escalona V. (2007) Double skin façades – cavity and exterior openings dimensions for saving energy on mediterranean climate, Building Simulation, Jan, 2007

[12] Phillips D. (2009) Ventilating façades. Ashrae Journal. Apr 1;51(4):16.

[13] Choi W, Joe J, Kwak Y, Huh JH. (2012) Operation and control strategies for multi-storey double skin facades during the heating season. Energy and buildings. Jun 1;49:454,65.https://doi.org/10.1016/j.enbuild.2012.02.047

[14] Sharma A, Tyagi VV, Chen CR, Buddhi D. (2009) Review on thermal energy storage with phase change materials and applications. Renewable and Sustainable energy reviews. Feb 1;13(2):318,45.https://doi.org/10.1016/j.rser.2007.10.005

[15] Pasupathy K, Lin S, Hu Q, Luo H, Ke PC. (2008) Direct plant gene delivery with a poly (amidoamine) dendrimer. Biotechnology Journal: Healthcare Nutrition,Technology.,Aug;3(8):1078,82.https://doi.org/10.1002/biot.200800021

[16] Zhou Z, Zhang Z, Zuo J, Huang K, Zhang L. (2015) Phase change materials for solar thermal energy storage in residential buildings in cold climate. Renewable and Sustainable Energy Reviews. Aug 1;48:692-703. https://doi.org/10.1016/j.rser.2015.04.048

[17] Ghalambaz M, Mohammed HI, Naghizadeh A, Islam MS, Younis O, Mahdi JM, Chatroudi IS, Talebizadehsardari P. (2021) Optimum placement of heating tubes in a multi-tube latent heat thermal energy storage. Materials. Mar 5;14(5):1232. https://doi.org/10.3390/ma14051232

[18] Du K, Calautit J, Wang Z, Wu Y, Liu H. (2018) A review of the applications of phase change materials in cooling, heating and power generation in different temperature ranges. Applied energy. Jun 15;220:242,73.https://doi.org/10.1016/j.apenergy.2018.03.005

[19] Yang Q, Liu M, Shu C, Mmereki D, Uzzal Hossain M, Zhan X. (2015) Impact Analysis of Window-Wall Ratio on Heating and Cooling Energy Consumption of Residential Buildings in Hot Summer and Cold Winter Zone in China. Journal of engineering.;2015(1):538254. https://doi.org/10.1155/2015/538254

[20] Alghoul SK, Rijabo HG, Mashena ME. (2017) Energy consumption in buildings: A correlation for the influence of window to wall ratio and window orientation in Tripoli, Libya. Journal of Building Engineering. May 1;11:82-6. https://doi.org/10.1016/j.jobe.2017.04.003

[21] Bao S, Zou S, Li B, Chen Q, Zhao M. (2023) Summer thermal comparative experimental study of double plant-skin façades and double skin façades. Journal of BuildingEngineering.,Aug,1;72:106641.https://doi.org/10.1016/j.jobe.2023.106641

[22] Babota F, Iernuțan RA. (2019) Calculation and analysis of corrected thermal resistance in a common dwelling building in Romania, in various thermal insulation options–The exterior wall. Procedia Manufacturing. Jan 1;32:442-9. https://doi.org/10.1016/j.promfg.2019.02.238

[23] Eromobor SO, Das DK, Emuze F. (2021) Influence of building and indoor environmental parameters on designing energy-efficient buildings. International Journal of Building Pathology and Adaptation.May,18;39(3):507,24.https://doi.org/10.1108/IJBPA-05-2020-0035

[24] Goia F, Haase M, Perino M. (2013) Optimizing the configuration of a façade module for office buildings by means of integrated thermal and lighting simulations in a total energy perspective. Applied energy.,Aug,1;108:515,27.https://doi.org/10.1016/j.apenergy.2013.02.063

[25] Gratia E, De Herde A. (2004) Natural ventilation in a double-skin facade. Energy andbuildings.Feb,1;36(2):137,46.https://doi.org/10.1016/j.enbuild.2003.10.008

[26] Harmati N, Magyar Z. (2015) Influence of WWR, WG and glazing properties on the annual heating and cooling energy demand in buildings. Energy Procedia. Nov 1;78:2458-63. https://doi.org/10.1016/j.egypro.2015.11.229

[27] Kang Y, Ma N, Bunster V, Chang VW, Zhou J. (2022) Optimizing the Passive House Planning Package simulation tool: A bottom-up dynamic approach to reduce building performance gap. Energy and buildings. Dec 1;276:112512. https://doi.org/10.1016/j.enbuild.2022.112512

[28] Lechner N. (2014) Heating, cooling, lighting: Sustainable design methods for architects. John wiley & sons; Oct 1