Optimization of Window-to-Wall Ratio for Energy Efficiency and Comfort in Office Buildings Across Diverse Climates in Iran

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Abstract: *In designing office buildings across Iran's varied climates—ranging from hot-humid to hot-dry and cold—achieving optimal window-to-wall ratios is crucial. This study investigates the impact of fenestration on energy performance and occupant comfort, focusing on balancing natural lighting and thermal management. Through simulations using DesignBuilder software, different window-to-wall ratios are evaluated for their effectiveness in mitigating solar heat gain and enhancing daylight utilization. The findings provide practical insights for architects and engineers to optimize building designs tailored to specific climatic conditions, aiming to foster sustainable and comfortable office environments.*

Keywords: *window-to-wall ratio, office buildings, energy efficiency, climatic zones, DesignBuilder simulation, Iran*

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I. INTRODUCTION

In designing office buildings, particularly in diverse climates like those found in Iran—ranging from hot-humid to hot-dry and cold—it is crucial to determine the optimal window-to-wall ratio. This ratio significantly influences both the energy performance and occupants' comfort within these structures. Understanding the ideal balance of fenestration can mitigate energy consumption, enhance natural lighting, and optimize indoor environmental quality. This study explores the varying climatic conditions across Iran and evaluates the appropriate window-to-wall ratios tailored to each climate zone, aiming to provide practical insights for architects and engineers striving to achieve sustainable and comfortable office environments.

When necessary, windows allow natural light and the direction of the wind to enter the building. However, significant heat gain may result from solar radiation that enters the room through the windows. Size and orientation of windows are two ways to minimize heat gain. Windows can also affect the possibility for harvesting sunshine by lowering lighting loads without sacrificing the thermal and visual comfort of building occupants. A precise calibration between the orientation and sizing of openings, as well as the visual and heat transmission properties of glass, is necessary to achieve a balance between heat gain and daylight penetration. In terms of both quantity and duration, solar radiation intensity is lowest on north-facing walls or openings, and is highest on south-facing facades. Throughout the year, walls or openings with an east or west orientation get a lot of solar radiation.

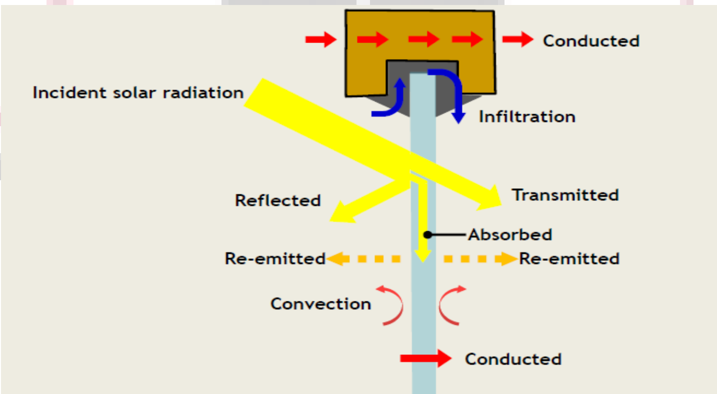


Figure 1 Window Shape and Sizing

A. Climate Zones in Iran

Iran features diverse climate zones, each presenting unique challenges and opportunities for designing office buildings. The hot-humid regions, such as along the Caspian Sea coast, experience high temperatures combined with significant humidity levels throughout much of the year. In contrast, the hot-dry areas, including central and southern parts of the country, endure scorching temperatures with minimal humidity and occasional sandstorms. Lastly, the cold climates, prevalent in the mountainous regions and north-western areas, bring cold winters and moderate summers. Understanding these distinct climatic conditions is crucial for determining the appropriate window-to-wall ratio that balances energy efficiency, thermal comfort, and natural lighting in office building design across Iran.

Figure 2 Climate Zones in Iran

B. Phase Change Materials

Energy stored as latent heat results in a reduction in storage volume compared to energy stored as effective heat. Phase change materials can store large amounts of thermal energy in the form of latent heat, which can be absorbed or released when the material phase changes from solid to liquid or vice versa. PCM has an energy storage capacity approximately ten times higher than concrete. PCM can be used in wall panels, concrete, ceilings and floors, insulation, shutters/shutters, air conditioning systems and cold ceilings. PCM can store thermal energy for minutes, hours, days, months or years for future use. The choice of phase change material will depend on the thermophysical, chemical and kinematic properties of the phase change material, the associated costs and its application.

C. PCM – Advantages and Disadvantages

While PCM integrated walls appear to offer good energy savings in theory, further study focusing on genuine, full-scale buildings under real operational conditions is required to validate the practicality and dependability of PCM. The PCM solidification time is affected by ambient temperature and airflow speeds. Building components with PCM enhancements offer a great potential for a relative reduction in roof and wall cooling loads of 30–50%. The high initial cost, flammability of organic PCMs, not complete melting or solidification cycle due to unfavourable conditions, leakage, etc. are some of the problems impeding the real-time application of PCMs. Paraffin's inexpensive cost, chemical stability, non-corrosiveness, and high latent heat of fusion make it the preferable material; yet, paraffin has drawbacks, including low thermal conductivity and flammability.

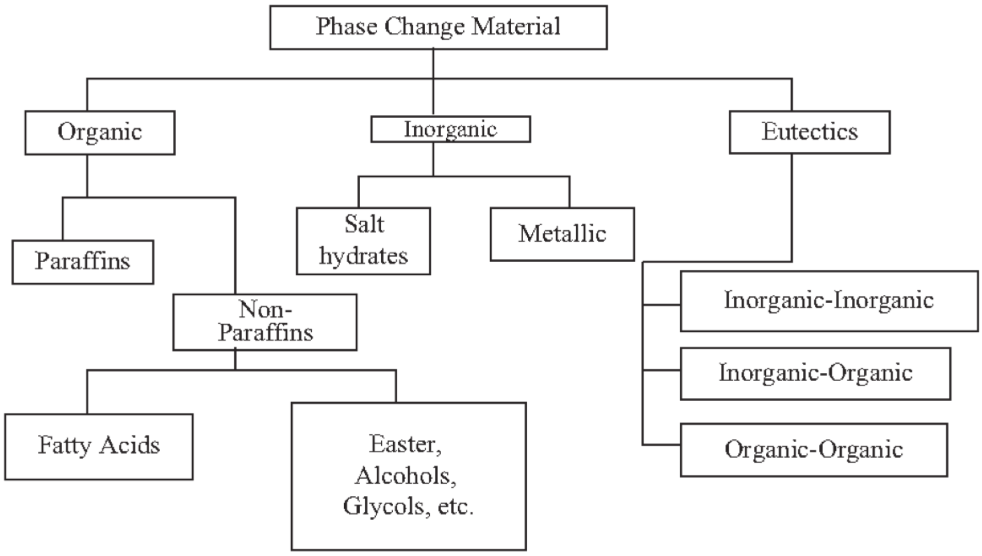


Figure 3 Classification of PCMs

D. Applications of PCM

The transportation and storage of biopharmaceutical foods, poultry, and the milk, boilers and waste heat recovery, cold storage, solar water heaters, telecommunications, heat sinks, hot and cold storage, insulation for buildings and piping products, clothing and textiles, etc. are among the many uses for PCMs. PCMs maintain their latent heat throughout thousands of cycles without experiencing any alteration in their thermophysical characteristics. The PCMs in buildings find its way as a passive or active storage system. The passive storage systems utilize the naturally available heat or cold energy which is stored in the PCMs and used later on when needed, while active storage systems utilize that from manmade heat or energy sources. In both cases, storage of heat or cold energy is essential to match the supply and demand with respect to time and power. PCMs could be utilized in three ways: (i) Integrating PCMs in building walls and ceilings, (ii) PCMs used with other building components other than walls and ceilings, and (iii) PCMs used in heat and cold storage units (Tyagi & Buddhi 2007a).

E. Importance of Window-to-Wall Ratio

The window-to-wall ratio is a critical factor in the design and performance of office buildings, especially in varying climates like those found in Iran. Its importance stems from several key aspects that directly impact energy efficiency, occupant comfort, and overall building sustainability:

- **Energy Efficiency:** The proportion of windows to walls significantly influences the building's energy consumption. In hot-dry climates, for instance, a high window-to-wall ratio could lead to increased solar heat gain, requiring more energy for cooling. Conversely, in cold climates, a higher ratio can enhance passive solar heating during colder months, reducing heating demands. Optimizing this ratio helps architects balance the need for natural light with the control of solar heat gain and loss, thereby improving the building's overall energy performance.

- **Natural Lighting:** Windows play a crucial role in providing natural daylight, which not only enhances visual comfort for occupants but also reduces reliance on artificial lighting during daylight hours. A well-balanced window-to-wall ratio ensures adequate daylight penetration deep into the office space, promoting a healthier and more productive indoor environment. Strategic placement and sizing of windows can mitigate glare and provide even illumination throughout the day.

- **Thermal Comfort:** Proper fenestration design, dictated by the window-to-wall ratio, helps regulate indoor temperatures and reduce thermal discomfort. In hot-humid climates, for example, minimizing direct sunlight exposure through appropriate shading and window placement can prevent overheating. In cold climates, windows designed to maximize solar gain during winter contribute to maintaining comfortable indoor temperatures. Effective thermal insulation and air sealing around windows further enhance thermal comfort by minimizing drafts and heat loss.

- **Daylighting and Views:** Beyond energy savings and comfort, windows contribute to occupants' well-being by connecting them to the outdoor environment. A thoughtfully designed window-to-wall ratio not only allows for ample daylight but also provides views of the surroundings, fostering a more pleasant and productive workplace environment. Access to natural views has been shown to improve mood, productivity, and overall satisfaction among building occupants.

The window-to-wall ratio is a critical design parameter that architects and engineers in Iran and similar climates must carefully consider. It plays a pivotal role in achieving energy-efficient, comfortable, and visually appealing office spaces, thereby contributing to sustainable building practices and enhancing occupants' quality of life.

II. LITERATURE REVIE

Maleki and Dehghan (2020): This study focused on optimizing window configurations in Isfahan's hot, dry climate to enhance energy efficiency in residential buildings. By analyzing different window angles and using low-emissivity glass, significant energy savings of up to 21% were achieved, particularly with southern-facing windows, emphasizing their role in reducing overall energy consumption.

Dardouri et al. (2023): Investigated the integration of phase change materials (PCMs) in Mediterranean climate buildings to reduce energy demand. Using EnergyPlus simulations, the study highlighted PCM's effectiveness in lowering energy consumption by up to 41.6%, with varying efficiencies based on PCM melting temperatures and application locations within building envelopes.

Ahmadnejad et al. (2022): Employed genetic algorithms to optimize window designs in Tabriz's cold climate, aiming to balance daylighting and thermal performance. Through parametric analysis, the study identified optimal window-to-wall ratios and sill heights that enhanced daylight illuminance by up to 10.3% and reduced discomfort hours by as much as 23.8%.

Nazari et al. (2023): Explored window optimization strategies for energy efficiency and occupant comfort in Tehran's office buildings across different orientations. Utilizing the NSGA-II algorithm, the study emphasized the critical role of shading parameters in minimizing energy usage while managing visual comfort, particularly in east and west-facing orientations.

Murathan and Manioğlu (2024): Implemented phase change materials (PCM) in building envelopes across Istanbul and Diyarbakir to improve energy efficiency and indoor comfort. The study's simulations using EnergyPlus revealed significant energy savings of up to 11.96% in Istanbul and 9.69% in Diyarbakir, along with improved thermal comfort levels across different zones within the buildings.

Pouran et al. (2024): Examined the energy-saving potential of PCM and Double Skin Facades (DSF) in Tehran, Tabriz, and Kish Island climates. By integrating PCM into external walls and partition walls, the study demonstrated substantial energy savings and highlighted PCM's role in optimizing building performance across varying climatic conditions.

Sharma et al. (2024): Investigated the integration of phase change materials (PCM) with HVAC systems to enhance energy efficiency. Using the TOPSIS approach, the study optimized PCM thickness and fin configurations, achieving significant energy savings during operational periods and demonstrating the potential for sustainable HVAC solutions.

Arumugam and Ramalingam (2024): Evaluated PCM and insulation integration in office buildings under Chennai's climate to enhance thermal comfort. The study identified effective combinations of PCM thickness and insulation that maintained comfortable indoor temperatures and reduced thermal discomfort, highlighting their applicability in warm climate conditions.

Zheng et al. (2024): Conducted a comprehensive study on the impact of glazing properties and PCM thickness on building energy performance across various climatic zones in China. Using Design Builder simulations, the research optimized glazing SHGC and PCM thickness to achieve substantial energy savings and economic benefits in different climate contexts.

Ahmad and Memon (2024): Analyzed cooling energy savings in residential buildings worldwide through PCM-integrated envelopes and ventilation strategies. The study assessed PCM's role in enhancing thermal comfort and reducing energy consumption across diverse climate zones, emphasizing its potential as a sustainable solution for building energy efficiency.

III. OBJECTIVES

1. To analyse the office building by using Design Builder software.
2. To compare the results of office building by using different PCM material.

IV. METHODOLOGY

Analyzing a building in DesignBuilder typically involves several steps to assess its energy performance, thermal comfort, daylighting, and other relevant factors. Below are the key steps in the analysis process:

- Building Geometry Input: Start by creating the building geometry within DesignBuilder. This involves specifying the building's layout, including walls, floors, roofs, windows, doors, and any other structural elements.
- Material Properties: Define the material properties of each building component such as walls, roofs, windows, and doors. This includes parameters such as thermal conductivity, specific heat, density, and optical properties for windows.
- Climate Data Input: Import or select the appropriate climate data for the location of the building. DesignBuilder provides access to a range of weather files representing various climates worldwide.
- Occupancy and Activity Profiles: Define the occupancy schedules and internal heat gains within the building. This includes specifying the number of occupants, their activity levels, lighting, equipment, and other internal heat sources.
- HVAC System Setup: Configure the heating, ventilation, and air conditioning (HVAC) system for the building. This involves selecting HVAC equipment types, capacities, control strategies, and operating schedules.
- Simulation Settings: Set up simulation parameters such as simulation duration, time step, and convergence criteria. These settings ensure accurate and efficient simulation results.
- Energy Simulation: Perform an energy simulation using DesignBuilder's simulation engine. This calculates the energy consumption of the building based on the input parameters, weather data, and operating conditions.
- Results Analysis: Analyze the simulation results to evaluate the building's energy performance. DesignBuilder provides various output reports, graphs, and visualizations to interpret the results effectively.

A. Theory of a Thermal Energy Storage System

There are various forms of energy storage, which include thermal energy storage, electrical energy storage like batteries, and mechanical energy storage like the energy in an anchor wheel. Based on the type of heat storage medium used, thermal energy storage can be categorized as sensible, latent, thermochemical, or any combination of these. Sensible heat storage uses temperature changes in the surrounding air to store, release, or absorb heat. The following equation can be used to compute the amount of heat absorbed or released, which is dependent on the environment's heat capacity, the pace at which temperatures vary, and the amount of material:

$$Q = \int_{T_1}^{T_2} mC_p dT = mC_p(T_2 - T_1) \tag{3.1}$$

where Q is the heat released or stored (kJ), T1 is the temperature (oC), T2 is the final temperature (oC), m is the material to store thermal energy (kg) and Cp is the heat storage capacity (kJ/kgoC). In thermochemical energy storage systems, when molecular bonds are broken or formed in a completely reversible chemical reaction, heat is stored or released, and the heat released or stored is obtained from the following equation:

$$Q = a_r x\ m\ x\ \Delta h_r \tag{3.2}$$

where ar is the reactant fraction and Δhr is the heat of reaction per unit mass. It is evident that the amount of storage material, the endoergic reaction's heat, and the pace of conversion all affect how much heat is stored. Six Latent heat storage is the mechanism by which heat is either released or held as melting or freezing heat during environmental phase transition processes. The following formula can be used to determine how much latent heat is released or retained.:

$$Q = m\ x\ \mathrm{LH} \tag{3.3}$$

where LH, depending on the quantity of material and the temperature at which its phase shift occurs, is the latent heat (kJ/kg), which can be emitted (melting) or absorbed (solidification). Figure 3.1 illustrates the distinction between latent and visible heat storage.

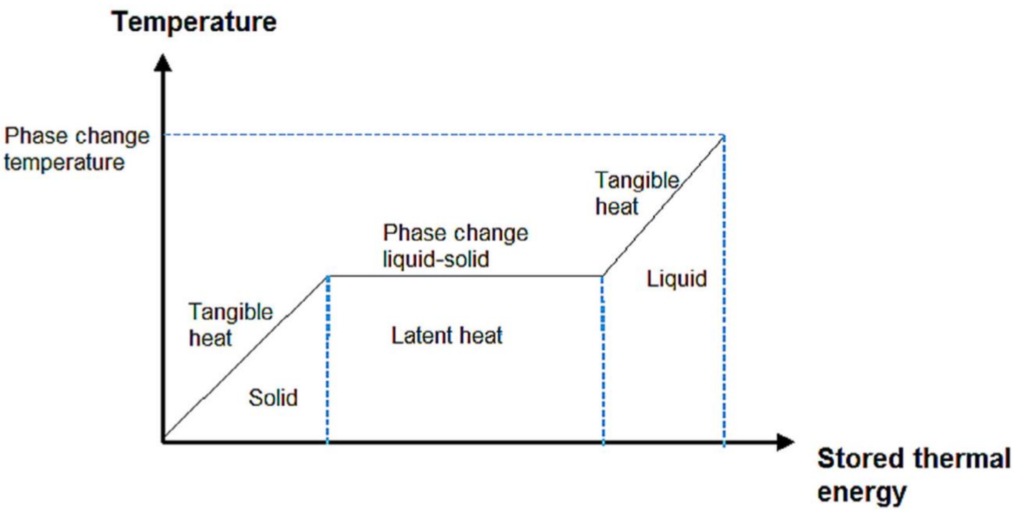


Figure 4 The variance between 'sensible and insensible' energy storage

Latent heat storage using phase change materials (PCMs) offers a high heat storage density and the capacity to absorb or release substantial amounts of heat during phase transitions, with minimal changes in volume and temperature. PCMs can store heat at a rate 5 to 14 times greater per unit volume compared to sensible heat storage materials like water and stone. However, they encounter challenges such as high cost, low thermal conductivity, and instability in thermophysical properties over multiple thermal cycles.

B. Energy Equation of a (PCM) during a 'Phase Change'

Various equations are provided to model the phase change material performance. One of the most often used and reliable formulas for assessing the thermal performance of phase-change materials is the enthalpy equation:

$$\frac{\partial H}{\partial T} = \frac{1}{r}\frac{\partial}{\partial r}\left(\alpha r \frac{\partial h}{\partial r}\right) + \frac{\partial}{\partial Z}\left(\alpha \frac{\partial h}{\partial Z}\right) - \rho l_f \frac{\partial f}{\partial t} \tag{3.4}$$

This equation shows the distribution in two distinct directions with one transient term and two stable terms. The final term on the right side of the equation adds the phase change effect. H is defined as follows in the following equation:

$$H(T) = h(T) + \rho_s f l_f \tag{3.5}$$

$$h(T) = \int_{T_m}^{T} \rho C_p dT \tag{3.6}$$

An equation for the moving boundary is needed to solve this equation, which is defined as follows:

$$\frac{dr}{dT} = \frac{k}{\rho L}\frac{dT}{dx} \tag{3.7}$$

The set of Equations (3.1) to (3.7) can be solved numerically for different boundary and initial conditions for phase change materials. In this study, the equations are solved by DesignBuilder using finite difference method (FDM).

C. Physical Model

The office building dimensions were considered to be 8m x 16m with a height of 3.5m: this is based on the study of Shaei et al (2019). The building is oriented from east to west, as depicted in Figure 3. DesignBuilder software was employed for building simulation in this study. This software utilizes the EnergyPlus analysis engine to compute solar heat gain and energy consumption associated with lighting, heating, and cooling loads. The simulated building model in Design Builder is shown in Figure 3.2, with lighting levels set at 400 Lux according to ASHRAE standards.

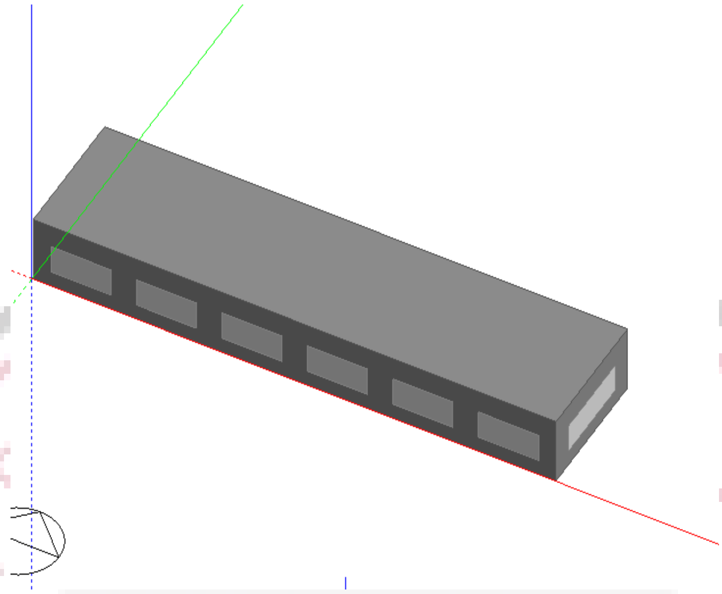


Figure 5 Simulated building in the Design Builder

The building's simulation, which followed the ASHRAE standard, used 22 ◦C for the heating setpoint and 24 ◦C for the cooling setpoint. Table 3.1 also shows the building's features with regard to orientation, occupancy rate, and other factors.

Table 3.1: Characteristics of building

Tittle	Characteristics
Building type	Office
Location	Bhopal
Number of floors	1
Floor height	3.5m
Occupation (persons/m^2)	7 (ASHRAE standard)
Office hours	8:00 a.m.–4:00 p.m.
Orientation	North–south
Illuminance	400 Lux

In the simulated building, for double-pane glass, the thickness of each pane is 3 mm, the thickness of the air layer between is 6 mm, and the thermal transfer coefficient is 3.3 W/m2K. Also, the window frame was made of Unplasticized Polyvinyl Chloride (UPVC). The materials used in the sample building are represented in Table 3.2.

Table 3.2: The building materials simulated in the DesignBuilder (Shaeri et al. 2019)

	‘Containing Layer’	‘Layer Thickness (mm)’	‘U-Value W/(m^2K)’	‘Rc-Value (m^2K)/W’
	Brickwork Outer Leaf	100	0.35	2.85

Exterior wall	XPS Extruded Polystyrene	100		
	Concrete Block	100		
	Gypsum Plastering	10		
Roof	Asphalt	10	0.47	2.09
	Fiber board	10		
	XPS Extruded Polystyrene	40		
	Concrete	10		
	Gypsum Plastering	15		

Table 3.3: The modified building materials simulated in the DesignBuilder

	(Containing Layer)	**(Layer Thickness (mm))**	**(U-Value W/(m^2K))**	**(Rc-Value (m^2K)/W)**
Exterior wall	Brickwork Outer Leaf	100	0.35	2.85
	BioPCMs M182/Q21 (indicated as PCM21)	100		
	Concrete Block	100		
	Gypsum Plastering	10		
Roof	Asphalt	10	0.47	2.09
	Fiber board	10		
	BioPCMs M182/Q21 (indicated as PCM21)	40		
	Concrete	10		
	Gypsum Plastering	15		

The Table 3.2 shows the building materials simulated in the DesignBuilder adopted from the Shaeri et al. (2019). This table has been modified by replacing the PCM material XPS Extruded Polystyrene with BioPCMs M182/Q21 (indicated as PCM21). In this work, BioPCMs M182/Q21 (indicated as PCM21) is used in the simulation. The main characteristics of this type of 'PCM' are listed in Table 3.4.

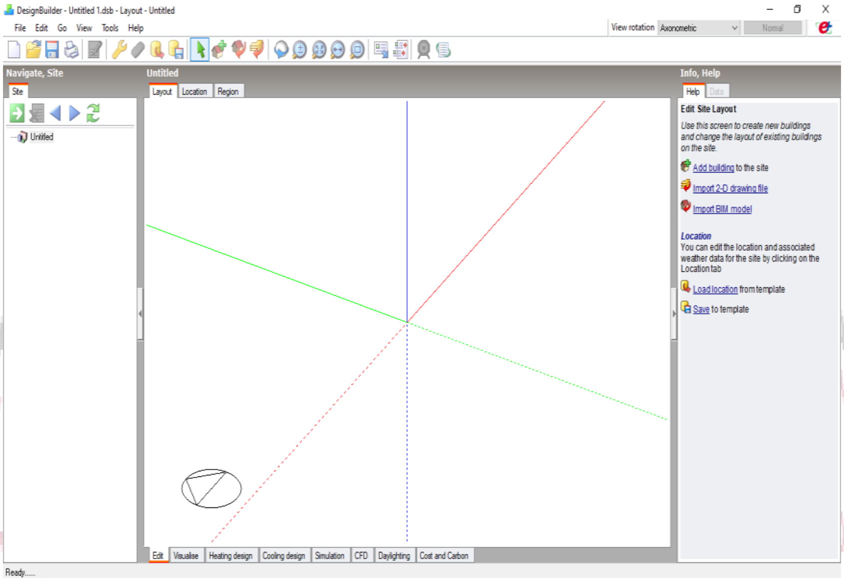
Table 3.4: Thermophysical properties of Bio (PCMs) M182

'Property (Unit)'	**'Value'**
Density (kg/m^3)	235
Specific heat capacity (J/kgK)	1970
Thermal conductivity (W/mK)	0.20

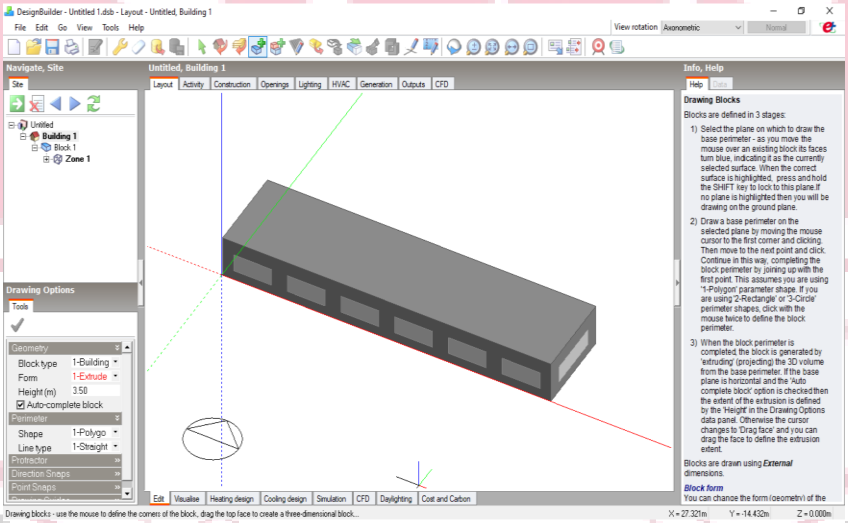
D. Simulation Steps

First Step: Modelling of building in DesignBuilder

In this step, one can develop the model of building using different options such as import plan of building, BIM model etc. Here, the office building dimensions were considered to be 8m x 16m with a height of 3.5m: this is based on the study of Shaei et al (2019).



(a)



(b)

Figure 6 Modelling of building in the Design Builder

Second Step: Activity

In this data building activity data has been set. In the simulation of the building, based on the ASHRAE standard, the heating setpoint was considered 22 ◦C, and the cooling setpoint was considered 24 ◦C.

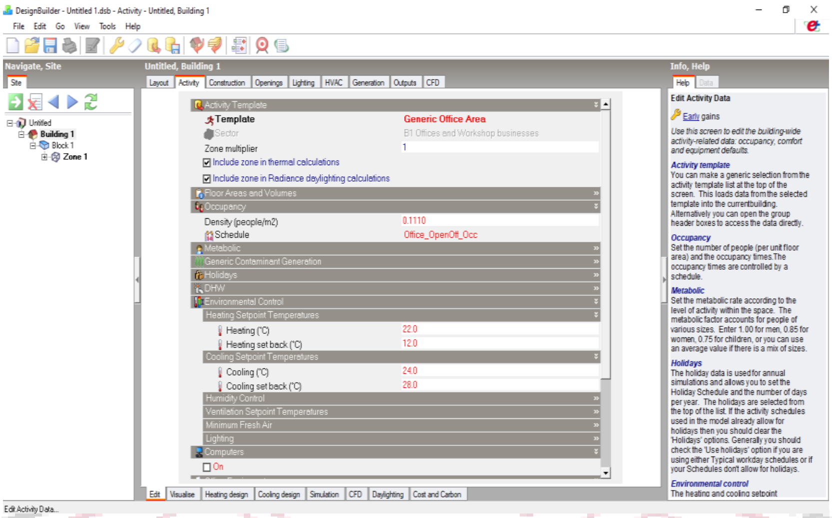
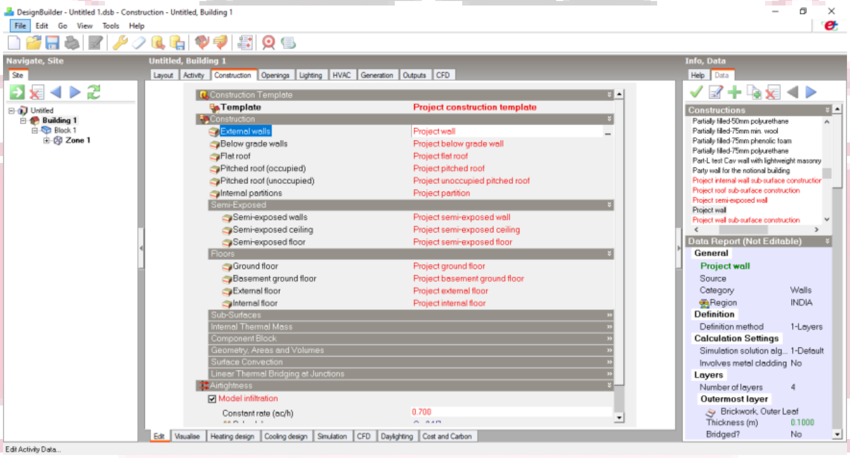


Figure 7 Building activity in the Design Builder

Third Step: Construction

Based on table 3.2, the properties of exterior wall and roof are defined in this step.



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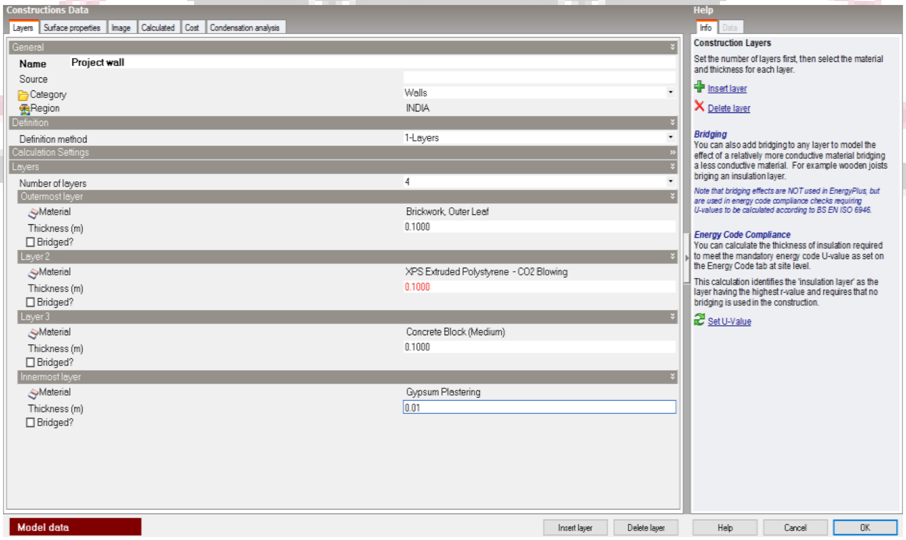

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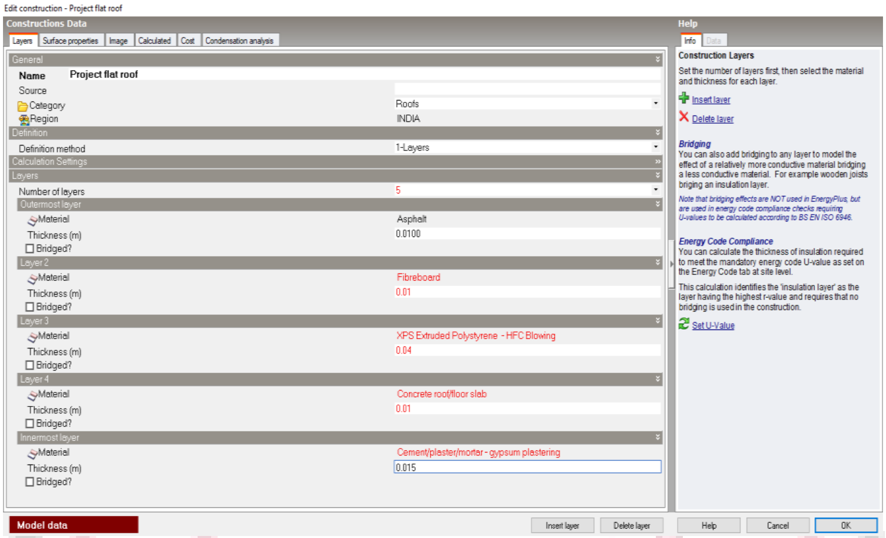

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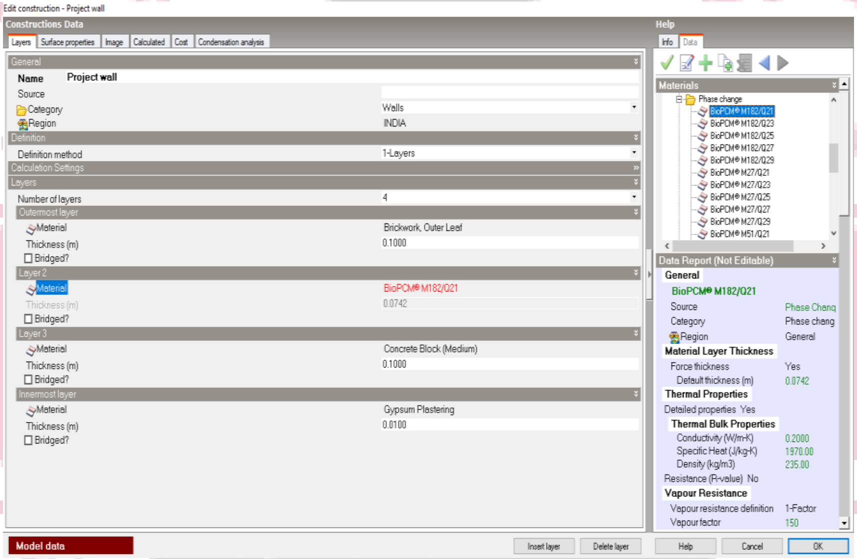

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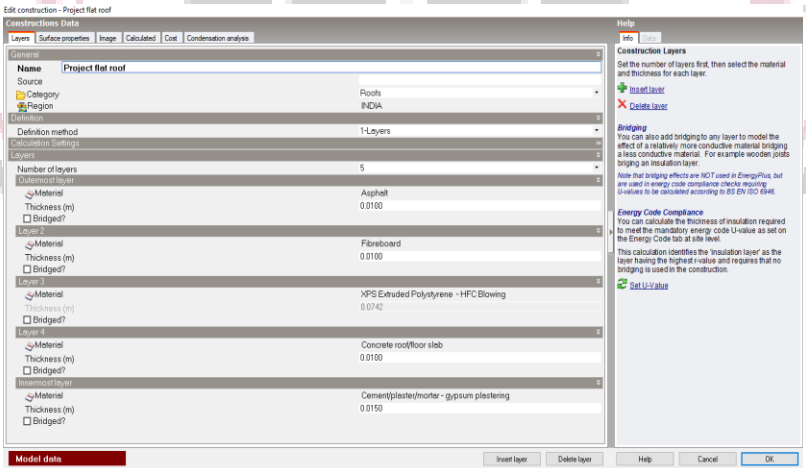


(e)

Figure 8 Building construction in the Design Builder

Fourth Step: Openings

In this step, default settings for window openings are applied.

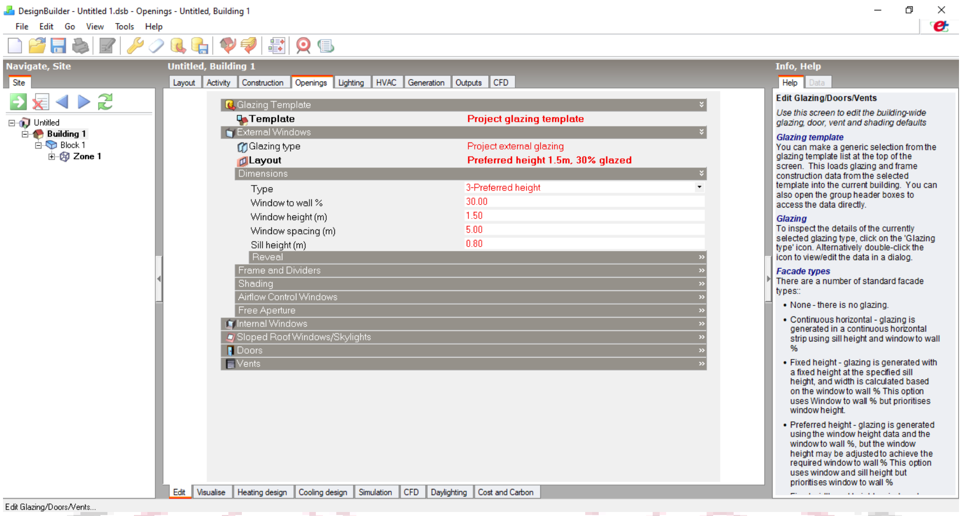


Figure 9 Building openings in the Design Builder

Fifth Step: Simulation

In this step, simulations are analysed.

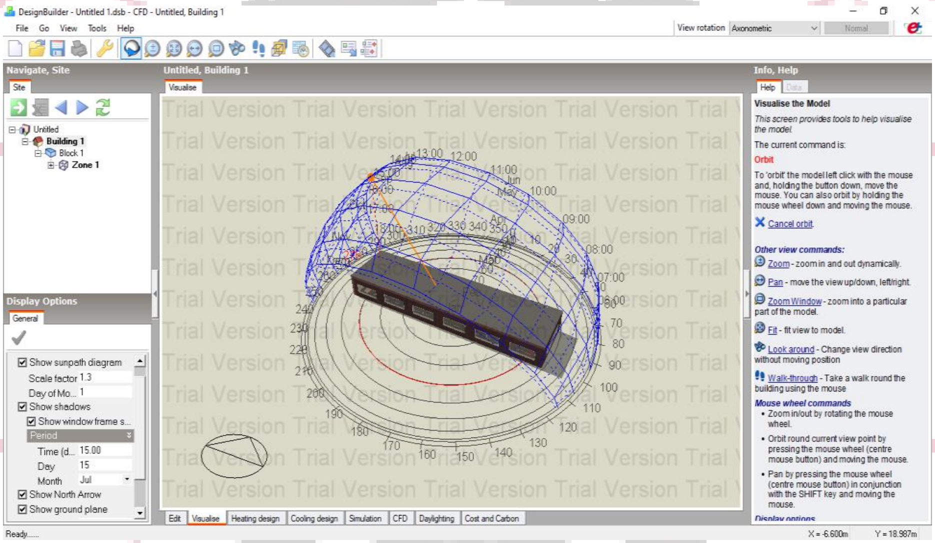


Figure 10 Simulation environment in the Design Builder

V. RESULT AND DISCUSSION

A. Simulation Results with XPS Extruded Polystyrene

In DesignBuilder, these parameters can be analyzed through simulations using building energy models that incorporate the properties of XPS insulation. By inputting relevant building characteristics, material properties, and environmental conditions, DesignBuilder can provide insights into how XPS insulation affects indoor thermal performance, including air temperature, radiant temperature, operative temperature, and their variations in response to changes in outside dry-bulb temperature. In DesignBuilder, the variation of air temperature, radiant temperature, operative temperature, and outside dry-bulb temperature with XPS (Extruded Polystyrene) insulation can be analyzed through simulation studies. XPS insulation is commonly used in building envelopes to reduce heat transfer and improve thermal comfort. With XPS insulation, the air temperature inside the building envelope is expected to be more stable compared to without insulation. XPS reduces heat transfer through conduction, thereby minimizing temperature fluctuations.

Figure 11 Variation of air temperature, radiant temperature, operative temperature and outside dry-bulb temperature with XPS Extruded Polystyrene

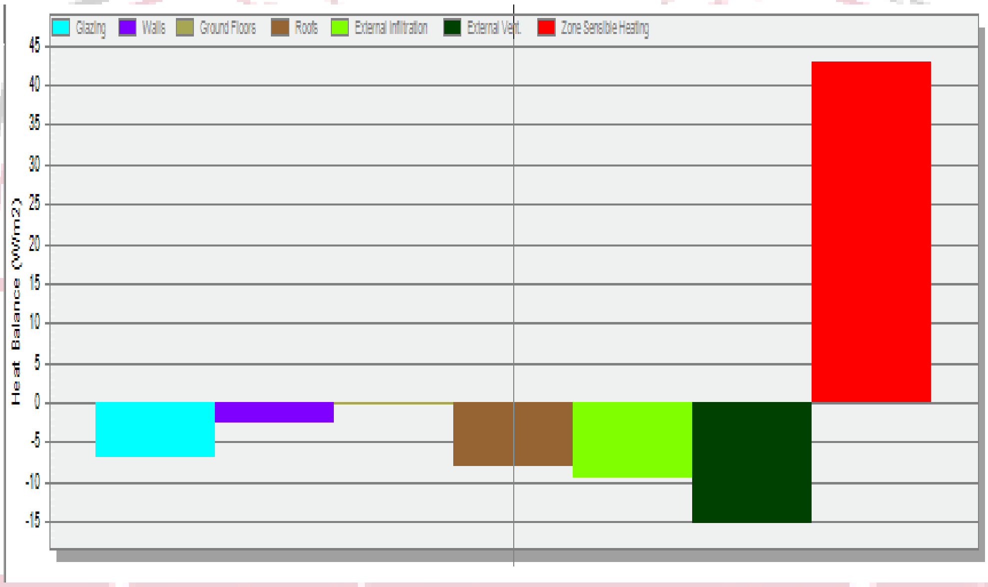


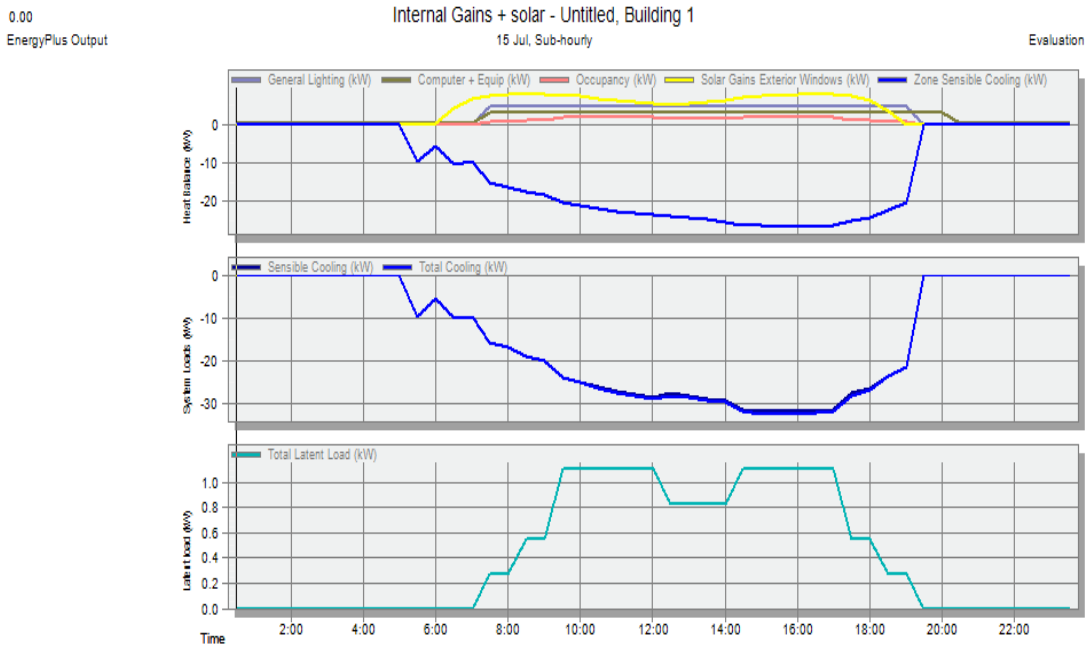
Figure 12 Variation of other results with XPS Extruded Polystyrene

Radiant temperature refers to the average temperature of all surrounding surfaces as perceived by an occupant. With XPS insulation, the radiant temperature may exhibit a slight decrease due to reduced heat transfer through building surfaces. Insulation helps in maintaining a more consistent indoor temperature, leading to a more stable radiant environment. Operative temperature is the combined effect of air temperature and radiant temperature and is indicative of thermal comfort. With XPS insulation, the operative temperature tends to be more comfortable as it mitigates both convective and radiant heat transfer, resulting in a more stable indoor thermal environment. The outside dry-bulb temperature remains unaffected by the presence of XPS insulation. However, the rate of heat transfer through the building envelope is significantly reduced, leading to less influence of exterior temperature variations on indoor conditions.

Temperature and Heat Loss

EnergyPlus Output	Evaluation
Air Temperature (°C)	22.00
Radiant Temperature (°C)	19.02
Operative Temperature (°C)	20.51
Outside Dry-Bulb Temperature (°C)	10.00
Glazing (W/m2)	-6.99
Walls (W/m2)	-2.68
Ground Floors (W/m2)	-0.38
Roofs (W/m2)	-8.12
External Infiltration (W/m2)	-9.63
External Vent. (W/m2)	-15.37
Zone Sensible Heating (W/m2)	43.03

Figure 13 Result output with XPS Extruded Polystyrene



	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
General Lighting (kW)	0.00	0.00	0.00	4.73	4.73	4.73	4.73	4.73	4.73	0.00	0.00
Computer + Equip (kW)	0.15	0.15	0.15	2.78	2.78	2.78	2.78	2.78	2.78	2.78	0.15
Occupancy (kW)	0.00	0.00	0.00	0.45	1.80	1.80	1.35	1.80	0.90	0.00	0.00
Solar Gains Exterior Windows (kW)	0.00	0.00	0.24	7.59	7.12	5.24	6.27	7.65	6.00	0.00	0.00
Zone Sensible Cooling (kW)	0.00	0.00	-5.64	-16.18	-20.93	-23.48	-25.17	-26.56	-24.24	0.00	0.00
Sensible Cooling (kW)	0.00	0.00	-5.64	-16.82	-24.89	-28.38	-29.21	-31.73	-26.48	0.00	0.00
Total Cooling (kW)	0.00	0.00	-5.64	-16.82	-24.89	-28.87	-29.58	-32.24	-26.81	0.00	0.00
Total Latent Load (kW)	0.00	0.00	0.00	0.28	1.11	1.11	0.83	1.11	0.55	0.00	0.00

Figure 14 Variation of latent load, system load and heat balance with XPS Extruded Polystyrene

By conducting simulations with and without XPS insulation, DesignBuilder can quantify the impact of insulation on latent load, system load, and heat balance, providing valuable insights for optimizing building performance and energy efficiency. In DesignBuilder, the variation of latent load, system load, and heat balance with XPS (Extruded Polystyrene) insulation can be analyzed through detailed energy simulations. XPS insulation affects building performance by reducing heat transfer, which in turn influences various aspects of the building's thermal behavior and energy requirements. The latent load refers to the energy required to remove moisture from the air, typically through the operation of HVAC systems. With XPS insulation, the reduction in heat transfer can lead to lower air infiltration rates and more stable indoor humidity levels. Consequently, the latent load may decrease as the need for dehumidification decreases due to improved building envelope performance.

System load encompasses both sensible and latent loads, representing the total energy demand for maintaining thermal comfort within a building. With XPS insulation, the reduction in heat transfer across the building envelope results in lower heating and cooling loads. This can lead to reduced energy consumption for HVAC systems, resulting in a decrease in the overall system load. The heat balance of a building is the equilibrium between heat gains and losses, considering various factors such as solar radiation, internal heat sources, and heat transfer through the building envelope. With XPS insulation, the heat balance is optimized by reducing heat losses in winter and heat gains in summer, resulting in a more stable and comfortable indoor environment.

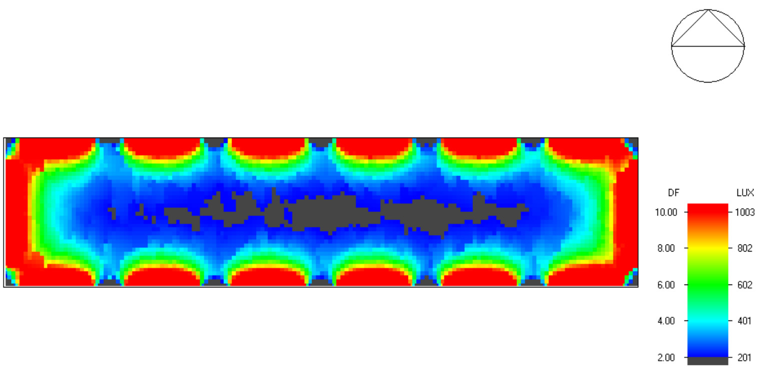


Figure 15 Illuminance level with XPS Extruded Polystyrene

In DesignBuilder, the illuminance level with XPS (Extruded Polystyrene) insulation can be evaluated through lighting simulation studies. XPS insulation primarily affects illuminance levels indirectly by influencing daylight penetration and distribution within the building. XPS insulation reduces heat transfer through the building envelope, which can lead to tighter construction with fewer air gaps. This can affect the amount of daylight entering the building through windows, as well as the distribution of daylight within interior spaces. With reduced heat loss or gain through the envelope, occupants may experience more consistent daylight levels throughout the day. The thermal properties of XPS insulation can influence the distribution of daylight within a building. By reducing heat transfer through walls, floors, and roofs, XPS insulation helps maintain more uniform indoor temperatures, which can in turn contribute to more consistent daylight distribution throughout the space. This may result in a more evenly lit environment, with fewer areas experiencing glare or shadowing.

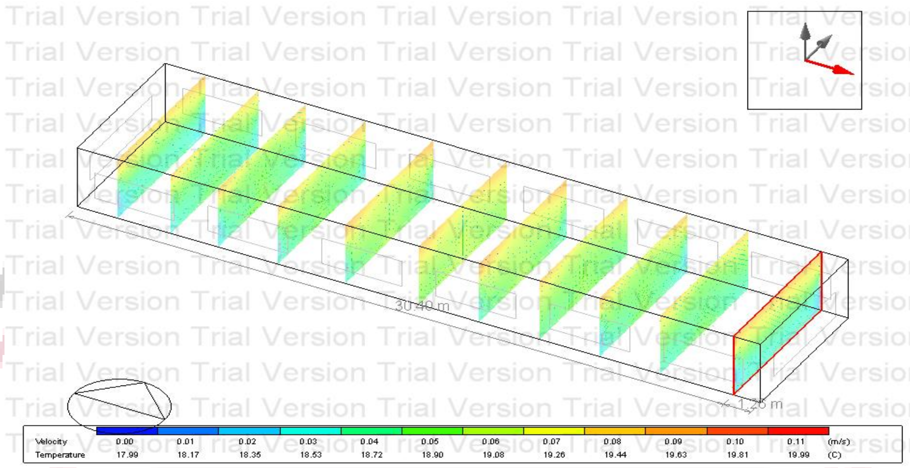


Figure 16 Distribution of velocity and temperature with XPS Extruded Polystyrene

B. Simulation Results with BioPCMs M182/Q21 (Indicated as PCM21)

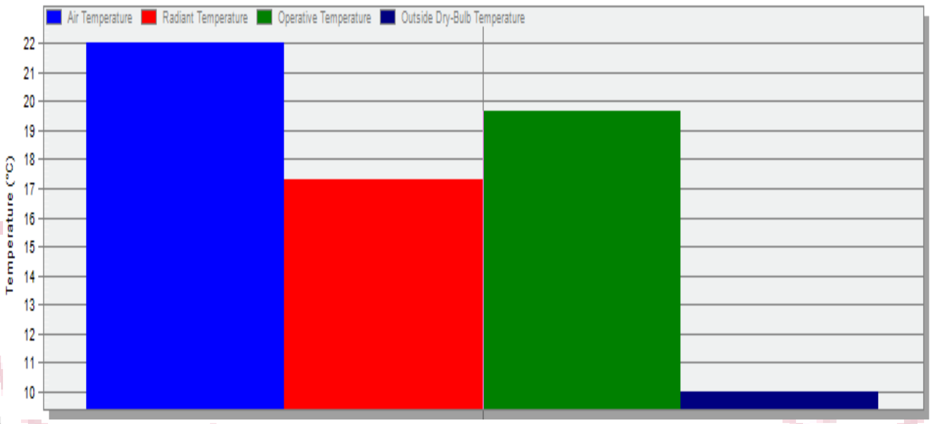


Figure 17 Variation of air temperature, radiant temperature, operative temperature and outside dry-bulb temperature with PCM21

In DesignBuilder, the variation of air temperature, radiant temperature, operative temperature, and outside dry-bulb temperature with PCM21 (Phase Change Material with a melting temperature around 21°C) can be assessed through thermal simulation studies. PCM21 is utilized in building envelopes to mitigate temperature fluctuations and improve thermal comfort. PCM21 absorbs and releases heat during its phase change, helping to stabilize indoor air temperature fluctuations. During periods of high ambient temperature, PCM21 absorbs heat as it melts, preventing rapid temperature increases. Conversely, during cooler periods, PCM21 releases stored heat as it solidifies, helping to maintain indoor temperatures. This leads to a more stable and moderated air temperature profile within the building. Radiant temperature is influenced by the temperature of surrounding surfaces. PCM21 moderates temperature swings by absorbing and releasing heat, thereby reducing the temperature differential between building surfaces and enhancing radiant comfort for occupants.

Operative temperature, which combines air temperature and radiant temperature, is a key indicator of thermal comfort. PCM21 contributes to maintaining a more stable operative temperature by moderating both convective and radiant heat transfer. This results in a more comfortable indoor environment for occupants. PCM21 does not directly influence the outside dry-bulb temperature. However, its presence in the building envelope mitigates the impact of external temperature fluctuations on indoor conditions by absorbing or releasing heat as needed to maintain thermal comfort.

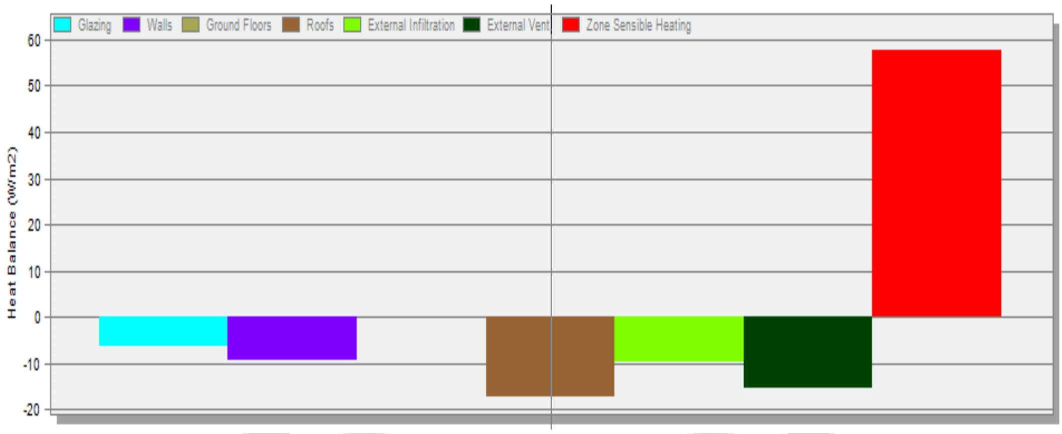


Figure 18 Variation of other results with PCM21

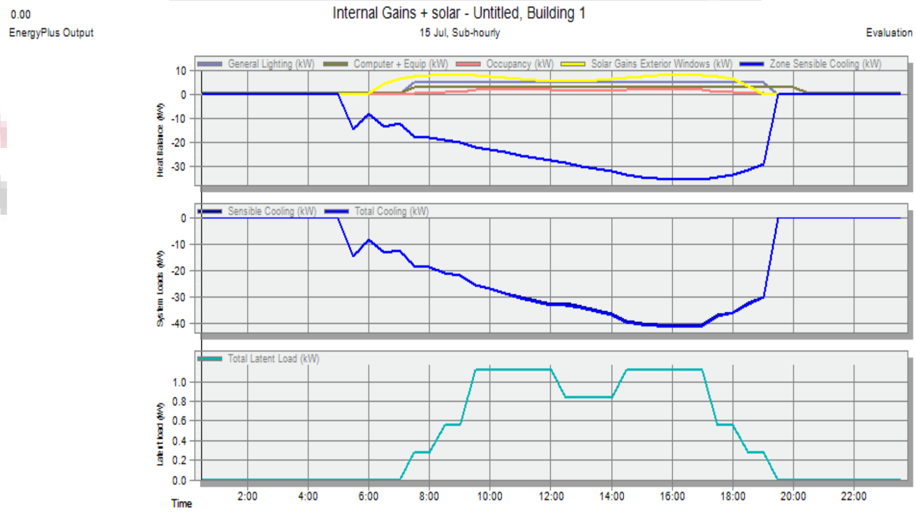
Temperature and Heat Loss

EnergyPlus Output

Evaluation

Air Temperature (°C)	22.00
Radiant Temperature (°C)	17.31
Operative Temperature (°C)	19.65
Outside Dry-Bulb Temperature (°C)	10.00
Glazing (W/m2)	-6.34
Walls (W/m2)	-9.23
Ground Floors (W/m2)	0.02
Roofs (W/m2)	-17.04
External Infiltration (W/m2)	-9.63
External Vent. (W/m2)	-15.37
Zone Sensible Heating (W/m2)	57.49

Figure 19 Results output with PCM21



Time	2:00	4:00	6:00	8:00	10:00	12:00	14:00	16:00	18:00	20:00	22:00
General Lighting (kW)	0.00	0.00	0.00	4.77	4.77	4.77	4.77	4.77	4.77	0.00	0.00
Computer + Equip (kW)	0.15	0.15	0.15	2.81	2.81	2.81	2.81	2.81	2.81	2.81	0.15
Occupancy (kW)	0.00	0.00	0.00	0.45	1.81	1.81	1.36	1.81	0.91	0.00	0.00
Solar Gains Exterior Windows (kW)	0.00	0.00	0.25	7.62	7.14	5.25	6.29	7.68	6.02	0.00	0.00
Zone Sensible Cooling (kW)	0.00	0.00	-8.32	-18.23	-23.05	-27.80	-32.21	-35.43	-33.39	0.00	0.00
Sensible Cooling (kW)	0.00	0.00	-8.32	-18.89	-27.04	-32.74	-36.29	-40.64	-35.65	0.00	0.00
Total Cooling (kW)	0.00	0.00	-8.32	-18.89	-27.04	-33.29	-36.70	-41.21	-35.98	0.00	0.00
Total Latent Load (kW)	0.00	0.00	0.00	0.28	1.12	1.12	0.84	1.12	0.56	0.00	0.00

Figure 20 Variation of latent load, system load and heat balance with PCM21

In DesignBuilder, the variation of latent load, system load, and heat balance with PCM21 (Phase Change Material with a melting temperature around 21°C) in building design can be analyzed using thermal simulation modules. PCM21 is incorporated into building envelopes to regulate temperature fluctuations and enhance energy efficiency (See fig. 4.9). PCM21 assists in managing latent loads by absorbing or releasing heat during its phase change, thereby reducing the need for mechanical dehumidification. As PCM21 absorbs moisture, it moderates indoor humidity levels, potentially decreasing the latent load by reducing the demand for air conditioning systems to dehumidify the air.

PCM21 influences the overall system load by reducing both sensible and latent loads. By stabilizing indoor temperatures, PCM21 decreases the need for heating and cooling, consequently lowering energy consumption associated with HVAC systems. Additionally, by managing humidity levels, PCM21 further reduces the load on air conditioning systems, resulting in additional energy savings. PCM21 contributes to maintaining a balanced heat profile within the building by absorbing and releasing heat as needed to stabilize indoor temperatures. During peak temperature periods, PCM21 absorbs excess heat, preventing overheating and reducing the need for active cooling. Conversely, during cooler periods, PCM21 releases stored heat, helping to maintain comfort conditions without relying heavily on heating systems. This balanced heat exchange promotes thermal comfort while reducing energy consumption.

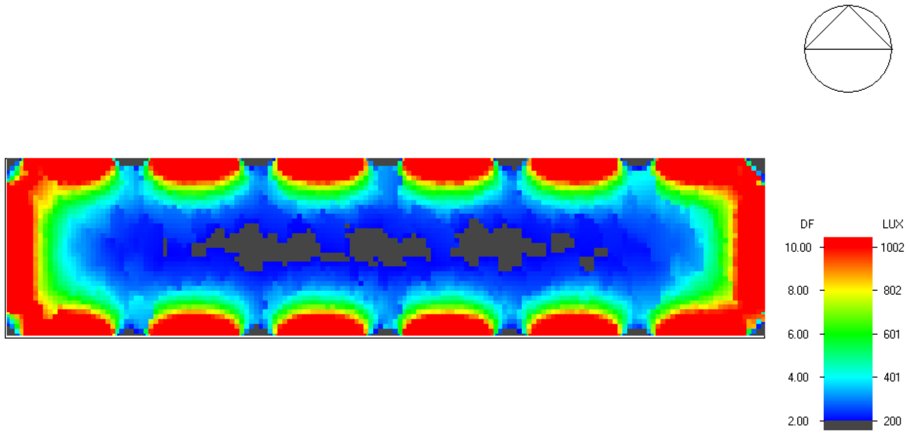


Figure 21 Illuminance level with PCM21

In DesignBuilder, the illuminance level with PCM21 insulation can be evaluated through lighting simulation studies. XPS insulation primarily affects illuminance levels indirectly by influencing daylight penetration and distribution within the building. PCM21 insulation reduces heat transfer through the building envelope, which can lead to tighter construction with fewer air gaps. This can affect the amount of daylight entering the building through windows, as well as the distribution of daylight within interior spaces. With reduced heat loss or gain through the envelope, occupants may experience more consistent daylight levels throughout the day. The thermal properties of PCM21 insulation can influence the distribution of daylight within a building. By reducing heat transfer through walls, floors, and roofs, PCM21 insulation helps maintain more uniform indoor temperatures, which can in turn contribute to more consistent daylight distribution throughout the space. This may result in a more evenly lit environment, with fewer areas experiencing glare or shadowing.

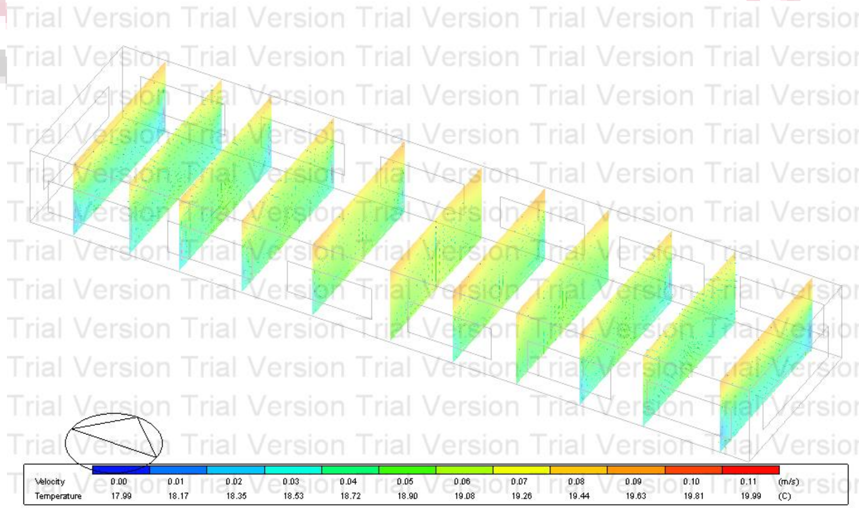


Figure 22 Distribution of velocity and temperature with PCM21

C. Overall Comparison

Based on the comparison of output in terms of air temp., radiant temp., operative temp., dry bulb temp., heat transfer in glazing, walls, ground floors, roofs, external infiltration, external vent and zone sensible heating, PCM 21 perform well and has the highest performance than with XPS Extruded Polystyrene.

Temperature and Heat Loss

EnergyPlus Output	Evaluation
Air Temperature (°C)	22.00
Radiant Temperature (°C)	19.02
Operative Temperature (°C)	20.51
Outside Dry-Bulb Temperature (°C)	10.00
Glazing (W/m2)	-6.99
Walls (W/m2)	-2.68
Ground Floors (W/m2)	-0.38
Roofs (W/m2)	-8.12
External Infiltration (W/m2)	-9.63
External Vent. (W/m2)	-15.37
Zone Sensible Heating (W/m2)	43.03

(a) With XPS Extruded Polystyrene

Temperature and Heat Loss

EnergyPlus Output	Evaluation
Air Temperature (°C)	22.00
Radiant Temperature (°C)	17.31
Operative Temperature (°C)	19.65
Outside Dry-Bulb Temperature (°C)	10.00
Glazing (W/m2)	-6.34
Walls (W/m2)	-9.23
Ground Floors (W/m2)	0.02
Roofs (W/m2)	-17.04
External Infiltration (W/m2)	-9.63
External Vent. (W/m2)	-15.37
Zone Sensible Heating (W/m2)	57.49

(b) With PCM21

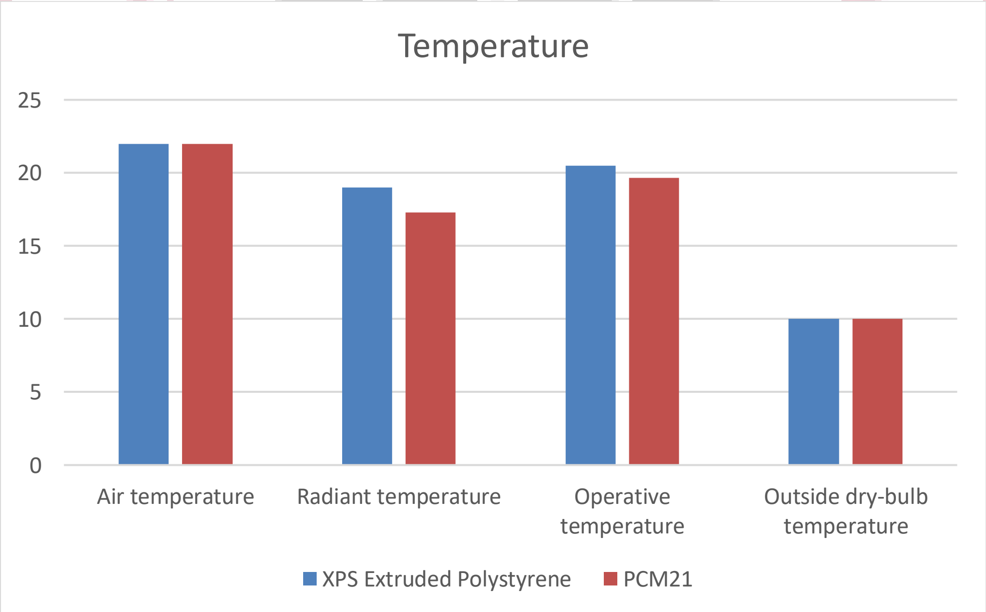


Figure 23 Temperature comparison results with different PCM material

PCM21 exhibits better control over these parameters by effectively moderating temperature fluctuations within the building envelope. Its ability to absorb and release heat during phase change contributes to maintaining more stable and comfortable indoor conditions compared to XPS insulation. PCM21 demonstrates superior performance in regulating heat transfer through these building components. By actively managing thermal energy through phase change processes, PCM21 minimizes heat gain or loss, leading to reduced energy consumption for heating and cooling compared to XPS insulation. PCM21 helps in reducing external infiltration by maintaining more stable indoor temperatures, thereby minimizing the pressure differences that drive air leakage through the building envelope. This contributes to better energy efficiency and indoor air quality compared to XPS insulation.

PCM21's thermal properties contribute to maintaining more stable indoor conditions, reducing the need for mechanical ventilation and associated energy consumption, compared to XPS insulation. PCM21 demonstrates better performance in reducing the need for zone sensible heating due to its ability to store and release heat, effectively maintaining comfortable indoor temperatures without relying heavily on supplemental heating compared to XPS insulation. In summary, PCM21 offers superior thermal performance and energy efficiency compared to XPS insulation across various parameters in DesignBuilder simulations. Its ability to actively manage heat transfer and maintain stable indoor conditions makes it a favorable choice for enhancing building performance and occupant comfort.

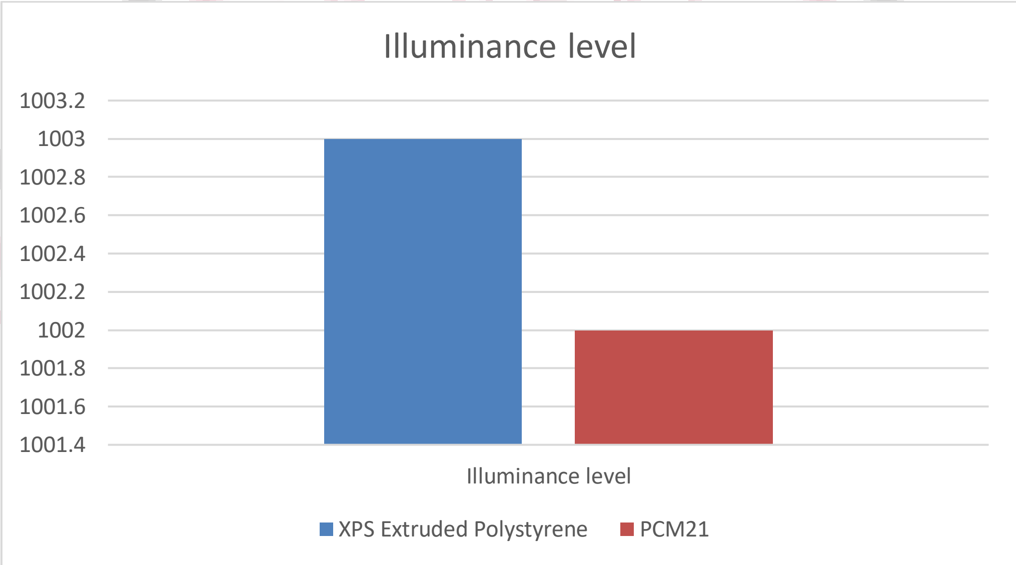


Figure 24 Illuminance level comparison

Based on the comparison of illuminance level, PCM 21 perform well and has the highest performance than with XPS Extruded Polystyrene. PCM21 aids in moderating daylight penetration by stabilizing indoor temperatures. By absorbing excess heat during periods of high solar radiation and releasing it when sunlight diminishes, PCM21 helps maintain a more consistent indoor environment. This stability contributes to more predictable daylight levels throughout the day, enhancing overall illumination within the building.

PCM21 contributes to more uniform daylight distribution within the building by reducing temperature differentials across surfaces. By minimizing heat gain or loss through the building envelope, PCM21 helps prevent localized temperature variations that can lead to uneven lighting conditions. This promotes a more evenly lit environment, reducing the occurrence of glare and shadowing.

PCM21 enhances visual comfort by ensuring a more consistent and balanced lighting environment. With reduced fluctuations in indoor temperatures, occupants experience fewer variations in daylight levels, leading to improved visual comfort and productivity. Additionally, PCM21's ability to stabilize indoor conditions minimizes the need for artificial lighting adjustments, further enhancing occupant satisfaction.

In summary, PCM21 outperforms XPS insulation in terms of illuminance levels by promoting more stable and uniform daylight distribution within the building. Its ability to moderate indoor temperatures enhances visual comfort, reduces energy consumption, and creates a more pleasant and productive indoor environment for occupants.

PCM21 exhibits better control over these parameters by effectively moderating temperature fluctuations within the building envelope. Its ability to absorb and release heat during phase change contributes to maintaining more stable and comfortable indoor conditions compared to XPS insulation.

PCM21 demonstrates superior performance in regulating heat transfer through these building components. By actively managing thermal energy through phase change processes, PCM21 minimizes heat gain or loss, leading to reduced energy consumption for heating and cooling compared to XPS insulation.

PCM21 helps in reducing external infiltration by maintaining more stable indoor temperatures, thereby minimizing the pressure differences that drive air leakage through the building envelope. This contributes to better energy efficiency and indoor air quality compared to XPS insulation.

PCM21's thermal properties contribute to maintaining more stable indoor conditions, reducing the need for mechanical ventilation and associated energy consumption, compared to XPS insulation.

PCM21 demonstrates better performance in reducing the need for zone sensible heating due to its ability to store and release heat, effectively maintaining comfortable indoor temperatures without relying heavily on supplemental heating compared to XPS insulation.

In summary, PCM21 offers superior thermal performance and energy efficiency compared to XPS insulation across various parameters in Design Builder simulations. Its ability to actively manage heat transfer and maintain stable indoor conditions makes it a favorable choice for enhancing building performance and occupant comfort.

VI. CONCLUSION

This research underscores the critical role of the window-to-wall ratio in optimizing energy efficiency and indoor environmental quality in office buildings across diverse climates in Iran. By analyzing various climatic zones—from hot-humid to cold regions—the study demonstrates that the appropriate fenestration design significantly influences both energy consumption and occupant comfort. In hot-dry climates, reducing solar heat gain through lower window-to-wall ratios proves effective, while in colder regions, higher ratios can enhance passive solar heating. Moreover, integrating phase change materials (PCMs) with optimized window designs shows promise in further improving thermal performance. These findings offer valuable guidelines for architects and engineers to enhance sustainability and comfort in office building design, aligning with global efforts towards energy-efficient construction practices.

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