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Master of Architecture – Sustainable Design

The Impact of Using Phase Change Materials for Enhancing Thermal Performance of Residential Building Walls in The Extreme Conditions of Mediterranean Region: A Case of Jerusalem

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[The Impact of Using Phase Change Materials for Enhancing Thermal Performance of Residential Building Walls in The Extreme Conditions of Mediterranean Region: A Case of Jerusalem]

[MOHAMMAD ALHASANI]

in partial fulfillment of the requirements for the degree of Master in Renewable Energy & Sustainability.

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[The Impact of Using Phase Change Materials for Enhancing Thermal Performance of Residential Building Walls in The Extreme Conditions of Mediterranean Region: A Case of Jerusalem]

MOHAMMAD IBRAHIM ALHASANI

ABSTRACT

Increasing of energy consumption in residential buildings recently has received a significant concern on the thermal performance of buildings. Reducing energy consumption resulting from the heating and cooling demands of a building and limiting heat loss or gain can play a main role in buildings' saving energy. The thermal insulation of building walls has a significant impact on energy conservation. In this study, a group of models was developed to achieve the best thermal performance for the external walls of residential buildings. Composite wall models enhanced with selected insulation materials have been thermally examined in the extreme conditions in the Mediterranean region to determine the impact of the used materials on the thermal performance of buildings envelopes and energy consumption, with validating results through FLUENT software. The study’s methodology is based on two main stages, analyzing the wall models, and evaluating the most effective thermal performance and the developed ones using FLUENT software based on the location of the insulation layer, thickness, and thermal behavior. The second is investigating heating and cooling loads during winter and summer via DesignBuilder software. The study showed that using Phase Change Material (PCM) insulation materials in the building wall composition has a significant impact on the thermal performance of the building envelope, thermal heat transfer, temperature distribution, and on heating and cooling loads. The heat transfer calculations appeared that the average temperature of the internal surface of the wall can be reduced significantly by almost (1.5-3.5) °C in the summer and by almost (2-6.5) °C in winter when applying Paraffin in an appropriate thickness and location within extreme conditions compared to the system without an insulation layer. The energy calculations of heating and cooling loads obtained showed a reduction in energy demand when using PCM. The saving of heating energy in January was 35.5%, whereas the saving of cooling energy in August was 41.9%. Moreover, the reduction amount of annual energy load was 3013.57kWh with a saving of 40.1% and the payback period was 2.5 years.

Keywords

Building Energy Consumption, Energy Efficient Building, Thermal Performance, Conventional Materials, Phase Change Material, Heating and Cooling Loads

[أثر استخدام مواد متغيرة الطور لتحسين الأداء الحراري لجدران المباني السكنية في الظروف المناخية القاسية لمنطقة البحر الأبيض المتوسط: القدس كحالة دراسية]

محمد إبراهيم الحسني

المستخلص

تلقى الاستهلاك المتزايد للطاقة في المباني السكنية مؤخرًا اهتمامًا كبيرًا بالأداء الحراري للمباني. يؤدي تقليل استهلاك الطاقة الناتج عن متطلبات التدفئة والتبريد للمبنى والحد من فقدان الحرارة أو اكتسابها دورًا رئيسيًا في توفير الطاقة للمباني. العزل الحراري لجدران المبنى له تأثير كبير أيضاً على الحفاظ على الطاقة. في هذه الدراسة تم تطوير مجموعة من النماذج لتحقيق أفضل أداء حراري للجدران الخارجية للمباني السكنية. تم فحص نماذج الجدران المركبة المعززة بمواد عزل حراري مختارة في الظروف القاسية في منطقة البحر الأبيض المتوسط لتحديد تأثير المواد المستخدمة على الأداء الحراري لأغلفة المباني واستهلاك الطاقة، مع التحقق من النتائج من خلال برنامج المحاكاة. تعتمد منهجية الدراسة على مرحلتين رئيسيتين؛ تحليل نماذج الجدران، وتقييم الأداء الحراري الأكثر فعالية للجدران باستخدام برنامج FLUENT من خلال دراسة أثر موقع طبقة العزل، والسمك، والسلوك الحراري. بالإضافة إلى فحص أحمال التدفئة والتبريد في الشتاء والصيف باستخدام برنامج DesignBuilder. أوضحت الدراسة أن استخدام مواد العزل PCM في تكوين جدار المبنى له تأثير كبير على الأداء الحراري لغلاف المبنى، والانتقال الحراري، وتوزيع درجات الحرارة، وعلى أحمال التدفئة والتبريد. أظهرت حسابات انتقال الحرارة أن متوسط درجة الحرارة للسطح الداخلي للجدار يمكن أن ينخفض بشكل ملحوظ بما يقارب (3.5-1.5) درجة مئوية في الصيف وحوالي (6.5-2) درجة مئوية في الشتاء عند تطبيق البارافين بشكل مناسب من حيث السماكة والموقع في ظل الظروف القاسية مقارنة بنظام الجدران بدون طبقة عازلة. كما أظهرت حسابات الطاقة التي تم الحصول عليها لأحمال التدفئة والتبريد انخفاضًا في الطلب على الطاقة عند استخدام مادة PCM؛ حيث بلغت نسبة التوفير في طاقة التدفئة لشهر يناير 35.5٪، بينما بلغت نسبة التوفير في طاقة التبريد لشهر أغسطس 41.9٪. علاوة على ذلك، بلغ مقدار الخفض من حمل الطاقة السنوي 3013.57 كيلوواط ساعة مع توفير بنسبة 40.1٪ وبالتالي فترة الاسترداد 2.5 سنة.

DECLARATION

I declare that the Master Thesis entitled “The Impact of Using Phase Change Materials for Enhancing Thermal Performance of Residential Building Walls in The Extreme Conditions of Mediterranean Region: A Case of Jerusalem” is my original work, and herby certify that unless stated, all work contained within this thesis is my independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

Student Name………………………………….

Signature:———————————— Date:————————

List of Abbreviations

WWR%: Window to Wall Ratio

SHGC: Solar Heat Gain Coefficient

U –Value: Transmittance Value

ASHRAE: The American Society of Heating, Refrigerating and Air-Conditioning Engineers

HVAC: Heating, ventilating, and air conditioning

CFD: Computational Fluid Dynamics

PMV: The predicted mean vote index

PPD: The predicted percentage of dissatisfied

PCM: Phase Change Material

XPS: extruded polystyrene

c: specific heat capacity (J/(kg K))

λ: Thermal conductivity (W/(m K))

L: latent heat of fusion (kJ/kg)

R: thermal resistance (m^2 K/W)

T: temperature (°C)

U: thermal transmittance (U-value) (W/(m^2 K)

ρ: density (kg/m3)

C: Celsius (°C)

Cs: heat capacity (J/kg·K)

K: Kelvin (^{o} K)

Ps: Saturation pressure (Pa)

P: Actual vapor pressure (Pa)

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Chapter One

Chapter One: Introduction

1.1 Preface

Providing an appropriate internal environment is one of the main requirements in buildings, whether for housing, work, or entertainment by achieving thermal environmental and health comfort for the occupants. However, preserving a comfortable environment represents a challenge for humanity to continue living and provide the appropriate climate and environment for humans inside and outside buildings, and this requires working to achieve environmental balance and stability at local and global levels to continue life on the surface of the earth, and not to produce more harmful pollutants to various elements of the environment considering the local climatic conditions, environment, social and economic conditions. Passive techniques also should be implemented to achieve the main goal of saving energy. Using thermal insulation is one of the effective passive strategies in buildings in order to reduce energy consumption and limit heat transfer through the building envelope, which maintains the thermal satisfaction for occupants in the interior spaces.

1.2 Statement of the Problem

- People suffer from the high amount of energy consumption and electric expenditures for heating and cooling needs and indoor thermal discomfort.
- The residential sector in Palestine is the highest consumption section of energy.
- According to global and local statistics, electric energy is the largest part of house energy consumption, however, Energy consumption is expected to increase due to urbanization, population growth, and climate change.
- Electric power consumption in Palestine has a high-value bill prices among the neighboring countries, and a high percentage of electrical energy consumption goes to heating and cooling.
- The total of renewable energy sounded not enough to bridge the gap in the increase in energy demand.
- Building walls are considered one of the largest causes of heat loss, so thermal insulation must be treated to reach building energy efficiency.
- New studies are needed on an appropriate isolation mechanism in the climatic region of the study using new materials.

1.3 Objectives of the Study

The thesis aims to find a proper isolation mechanism within the climatic environment of the study in the presence of different recent materials to enhance the thermal performance of residential buildings. The specific objectives of this thesis are as follows:

- Improving thermal performance of residential buildings walls in Palestine.
- Observing temperature distribution along the wall section.
- Maintaining the average internal surface temperature lower than the outside in the summer and higher in the winter.
- Investigating the impact of using new material (PCM) in the residential building wall.
- Reducing heating & cooling loads of the residential buildings.
- Saving energy of the residential buildings in Palestine.
- Determining the effectiveness of using new material (PCM) comparing to conventional insulation material (XPS) and cost benefits.

1.4 Research Significance (based on previous works)

- High energy consumption is often associated with the poor thermal performance of building envelopes (Vihola *et al.*, 2015). Three of the most important determinants that have a significant impact on the performance of walls in the building envelope are thickness, insulation location, and thermal behavior (Risberg, 2018), (Vihola *et al.*, 2015), which is important aspects to achieve building energy efficiency (*Green buildings Guidelines - State of Palestine*, 2013), as the decrease of building energy demand leads to a reduction of energy-saving needs (Lazzeroni *et al.*, 2017). And so on, this research has looked at enhancing the thermal performance of the residential building envelope (ext. walls) in a specific climatic zone to reach the best wall performance.
- Most studies (related to the study climate) for conventional insulating materials have focused on the determinants through numerical procedures such as thickness (Ozel, 2013), (Abdelgadir *et al.*, 2019), (Aktemur and Atikol, 2017) insulation location (Sobota and Taler, 2018), (Bekkouche *et al.*, 2013), (Al-Sanea and Zedan, 2011), (Wang *et al.*, 2016) and thermal behavior (Mohammad *et al.*, 2020), (Shahedan *et al.*, 2017), (Long and Ye, 2015) separately or linked with another determinant or other factors, without connecting the three main determinants together. Accordingly, the research is directed towards linking these main determinants, considering the impact of other factors.

- Some studies that intersected with the survey in the climatic region and in some aspects of the research framework, such as:
  - Muna (Awad, 2021), in her study, aimed to develop a software program to calculate optimal insulation thickness to be applied to residential buildings walls in different climatic regions considering economic parameters, devices efficiency, material type, and degree days. However, the study didn't consider the upper limit of the thickness desired to be used in the limited spaces or the variety of walls used in the climatic environment, also there is a deficiency in linking the three most important determinants that have the greatest impact on the performance of the walls in the building envelope. in addition to the inability to compare the optimized thickness, location of the insulator, and the type of insulator together, and finally ineffectiveness usage in existing buildings.
  - In the same direction, Lisa (Muallem, 2020) dealt with the development of simulation-based early design tool for apartments to control thermal performance and the energy consumption in buildings, counting the variables design parameters like orientation, layout, floor level, insulation thickness, glazing type, site density, and topography. As a result, 40-45% of energy consumption can be saved in a living space. The study focused on traditional materials and was limited to the use of insulation thickness and type with linking other parameters to clarify the effect on the thermal comfort of the building to infer the thermal performance of the wall.
  - Another research (Salameh, 2012) focused on the building envelope as a whole and on the external walls as an important component in affecting energy consumption. It aimed to improve the external wall systems and make them more efficient by using local materials with good thermal properties, and the need to use thermal insulation to reduce cooling and heating loads. The study also concluded that the traditional building practice methods do not consider a sustainable approach and need to be developed. However, the focus of the research was limited to the aspect of building materials and the use of thermal insulation without considering or linking it with other influencing factors.
  - Mohaibesh et al., in their recent study, evaluated the impact of adopting strategies of architectural design and material technologies to create a modern climate-resilient building in two different climatic zones in Palestine (Mohaibesh *et al.*, 2021). The results showed the significant thermal impact of the proposed model of the external wall in reducing heating and cooling loads (Mohaibesh *et al.*, 2021). Another hand, Haj Hussein et al. evaluated the effect of thermal mass

  on the indoor thermal environment of residential buildings in Palestine. They proposed different scenarios of models according to thermal insulation location in the wall that impacts the energy demand indeed (Hussein *et al.*, 2021). However, they examined the models in ordinary climate conditions. These give impetus to the development of new models to achieve better behavior of walls, reduce energy consumption, and investigate extreme climate conditions.
  - Moreover, previous studies recommended conducting more studies on the influence of PCMs in the different climatic conditions as well Mediterranean climate for different PCMs and wall components (Asker *et al.*, 2018).

- There is a lack of local studies looking at PCMs and their thermal performance, or even studies comparing the thermal performance between conventional materials and PCMs in the Mediterranean climate despite PCMs commercial products being available (Konstantinidou, Lang and Papadopoulos, 2018), or theoretical studies related to the study of climate, and thermal performance of walls, energy consumption, and heat transfer and a comparison of their effect on heating and cooling loads.
- This study links the most important determinants: thermal behavior, location, and thickness of thermal insulations to be used in the residential buildings, considering the other determinants and their impact.
- The study investigates PCM and compares its results with conventional materials and the possibility of its application in the same climatic environment, which is considered a significant direction for the practical applications of phase change materials (PCMs) in buildings.
- The contribution of the research lies in the use of a new thermal insulation material (PCM) in the external walls of residential buildings in Palestine, as it will help engineers, designers, and researchers to verify any current or future applied studies.
- Indeed, this study is one of the first local and regional studies to examine the thermal performance of PCM and compare it with conventional materials numerically based on the main determinants to observe the thermal performance of walls, heat transfer, and energy consumption, comparing results, and finding the feasibility of using new material, installation, cost, and the payback period.

1.5 Research Methodology

The framework of the research is divided into two main parts: First, the heat transfer study that is emphasized studying conventional insulation materials used within the local climatic environment through literature reviews, experience, and the local market. In addition to the phase change materials as new insulation materials. In parallel, a simulation study using FLUENT software is conducted to find the best performance of the insulated wall models used as well ensuring the results through a validation study. The heat transfer calculations have been done under extreme conditions in winter and summer in the Mediterranean region as the worst-case scenarios to monitor the ability of the material to isolate in extreme conditions without a system collapse, as well as due to the marked climate change and temperature fluctuations in recent years. In addition to obtaining the best practices of wall models to reach the energy efficiency of residential buildings compared with common practices in the local environment of Palestine in general and in Jerusalem particularly. The thermal performance of the building envelope has been studied to determine the most significant element in energy consumption through previous studies, in order to improve the thermal performance of residential buildings in Palestine. By using FLUENT software, a numerical investigation for selected wall models was conducted to observe the temperatures distribution through the walls sections at different heights by selecting points in the middle of each layer in addition to the internal and external surfaces, for the purpose of finding the best practices of walls construction. Locations of the insulation layer within walls sections are assumed to be towards the exterior, in the middle, and towards the interior. Thicknesses of insulation layers in this study are also assumed 4 cm XPS and 2 cm PCM for the full thickness applied cases, as the use of material with higher physical and thermal properties has an advantage in results if it is used with the same thickness of local materials with lower properties, in addition to relying on some close numbers in the use of the material from previous studies, and adopting a correct ratio between the two materials for comparison. The numbers decreased to 2 cm, and 1 cm for the last case to see the difference in the effectiveness of the materials in a lower thickness of double layers wall compared to a wall with a single layer of XPS material, also to observe the thermal behavior and compare the cases to find the best practices and conclude recommendations of using insulations. Based on the numerical investigation of cases and the heat distribution within walls sections, the temperature average of the internal surface of the walls will be examined and compared with other models in hot summer and cold winter (extreme conditions). These calculations have been verified by a selected similar case that used the same software. The second part is concerned with studying the energy of heating and cooling calculations, and comfort calculations. The heating and cooling loads of the residential building have been examined through a case study of an apartment in the city of Jerusalem under normal thermal boundary conditions. Energy demand was calculated for the month of January and August as being the months with the highest demand for energy. In addition to seeing the extent to which the heating and cooling loads are reduced. The percentage of energy saving in the case of applying PCM thermal insulation was examined based on the results of calculations of heating and cooling loads for the residential building. The study emphasized apartment type of buildings as the residential apartments are the largest in the urban environment and have the highest expenditures on electric energy according to (Abdel Jawad and Ayyash, 2019) and (Monna *et al.*, 2020). Also, materials prices and the cost estimates were studied in order to figure out the payback period and the feasibility of using new material within the Palestinian context. Moreover, comfort calculations were examined to predict the entire thermal comfort. The numerical investigation of the study will help to figure out the impact of using new material (PCM) in the residential building wall in the local area. And determining the effectiveness of using new material (PCM) comparing to traditional insulation material (XPS) based on the thermal behavior, thickness, location, cost, and the stage of construction. In addition, observing the potential of condensation occurring in the wall layers. See the figure below:

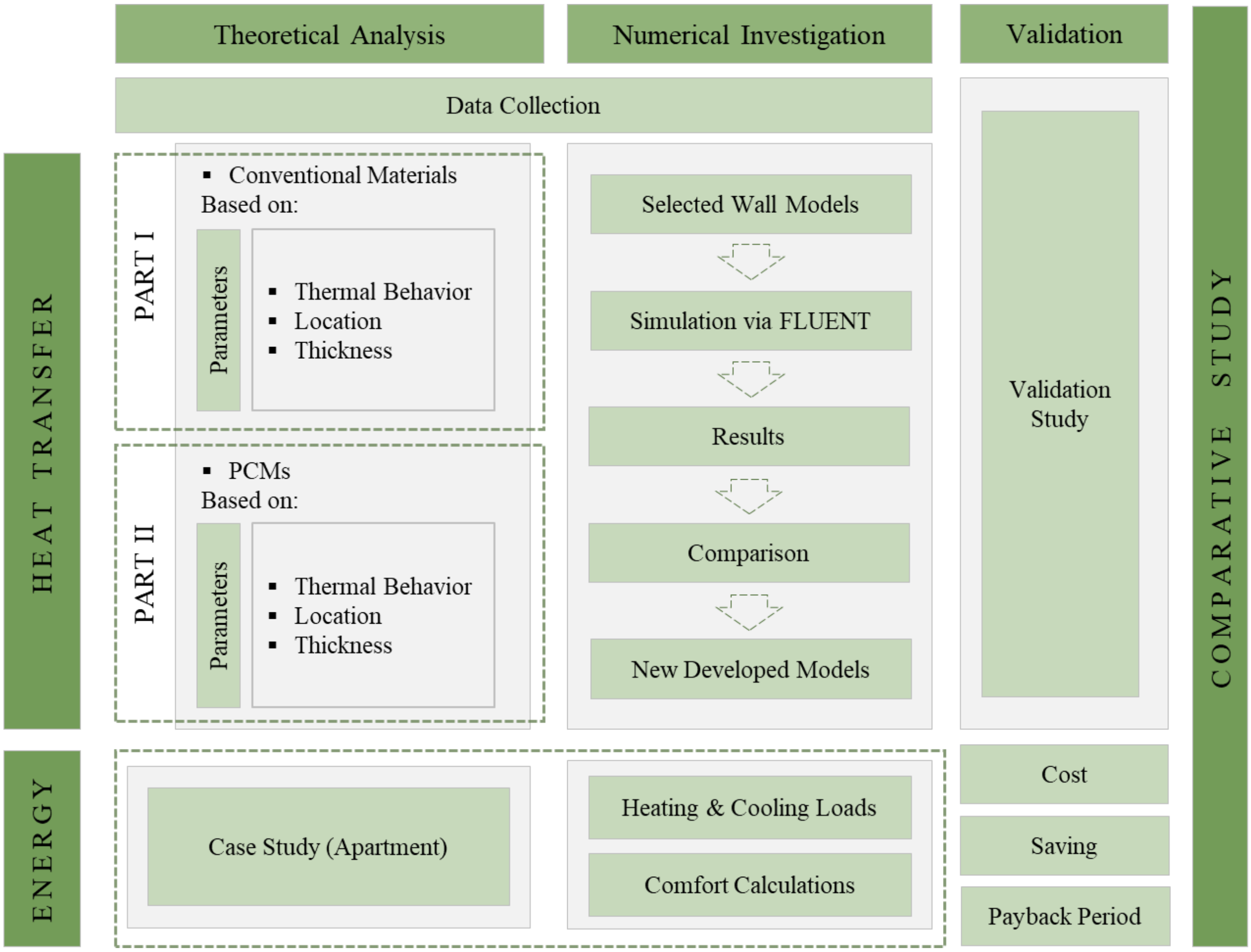


Figure 1 Research Methodology, Researcher.

1.6 Research Methods

Enhancing the energy efficiency of building walls (External walls) requires finding the best behavior of isolation mechanisms of the selected walls within the climatic region of the study. This includes studying conventional materials and PCMs theoretically and analytically, based on literature reviews and practical experience, in parallel with a numerical investigation over two stages divided into four phases as it is seen in the figures below; Firstly:

- A study of XPS and PCM through a numerical study via ANSYS (FLUENT) software on selected common models reaching out the best practices.
- The calculations relied on three parameters: Thermal Behavior, Thickness, and Location.
- The results will be validated based on a base case study.
- The model walls will be compared based on the parameters and the thermal performance will be observed to reach the best behavior of the cases.

Secondly:

- A study of the heating and cooling loads will be examined through a case study of an apartment in the city of Jerusalem under the normal thermal boundary conditions during January and August.
- The percentage of energy saving in case of applying PCM thermal insulation will be examined based on the results of heating and cooling loads.
- Materials prices and the cost estimates will be collected and studied to find the payback period.

To reach the best thermal performance of typical walls, the next figure shows the scenarios of developed walls to be used in the simulation process. In addition to the energy calculation of heating and cooling to monitor the contribution of using a new material Phase Change Material (PCM) in affecting the amount of building heating and cooling demands. This requires a thermal loads investigation using a case study of an apartment in the city of Jerusalem under thermal boundary conditions for the reference case without insulation and when the PCM thermal insulation layer is applied. Based on these loads' calculations, the percentage of energy saving can be estimated, the cost of using new materials, and the amount of energy load reduction.

The study also presented the effectiveness of using paraffin (PCM) as new material compared to extruded polystyrene insulation (XPS) based on a criterion that includes thermal behavior, thickness, location, cost, and the payback period. See the figures below:

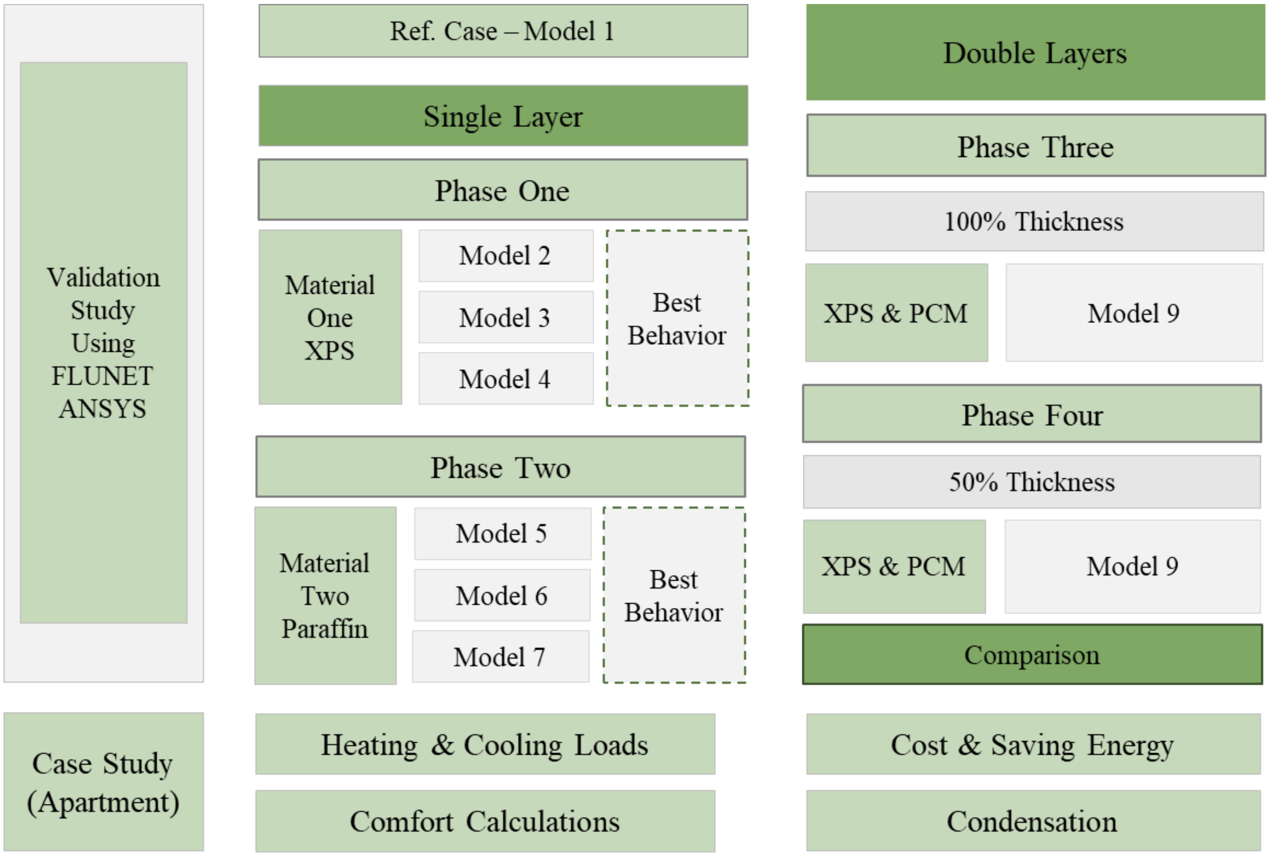


Figure 2 Research Methods

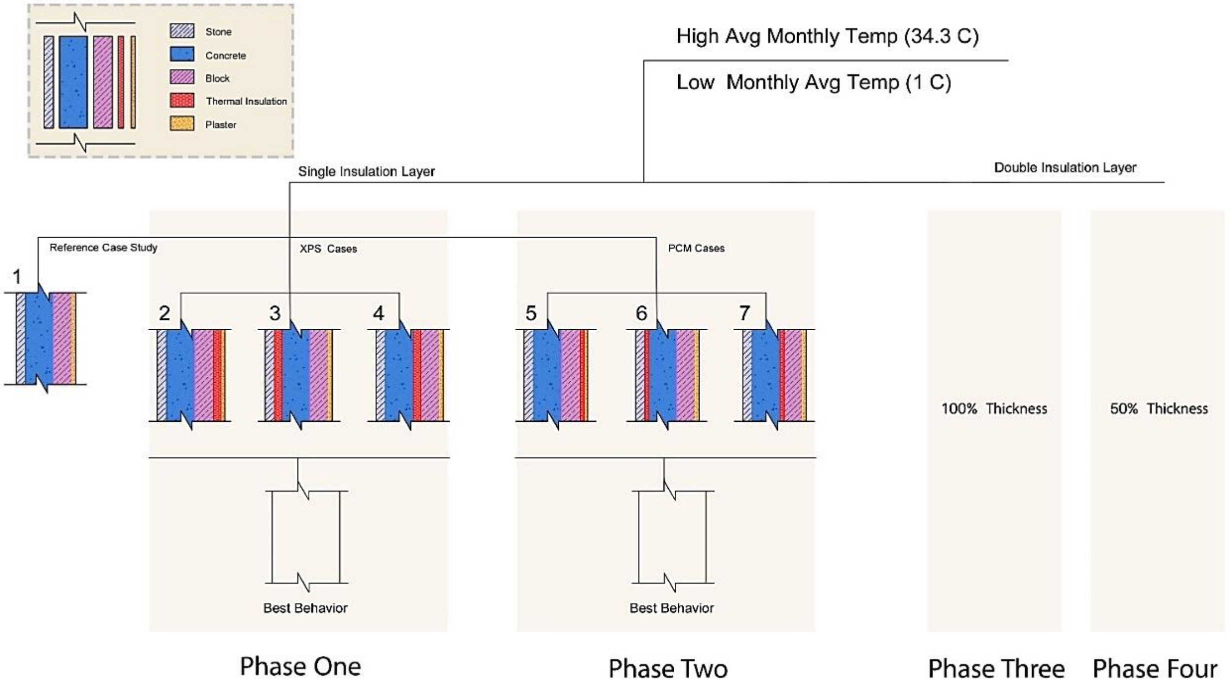


Figure 3 shows the model walls graph.

1.7 Research Structure

The research includes five chapters. The first chapter introduces focusing on the research statement, objectives, significance, and methodology. The second chapter is concerned with the theoretical aspect including global and local statistics of energy consumption, thermal performance of buildings, and considerations and determinants according to the sustainable aspect as well. The third chapter shows and compares conventional materials and phase change materials based on thermal properties, thickness, and locations of the material layer, in addition to the materials' price. The fourth chapter includes an analysis of the case study that is divided into three numerical investigations: heat transfer calculations, energy loads calculations, and thermal comfort calculations. In these calculations, analytical simulation was conducted to find results and make comparisons. Finally, the fifth chapter contains the research limitations, conclusion, and recommendations for future works.

Chapter Two

Chapter Two: Theoretical Aspect

2.1 Introduction

The increase in energy consumption has changed the earth's climate and increased global average temperatures. Due to the threats of climate change, the global trend aimed to expand the exploitation of renewable energy sources over fossil fuel energy. In addition, many countries have plans to reduce carbon dioxide emissions by enhancing the use of renewable energy and increasing building efficiency, aiming to develop new solutions that supply the energy needs of communities, and combining integrated technologies to develop innovative sustainable energy plans to reduce energy consumption. The research reviews, through previous studies, many strategic plans, and environmental initiatives to reduce emissions, enhance the use of renewable energy, increase building efficiency, reduce energy consumption, modern technologies, and other solutions that aim to meet and fill the energy needs of societies. In addition to other topics related to the research objectives.

2.2 Global Statistics of Residential Energy Consumption

Buildings sector takes a part of nearly 40% of the whole global energy consumption, and also are responsible for 38% of the greenhouse gas emissions (Sivanathan *et al.*, 2020). As with global population reached 7.63 billion (bn) in 2018, which increased by 77% compared to 4.30 billion in 1978, GDP per capita has grown by 77%. Hence, the global consumption of primary energy increased from 270.5 EJ (Exajoule =10^18 Joules) in 1978 to 580 EJ in 2018 (Kober *et al.*, 2020). And the primary energy consumption per capita is increased by 21% to reach 76.2 GJ in 2018, while it was 62.8 GJ in 1978. In addition that global energy-related CO2 emissions have increased by 87% (Kober *et al.*, 2020). The energy required is nearly 60% of the total energy consumed for cooling and heating space, which is the most significant energy usage percentage. (Abdelgadir *et al.*, 2019). Another study referenced that the energy consumed for buildings heating and cooling has reached as high as 61% of total residential building demand. The building envelope takes up 50% of the direct heating and cooling loads and 36% of the building's final global energy consumption (Q. Al-Yasiri and Szabó, 2021b). Most increases in the energy consumption next decades will come from non-OECD countries, since rapid population growth and strong economic growth lead to an increase the energy consumption (U.S.Energy Information Administration, 2019). Statistics indicated that energy consumption will increase by more than 70% between 2018 and 2050 (U.S.Energy Information Administration, 2019). Conversely, energy consumption will nearly increase by 15% in OECD (The Organization of Economic Cooperation and

Development) countries. In addition, growth in energy consumption is slower due to the improvements in energy consumption efficiency (U.S.Energy Information Administration, 2019). However, the recent statics of global energy consumption indicate a big transformation in the energy sector in the coming decades compared to the previous ones (Kober *et al.*, 2020). Despite the increase in energy demand, the growth in demand will mainly be covered by the increase in contributions from renewable energy, which is especially true in the electricity sector (Kober *et al.*, 2020).

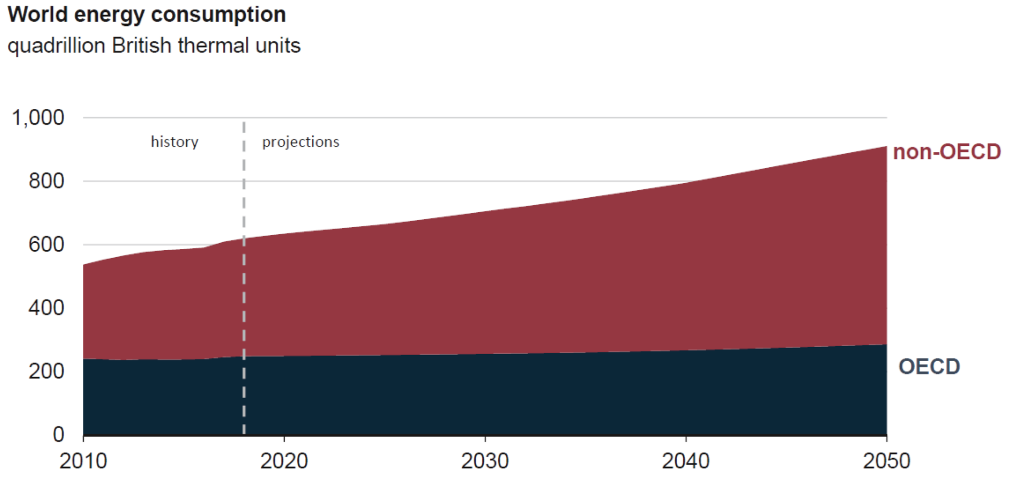


Figure 4 Shows the World Energy Consumption, Source: (U.S.Energy Information Administration, 2019).

Due to the population and income growth increase in world countries, Statistics show that the energy consumption in the buildings sector (including residential and commercial buildings) in non-OECD countries will increase about 2% per year, which is five times rapid than in OECD countries (U.S.Energy Information Administration, 2019). Otherwise, facilities energy consumption in OECD countries will be increased by 0.4% per year in the coming years (from 2018 to 2050), hence reflecting energy efficiency in these countries due to improving buildings structures, appliances and techniques used (U.S.Energy Information Administration, 2019), see the next figure.

The Mediterranean region is and will be influenced by climate change more than most other regions of the world during the 21st century, as the impact of temperatures rises, rainfall reduction, increased emissions, and other phenomena (Bleu, 2008). However, the energy demand (electricity) is rapidly growing in the region to mitigate climate change impacts (Bleu, 2008).

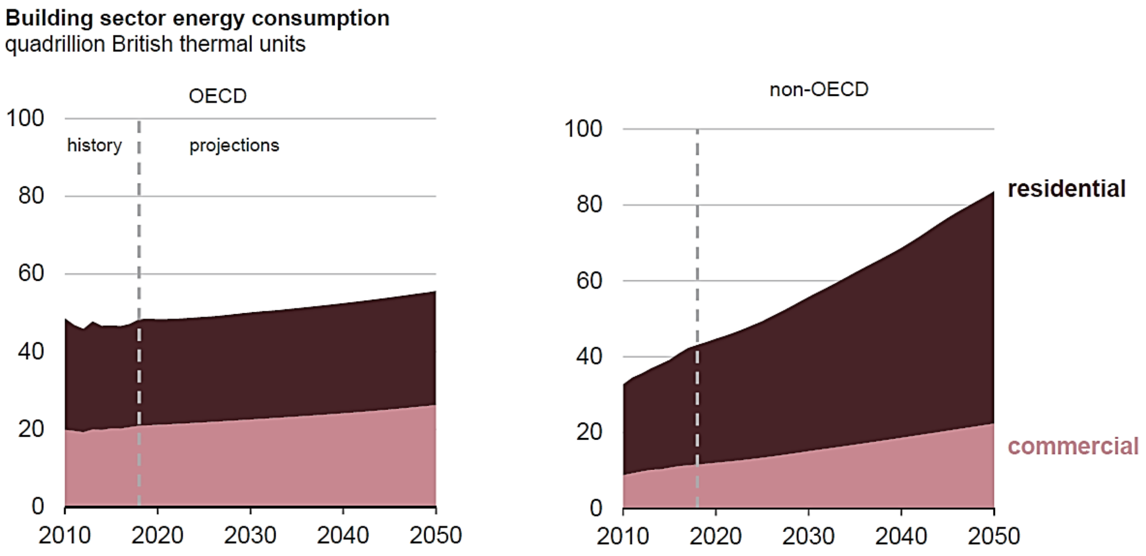


Figure 5 Shows Building Sector Energy Consumption in the world, Source:(U.S. Energy Information Administration, 2019).

2.3 Local Statistics of Residential Energy Consumption

Residential apartments represent the majority of buildings in Palestine almost 61.5% in 2017, as it reached 53% in the West Bank, and 65.6% in the Gaza Strip (Monna *et al.*, 2020). The increasing demand for electric energy as a result of population growth, accompanied by urban development and an increase in projects that require the provision of electrical energy, leads to an increase in pressure on the electric grid, and to achieve energy security, it is necessary to go towards renewable energy sources, which reduces emissions and preserves the environment (PCBS, 2013). Palestine imports all of its oil needs from Israel, and imports about 90% of its electrical energy needs, most of it from Israel (PCBS, 2013). It is essential to mention that the energy-dependent sectors would take the largest volume of emissions and air pollutants, as they accounted for 67.9% of the other sectors, the agricultural sector accounted for about 11.6% and the waste sector 20.5% of the number of emissions (PCBS, 2019).

The results indicated that the average household electricity consumption of electricity in Palestine for families that used electricity during July 2013 was 260 kWh, in which the imported energy (PCBS, 2013). The results also indicated that 86.8% of the households in Palestine had cooled their homes using power energy for electricity during July 2013 (PCBS, 2013). Among MENA countries, Palestine achieved the highest demand growth for primary energy from 2000 to 2012, as the residential sector in Palestine is the highest-consumption section of energy (Njore, 2016). About 57% of the electricity supplied was consumed in the residential sector, and the statistics in 2013 showed the two demand peaks were in

(August and January) (Njore, 2016). However, the results showed that the average household consumption of electricity in Palestine for families that used electricity during the month of January 2015 had reached 306 kWh (PCBS, 2015). On another side, 82.0% of the households in Palestine that used electricity had heated their house using electric energy during January 2015 (PCBS, 2015). (Abdel Hadi, 2013) has showed that exterior walls considered as the main aspect of building envelope which is responsible for making buildings more efficient and saving energy as well sustainable. Also, the study explained that building systems in Palestine didn't adopt the sustainability strategy, which leads to the increased running cost of the building(Abdel Hadi, 2013). As to the report issued by the World Bank Group focusing on the energy sector, the Palestinian territories depend mainly on energy imports from Israel to meet their electricity needs, which amount to 99% of the total supplies in the west bank and 64% in the Gaza strip as it is shown in the next figure (*Securing Energy for Development in the West Bank and Gaza*, 2017). The data shows the suffering of the Gaza strip from the lack of basic needs of electricity. In contrast, the hardship of the electricity shortage began to increase in the West Bank Western. With demand growing by 3.5% annually until 2030, the lack of investment in the electricity sector in the west bank will exacerbate the electricity shortage over time, and further deteriorate the currently deteriorating situation in the Gaza strip (*Securing Energy for Development in the West Bank and Gaza*, 2017).

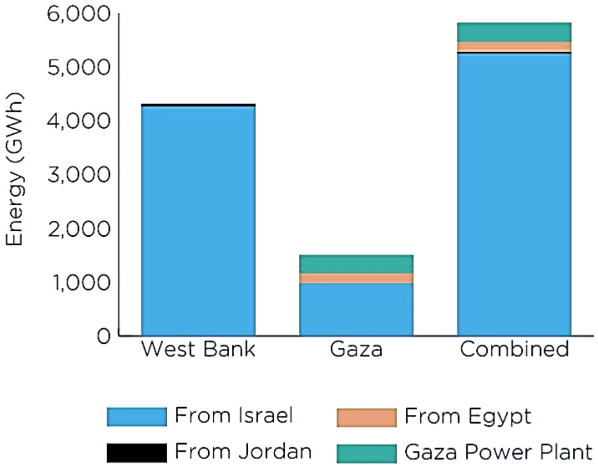


Figure 6 shows the Main Sources of Electricity in the West Bank and Gaza. Source:(Securing Energy for Development in the West Bank and Gaza, 2017).

The reliability rate of energy increased by 7% in 2019 compared to 2014 to reach a value of 86% instead of 80.3%. The ratio of household sector consumption to total energy consumption was about 38.8%

compared to other sectors, as this percentage is the second-highest in energy-consuming sectors. The annual per capita share of the electrical energy consumed was about 1,280 kWh/Capita.

Table 1 Shows energy Performance Indicators in Palestine, 2014-2019, Source:(PCBS, 2015).

Indicator	2014	2015	2016	2017	2018	2019
Renewable energy share in the total final energy consumption (%)	13.8	13.8	13.6	10.3	10.7	11.7
Energy Dependency Rate (%)	80.3	84.8	84.7	87.3	86.9	86.4
The Energy Consumption of the Household Sector to the total energy consumption (%)	38.4	41.4	39.7	38.4	38	38.8
Annual Electricity Consumption Per Capita (KWh/Capita)	1048	1151.4	1141.9	1138.3	1148.7	1280

According to the statistics recorded by the Palestinian Central Bureau of Statistics for the final energy consumption by sector and type of energy in the years (2010-2019), energy consumption rates are in increasing acceleration and the demand for it has increased, especially in recent years, as the first table shows that the amount of electrical energy consumption for the residential sector It increased by 75.6%, as it reached about 3662 GWh in 2019, while it was about 2085 GWh in 2010 (PCBS, 2019).

Table 2 An indicator that measures the amount of energy consumed by sector (Electricity), Source: (PCBS, 2019).

Electricity/yr. / Flow	(GWh) 2010	(GWh) 2011	(GWh) 2012	(GWh) 2013	(GWh) 2014	(GWh) 2015	(GWh) 2016	(GWh) 2017	(GWh) 2018	(GWh) 2019
Final energy consumption	2968	3506	4846	4744	4533	5095	5166	5262	5576	6213
Industry	349	299	1026	405	515	563	570	633	715	685.6
Households	2085	2178	2190	3128	2884	3197	3216	3248	3359	3662.4
Agriculture	11	5	6	37	36	39	34	32	29	37.4
Commerce & public services	523	1024	1624	1174	1098	1296	1346	1349	1473	1827.8

As for the energy consumed in the residential sector from oil products, the consumption rate in 2019 was approximately 4.2% lower than in 2010 due to the greater dependence of the residential sector on electricity consumption and a proportion of renewable energy (PCBS, 2019). Despite scientific progress and the introduction of new methods in sustainable design, the demand for renewable energy is still low compared to non-renewable energy. (Palestinian Central Bureau of Statistics, 2019). As there was no significant change in the rates of consumption and reliance on renewable energy, the residential sector's consumption value in 2010 was about 201 (1000TOE), while the consumption rate decreased in 2019 to reach 178 (1000TOE) at a rate of 12.9% (PCBS, 2019). Therefore, some researchers suggest using renewable energy instead of electricity, such (Salah and Abuhelwa, 2020), that the awareness of using renewable energy is the most effective solution for households. Conversely, the natural sources of energy in Palestine suffer from non-availability, unstable political conditions, high-density population, and financial crisis (Juaidi *et al.*, 2016) just as Palestine depends 100% of its fossil fuel on other countries for imports and 87% of the electricity imports (Juaidi *et al.*, 2016).

Table 3 An indicator that measures the amount of energy consumed by sector (Renewable Energy), Source:(PCBS, 2019).

Renewable Energy / Flows	(1000TOE) 2010	(1000TOE) 2011	(1000TOE) 2012	(1000TOE) 2013	(1000TOE) 2014	(1000TOE) 2015	(1000TOE) 2016	(1000TOE) 2017	(1000TOE) 2018	(1000TOE) 2019
Final energy consumption	201	204	194	193	219	218	222	164	169	197
Households	201	204	194	185	211	211	216	156	158	178

There is always a time and space contradiction between energy demand and energy supply, such as the difference in electrical load and discontinuity or limitation of energy source. According to local statistics, the share of renewable energy in the total final energy consumption is declining as a result of several determinants that can be inferred from the Israeli control over the main sources, the lack of expertise and competencies, the lack of necessary tools, and the lack of awareness towards sustainability. At the same time, the per capita energy consumption is increasing with a continuous acceleration as a result of the increase in the per capita energy consumption needs, especially the electric energy in the home, which is consumed in a large proportion for cooling and heating to obtain thermal comfort throughout the year. According to (Abdel Jawad and Ayyash, 2019), their study has displayed those urban areas of Palestine are the most consuming energy and spending on electricity, as well residential apartments are the largest percentage in the urban environment and the highest expenditure on electric energy.

2.4 Sustainable Energy Management in Palestine

Palestine Engineers Association Society decisions and vison aimed to solve problems of limited sources of water and energy and the high costs of the operational process of buildings, thus, a guideline for green buildings in Palestine was issued in line with international standards for green buildings, considering the specificity of the climatic, geographical and topographical conditions of the region (Green buildings Guidelines - State of Palestine, 2013). One of the most basic principles of sustainable buildings is their ability to adapt to the climate, reduce energy consumption and conserve it, as buildings must be designed and constructed so that dependence on fuel and other energy sources that are depleted and polluting the environment is reduced (Green buildings Guidelines - State of Palestine, 2013). At the same time, achieving the goal of their establishment, which is to protect people from climate conditions and fluctuations and to create a comfortable indoor environment (Green buildings Guidelines - State of Palestine, 2013). While energy resources in Palestine are less affordable among the countries in the middle east, fuel prices are almost double the price compared to the neighboring countries. According to the Paris Protocol, Palestinians have to pay an additional tax on the fuel by 17% as Palestinians procure most of the electricity and energy resources from Israel (Al Qadi, Sodagar and Elnokaly, 2018). Factually, Palestine’s resources and the ability to use for the production of renewable energy are restricted and limited (Badawy et al., 2021), (Marei, 2017), which leads to thinking of new ways of energy-saving buildings (Badawy et al., 2021). And due to the increase in population and the consequent increase in energy consumption and its harmful impact on the environment, in addition to the depletion of natural resources and the need to provide renewable energy as an alternative to limited imported energy.

There is a need for a sustainable approach in Palestine that can be implemented through innovative plans to reduce the energy amounts consumed and the operational cost of buildings since Palestine suffers from a lack of natural resources necessary for primary human needs, especially water and energy, in addition to the environmental pollution due to the dependency on energy (Green buildings Guidelines - State of Palestine, 2013). Despite the continuous increase in the demand for electric power, there are initiatives towards energy sustainability, and the local authorities in the past years have adopted several decisions, strategies, and agreements in order to find solutions to energy consumption and lacking, and how to improve the performance of newly constructed and existing buildings. The most important of them:

- The Palestinian National Authority has adopted a national strategy for energy development (2011-2013) which aims to increase the domestic production of electricity to cover almost 50% of energy consumption by 2020 and utilization of renewable energy (solar energy) (MAS, 2014).

- The Palestinian Authority has signed the Paris Agreement on Climate Change (Agreement, 2015).
- An Energy Efficiency Action Plan 2020-2030 aims to focus on actions to reduce electricity consumption in the residential sector (about 66% of total consumption) that would significantly impact final consumption (Njore, 2016).
- The Palestinian Energy and Natural resources Authority (PENRA) proposed a strategy for energy independence 2017-2022 to improve national power production, energy efficiency through increasing awareness, reducing losses, utilizing of national recourses, and Increasing the renewable energy recourses and reducing environmental impacts (Ismail, 2017).

2.5 Local Guides & Regulations for Energy Conservation

Energy retrofitting of residential buildings is a priority in current regulatory standards in order to reduce energy consumption (Calama-González et al., 2018). As for building technology in Palestine suffers from a lack of attention to climatic design, and several people make their homes without considering engineering consultancy. Therefore many buildings do not provide a comfortable environment for residents (Badawy et al., 2021). So, people resort to achieving this comfortable environment by using energy. However, when energy is valuable and limited as it's in Palestine, dealing with energy becomes difficult, which needs to be regulated. Recent construction regulations are directed strongly toward energy-efficient and low emissions buildings (López-Ochoa et al., 2021), and concern priorities of efficient energy consumption in residential buildings (Albatayneh, 2021b). However, there is a lack of regulatory approaches and indicators to count the potential of long-term strategies implemented in current buildings envelopes design (Baglivo et al., 2022). The local authorities have issued a code to handle modern constructions and develop the Palestinian building systems by reducing waste of energy, thermal design of buildings, protecting the environment from emissions and waste gases, and ensuring thermal satisfaction (Said and Alsamamra, 2019). The development of energy conservation policy is an important tool to reduce energy consumption in Palestine, which leads to reducing the dependency on foreign energy sources (Ismail, Moghavvemi and Mahlia, 2013). According to the requirements of the green building guidelines in Palestine to evaluate buildings, compliance with local and international laws must be adhered to (Green buildings Guidelines - State of Palestine, 2013).

The maximum thermal transfer value (U) for exposed external envelope elements (walls) is 0.5 W/ m^2.°K (Green buildings Guidelines - State of Palestine, 2013). The exposed walls in the Palestinian Energy Efficient Building Code showed the highest U-value (Rodríguez-Soria et al., 2014) compared to other countries (Alkhalidi, Kiwan and Hamasha, 2021), as the average U-value of outside walls in the Palestinian code ranges between 50% and 100% higher than all the countries in the study (Çamur and Abdallah, 2021). However, a study suggested U-value of 0.85 W/ m^2.°K as a new average that can save energy approximately 44% of the energy consumption in the residential buildings in Palestine compared to the values of International Energy Consumption Codes (Çamur and Abdallah, 2021).

2.6 Thermal Comfort Requirements

Retrofit strategies used in buildings ought to adapt to regulation standards, specific climate conditions, and improving indoor comfort conditions These issues are marked in the future because of climatic change (Calama-González et al., 2018). ASHRAE has been identified thermal comfort as “that condition of mind which expresses satisfaction with the thermal environment” (Monna et al., 2019). Using passive strategies could provide thermal comfort for occupants and minimize energy consumption in different climates, especially if more than one strategy involves reaching the same goal (Spentzou, Cook and Emmitt, 2018). Human comfort in the buildings depends on several factors: personal factors like the metabolic rate and clothing, environmental conditions around as relative humidity, air temperature, air velocity, and the mean radiant temperature (Code, 2004). The heat energy transmission through solid components of a building envelope is because of the difference between outdoor and indoor temperatures. Therefore, the building envelope materials can critically impact the energy required to achieve a comfortable environment within the building space. Moreover, materials of various properties have differences in heat transfer and can be compared based on R-values and U-values, where R-value = 1/ U-value. For example, the levels of Insulation and construction details impact the mean radiant temperature (MRT) of ceilings, floors, and walls, in which the MRT is basically the temperature of all surrounding surfaces, and the insulation (R values) impact the mean radiant temperature of roofs, floors, and walls (Muallem, 2020). The PMV could be prophesied through six variables that highly affect thermal comfort: air temperature, relative air velocity, mean air humidity, mean radiant temperature, and clothing and metabolic rate. Otherwise, the more rate of people dissatisfied means that thermal performance of the environment is not comfortable, which leads to consuming more energy to reach a state of thermal comfort (Muallem, 2020). For the EEBC (Code, 2004), for the external design temperatures for the different climatic zones in Palestine, where temperatures range from 4 to 7 °C in winter, and from 30 to 39°C in summer, and the recommended interior design temperatures for air-conditioned spaces in homes and apartment buildings range from 19 to 21 °C. Furthermore, another field study was conducted in summer and winter in the same climatic region of the study, as the data collected was analyzed statistically to set guidelines for calculations in thermal and energy, and the satisfaction criterion of 90% ranged between 19.5 and 26 ℃ for passive design conditions in winter and summer respectively. At the same time, during periods of active conditioning, the temperatures of 21.5 and 23 ℃ are supposed for winter and summer (Becker and Paciuk, 2009). Moreover, the proposed comfort zones for summer and winter (for typical indoor and seated person) are within 5 to 16 mm Hg water vapor pressure, as the temperatures for summer range between 22.8 and 26.1 ℃, and for winter from 20.0 to 23.9 ℃ (Fauzan *et al.*, 2010), as temperatures are shown in the graph below.

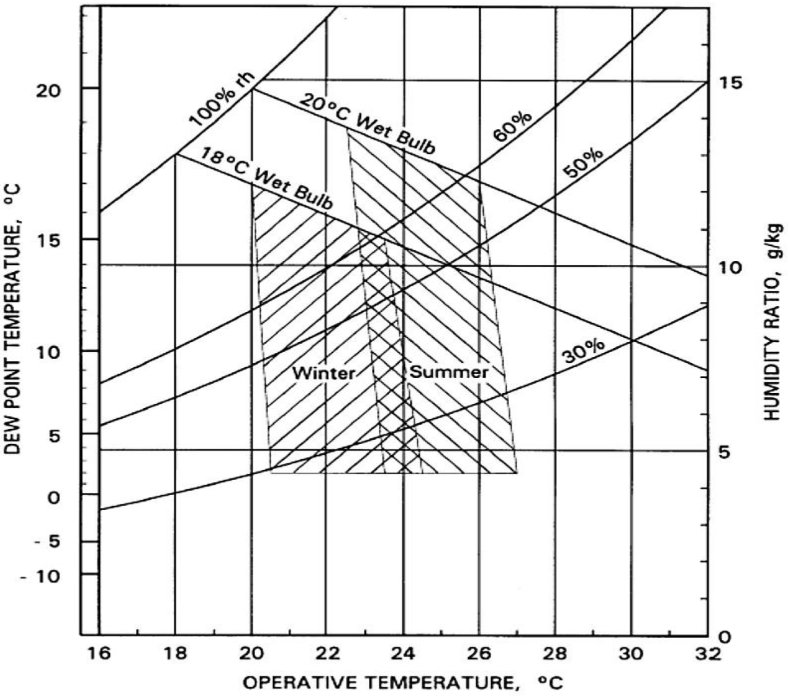


Figure 7 ASHRAE Summer and Winter Comfort Zones. Source:(Fauzan *et al.*, 2010)

2.7 Thermal Performance in Residential Buildings

The main function of buildings is to ensure a comfortable thermal environment for the occupants. This shows the success of buildings as its effects on their energy consumption and sustainability (Thapa and Panda, 2015). The building envelope includes walls, floors, roofs, windows, and doors. It separates different outside conditions of the building from inside conditions of the building, which is one of the main objectives of the envelope to control the heat energy flow, air movement, solar heat, and moisture penetration. In addition to building occupants protecting from outdoor threats, the inside conditions must be within a range that is contributory to occupant's comfort, safety, and health. The building systems should control space temperature, air quality, air movement, relative humidity, and lighting levels within acceptable boundaries. However, to preserve the required indoor conditions, building systems must control imposed energy loads by outdoor climatic conditions and the imposed energy loads by the indoor factors of the building itself. Previous studies conducted several analyses around the effect of the parameters on energy consumption, such as orientation, insulation, insulation thickness, infiltration rate, window to wall ratio, air distribution, cooling and heating, and other factors that play a role in thermal performance of buildings (Khalifa, 2013), (Albatayneh, 2021c). Referring to a paper that explained that climate change leads to a paradigm shift in building energy performance as the change impact is not equivalent for various building types, insulation levels, periods, and scenarios of the future weather. So that climate change must be counted in any future energy performance estimation of buildings (P. Tootkaboni, Ballarini and Corrado, 2021). Similarly, a paper predicted the life cycle energy performance of the residential buildings via simulation method of different climate zones. The further climatic change, the greater the heating and cooling energy of buildings (Zou *et al.*, 2021).

2.8 Thermal Parameters Effects on Energy Consumption

Thermal comfort is called when people are satisfied with a thermal environment (Muallem, 2020). While thermal performance has a relationship with energy consumption, people consume energy in order to reach comfort when they are dissatisfied with thermal conditions (Muallem, 2020). Optimization of building envelope parameters leads to a significant effect on cooling and heating loads, as a study showed in the Mediterranean climate zone (Albatayneh, 2021a). On the other hand, a study investigated the thermal performance parameters of building envelopes (walls), as results revealed the effect of different building materials of various thermal properties on thermal performance parameters (Balaji, Mani and Reddy, 2019). Controlling the heat gain and loss through building envelopes leads to other energy-efficient buildings (Muallem, 2020). There are various parameters related to envelop design that could be involved to enhance thermal comfort and energy consumption, such as building orientation, shape, and size, weather data, site context, thermal insulating materials, window to wall ratio, shading, and ventilation (Muallem, 2020). Also, urban form, building height and H/W ratio play a significant role in building performance (Mangan *et al.*, 2021), as well thermal inertia, which is a widely used parameter in the building environment controlled through transient state parameters like the periodic transmittance "u-value" (Soret *et al.*, 2021). Moreover, the occupant's actions have greatly impact on the energy demand (Bonte, Thellier and Lartigue, 2014).

2.9 Energy Efficiency of Building Envelope and Heat Transfer

Several buildings in Palestine have poor indoor environment as they are hot during summer and cold in winter. Thus, people use air conditioners or heaters for better comfort. However, these devices consume a lot of energy, so households must pay more for accepted room temperatures. The indoor environment can be improved significantly using thermal insulation as the thermal design of the building envelope aims to achieve the minimum heat transfer (gain or loss), save energy used in cooling or heating, raise the level of thermal comfort throughout the seasons of the year, and thus increase the operational life of the buildings (Code, 2004). Improving building energy efficiency leads to less energy consumption when maintaining comfort level, saving energy and expenses, and minimizing harmful emissions (Bataineh and Alrabee, 2018). The transfer of heat energy through wall components is caused by a variation temperature between the outdoor and indoor temperatures. Therefore, materials applied in the building envelope could have an important impact on the size of energy required to preserve an appropriate environment within the building space. Energy efficiency of the building envelope is basically examined through the envelope components such roof or walls besides to thermal bridging regions (O’Grady, 2018).

The thermal insulation has low thermal conductivity, and it's used in buildings to prevent heat loss or gain. Besides its essential economically, it enhances an accurate control of temperatures and users' protection (Abdelgadir *et al.*, 2019). Thermal energy storage is important to reduce the continuous increase of the gap between energy supply and demand (Younsi and Naji, 2017). There are three various methods to store thermal energy: latent heat, sensible heat, and thermochemical energy, so that in thermochemical storage materials, their use needs economic feasibility and technical study (Younsi and Naji, 2017).

2.10 Sensible Heat and Latent Heat of Materials

2.10.1 Phase Change Behavior and Physical Properties

Using PCMs due to their thermal storage capability (Khudhair and Farid, 2004) is one of the perfect strategies used for passive cooling and heating for energy efficiency (Rashad *et al.*, 2021) and (Q. Al-Yasiri and Szabó, 2021b). These materials have a higher latent heat of fusion, which makes them appealing for thermal storage systems (Lee, 2013). The thermal mass (inertia) decreases when the mass decreases in materials that affects the building envelope performance. However, to increase the thermal inertia, materials of high thermal capacity or thermal energy storage (TES) could be effective such as PCMs (Bamonte *et al.*, 2017). During the day PCM gains heat from the higher temperature medium, at this stage, the state of PCM is solid. Materials of PCM are characterized by their high storage capacity and therefore when they gain heat, they gain it slowly. By this process, the material limits the heat transfer through it and through the wall section. When the temperature reaches the melting point, the substance changes from a solid to a liquid, undergoing a mushy phase before complete melting (Kamali *et al.*, 2016). However, when the temperature decreases below the PCM melting temperature, the heat is released from the material and discharged towards the environment, certainly slowly and the PCM transforms from a liquid state to a solid form (Kamali *et al.*, 2016). The loop continues with this mechanism in order to conserve building energy and make the building envelope more efficient. Phase change materials must have a suitable melting point temperature when they applied in buildings that fits the local climatic conditions, and have a little change in volume over the phase change process (Sun *et al.*, 2020). There are three main approaches for using PCMs in buildings: Thermal Mass as a passive technique, and Heating and Cooling Systems as active techniques, since the thermal mass defines the part of building fabric which has a capacity to store and release higher quantities of heat during the daily thermal cycle (Report, 2022).

2.10.2 Sensible Heat

When materials are exposed to heat, they can store energy in a linear relation with temperature as it's seen in the next figure. While all materials could store sensibly heat, some materials are more efficient than others. The heat storage relies on the material's specific heat capacity (Cs). Sensible heat indicates the heat detected by a temperature change and latent heat refers to heat transfer related to phase transitions that the thermometer cannot detect (Graham, 2017).

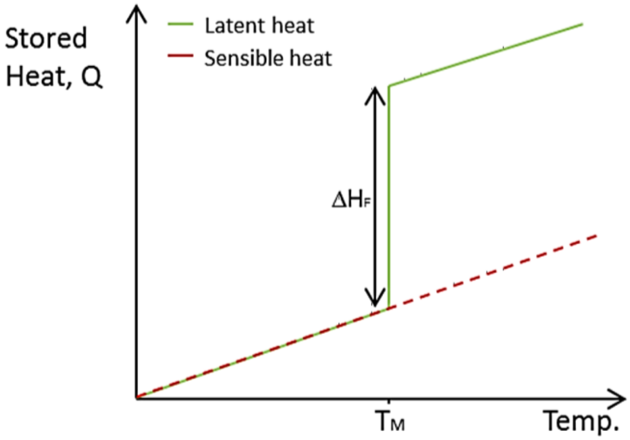


Figure 8 Comparison between SHS and LHS, ΔHF refers to the latent heat of fusion during melting, source:(Graham, 2017)

Phase change materials utilize latent heat storage (LHS), which allows the phase transitions including the melting and freezing (solid-liquid), the evaporation and condensation (liquid-gas), or change in crystalline structure (solid-solid) (Shchukina *et al.*, 2018), see the figure below:

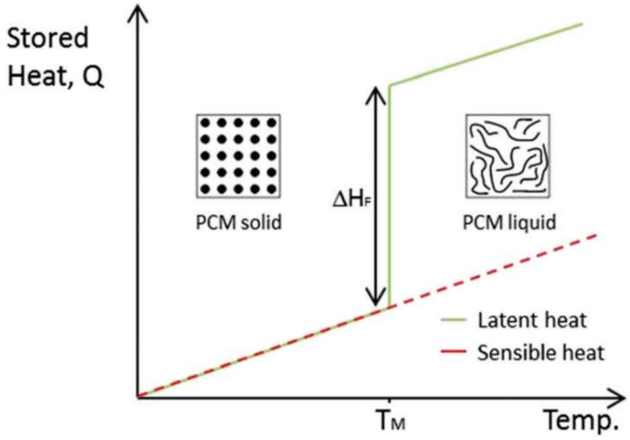


Figure 9 Comparison between SHS and LHS, DHF is the latent heat of fusion, source: (Shchukina *et al.*, 2018)

Sensible heat storage demands increasing or decreasing temperatures of the storage material (solid or liquid) in the transfer interaction to storing or releasing thermal energy (Min, 2019). It occurs over various temperatures during the charging and discharging without changing the material phase. In addition, the heat stored amount relies on the mass of material, temperature change, and heat capacity (Min, 2019).

The sensible heat storage equation can be expressed as,

$$Q = \int_{T_1}^{T_2} mC_p dt = mC_p(T_2 - T_1) \qquad \text{(Min, 2019), (Charles, 2019)} \qquad (1)$$

where (Q) is the sensible heat stored, (Cp) is the specific heat capacity at constant pressure, (m) is the mass of storage material, and (T1) and (T2) are the temperature range (Min, 2019), (Charles, 2019).

2.10.3 Latent Heat

Latent heat storage relies on absorbing storage material or releasing heat during the phase change at a constant temperature, as latent heat storage at a narrow temperature range gives a higher storage density (Min, 2019). As the total stored energy for TES system can be expressed as,

$$Q = m\int_{T_i}^{T_m} C_{p,solid} dT + m\Delta h + m\int_{T_m}^{T_f} C_{p,liquid} dT \qquad \text{(Min, 2019), (Charles, 2019)} \qquad (2)$$

Where the first term and last term are related to sensible heat of solid and liquid phases while the second one is latent heat during the transition phase. (*m*) refers to the mass of PCM, (T*m*) is the melting temperature, (T*i*) is an initial temperature, (T*f*) is the finish temperature, and (Δh) is the latent heat of fusion (Min, 2019), (Charles, 2019). PCMs allow the storage of large amounts of heat transfer energy in a narrow range of temperatures through their latent heat (Taylor, Tsafnat and Washer, 2016), as these materials can absorb or release a significant amount of heat during the phase transitions, which gives them the advantage to be implemented in wide applications (Chen *et al.*, 2015),(Zhou *et al.*, 2018). Simultaneously, Phase Change Materials have a significant role in different applications such as Thermal Energy Storage (Abuzaid and Reichard, 2016). It allows the heat to be stored and released later, which can be reserved via physical and chemical methods (Abuzaid and Reichard, 2016). Furthermore, the ability of PCMs to absorb thermal energy contributes to removing and reducing the heating and cooling needs by using latent and sensible heat storage, as is shown in the next figure (Abuzaid and Reichard, 2016).

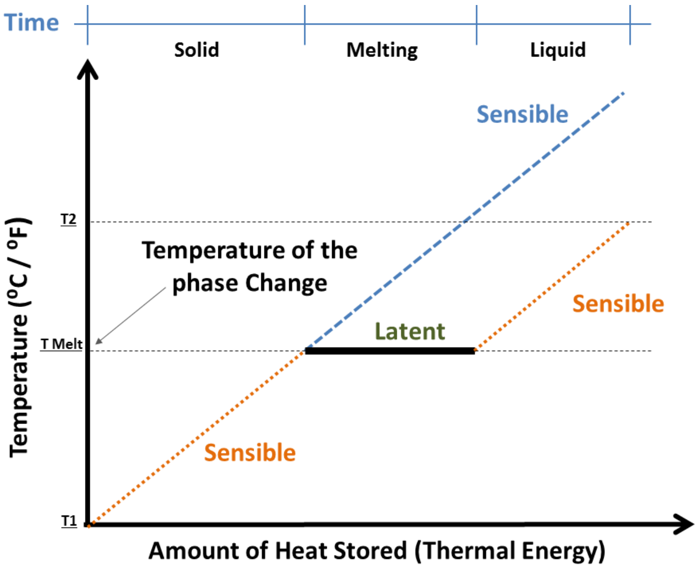


Figure 10 Temperature profile for changing phases by sensible and latent heat, source:(Abuzaid and Reichard, 2016)

When PCMs compared to traditional building materials based on thermal storage, PCMs present significant thermal storage enhancement over traditional materials which is obviously shown in the figure below (Whiffen and Riffat, 2013).

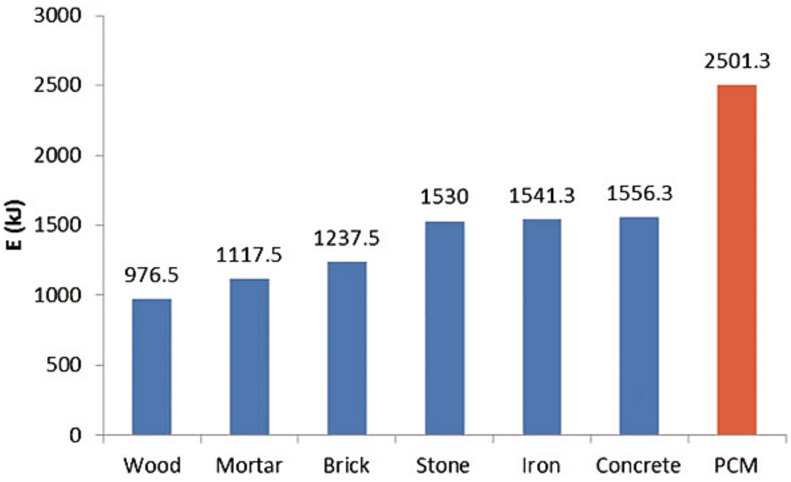


Figure 11 Comparison of energy stored and released during a 24 h period, source: (Whiffen and Riffat, 2013)

This difference is illustrated by the thickness required in storing 5700 kJ over the 10 K temperature range, as it’s seen in the next figure, which also shows the effective results that are effective over the PCMs transition temperature (Whiffen and Riffat, 2013).

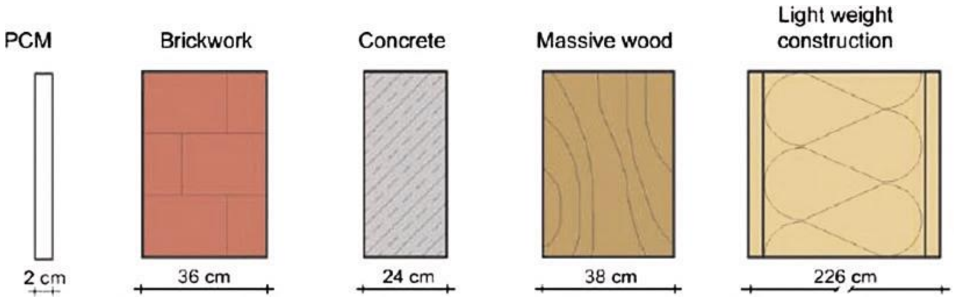


Figure 12 Comparison of thickness required to store 5700 kJ over 10 K, source: (Whiffen and Riffat, 2013)

2.11 Factors Affecting the Heat Loss Rate in Buildings

Factors that impact heat flow rate include the material conductivity, difference in temperatures across the material, material thickness, and the material area. Materials properties can make them have higher or lower resistance to heat transfer, making them better conductors or insulators. Conduction, radiation, and convection are the three heat transfer mechanisms in and out of the building. However, these factors don't only explain heat-transferring; they also give indicators on how several buildings are more comfortable than other ones (Younger, 1997). Risberg in his study mentioned that thermal storage is also affected by the heat capacity and density of various materials and the heat loss from the building (Risberg, 2018). Increasing the insulation and overall wall thickness in new buildings causes increasing thermal inertia, which impacts the building heat demand (Risberg, 2018). There are three main sources of heat loss in the building: the building envelope, ventilation, and air leakage, as the building envelope**,** takes the largest proportion in the rate of heat loss and then the rest of the sources (Vihola *et al.*, 2015).

The heat loss rate depends on the physical properties of the building envelope, and ventilation (Vihola *et al.*, 2015). Similarly, (Sheeja *et al.*, 2020) have assured that building walls take the highest proportion among the elements of the building envelope, then windows and roofs come. According to a study focused on saving energy of buildings in Italia, in which a case was modelled with conventional building materials and the total energy demand was calculated, the U-value of the composite wall (insulated wall) gave the highest value among elements of the building envelope (Khan, Asif and Mohammed, 2017). Indeed, exterior walls constitute the most significant percentage of the building envelope surfaces (Dawoud, 2016) and contain different thermal openings or bridges depending on the wall's materials. And it is also mainly exposed to external factors, so it’s more critical in gaining and transferring heat. Therefore, the research work on the dynamic thermal behavior of the walls and their impact on building energy use is important such they are significant components affecting energy efficiency (Tsilingiris, 2006).

2.12 Treatment of heat loss in the building

Using passive cooling and heating strategies in the past as wind-catcher, shading, courtyards, massive walls, and other techniques, are helping to reach a suitable percent of stability and thermal satisfaction. In parallel with the development of technology and modern tools, humans seek to achieve good ventilation in buildings, whether passive or active. Various measures could be considered for improving the energy efficiency of buildings, such as measures for improving the building’s envelope (like addition or improving insulation, changing colors, installing heat-insulating door or window frames, increasing thermal mass, etc.) (Diakaki, Grigoroudis and Kolokotsa, 2008). The research focused on the study of insulating strategies to achieve a certain level of thermal satisfaction for residential buildings users within a neighborhood. After that, to identify and evaluate strategies applied followed by some proposals and recommendations for local authorities. And in this research, the focus will be on the external walls (wall composition) of the building and the thermal transition through these walls.

The concept of sustainability introduced into design processes encouraged researchers to innovate thermal insulating materials by using natural and recycled materials as with the energy efficiency is evaluated upon varied factors in addition to thermal insulation thickness and the heating needed, further according to essential energy demand, CO2 emissions reductions and ecological properties of materials (Dikmen and Ozkan, 2016). One of the most important strategies used to save energy and reduce the operational cost of buildings is thermal insulation of the building envelope, and its presence in facilities established in Palestine was stipulated by the green building guidelines (*Green buildings Guidelines - State of Palestine*, 2013). The building heat loss has a critical effect on the energy assessment and the performance of the building. This is reflected in the energy consumption, as the heat loss and U value play a role to mark the building energy assessment thus when reducing the heat loss can improve the building performance scale. An estimating model was developed for heat loss rate in buildings to measure the amount of thermal power needed to recompense the heat loss by the walls, floor, roof and ventilation in the buildings, taking into account the thermal conductivity (U-values) of various building types, the exterior and interior temperatures difference and the building volume (Vihola *et al.*, 2015). While material choice is important in decreasing the building energy demand, thermal insulation in the building envelope plays a critical role in saving energy, especially when using the optimal insulation thickness (Khan, Asif and Mohammed, 2017). The heat storage of multilayer wall plays a part of decreasing and delaying the heat transfer from outside and moving through walls. This method considers sensible heat storage as it's proportional to the temperatures gradient (Brembilla, 2018). Conductive heat loss can be decreased by adding insulation to the exterior walls, ceilings, floors (Younger, 1997). It is essential to identify each composite's insulation types and levels to evaluate the envelope's effect on energy consumption and the building's thermal comfort (Younger, 1997). Previous studies on heat loss ensured the importance of choosing the appropriate thermal properties of the materials used in the walls and the necessity of using thermal insulation to reduce heat loss.

2.13 Conclusion

As a result of energy consumption rise and climate change, many countries had plans to enhance the use of renewable energy and increase building efficiency as well Palestine, which appeared in the statistics through this chapter. in addition to the global and local guides and regulations for energy conservation. Moreover, thermal comfort requirements and thermal performance in the residential buildings were explained, and parameters and factors affecting heat loss rate in buildings, which the walls and thermal insulation took a significant part.

Chapter Three

Chapter Three: Conventional Materials & Phase Change Materials

3.1 Introduction

Thermal insulation effectively reduces building energy consumption by decreasing the heat gain or loss through the building envelope. This process, which prevents undesirable temperature changes, reduces the demand for energy consumed by heating and cooling systems. There are several traditional insulation materials that have a significant impact in specific climatic regions compared to the other areas. According to the research and knowledge methodologies, experts seek to find innovative solutions in buildings and energy consumption by using modern technologies to produce materials with high thermal properties than before for use as insulating layers in building envelopes and with higher efficiency and performance in different thermal conditions.

3.2 Conventional Insulating Materials: Structure and Materials

Residential buildings without thermal insulation suffer from thermal discomfort despite using electric equipment in summer or winter. It's essential to mention that Monna et al. have investigated the thermal comfort of a typical Palestinian multi-story residential building based on the measurement and quantitative approach using the APCI (Average Perceived Comfort Index) (Monna *et al.*, 2019). Measurements emphasized that indoor air temperatures always remain below 16 °C in winter, which is below the comfort level. In summer, temperatures remain between 25 °C and 32 °C, which are outside the comfort zone, despite using electric fans in summer and portable electric and gas heaters in winter (Monna *et al.*, 2019).

3.2.1 The Impact of Using Thermal Insulation Type on Energy Consumption

Choosing the appropriate insulation material type and form relies on the application type, physical and thermal properties. Thermal insulation materials vary with their properties and the temperature influencing range (Shahedan *et al.*, 2017). The loss of heat transfer in building envelopes accounts for nearly 60–80% of the buildings' total heat transfer loss, which is important to create an appropriate indoor environment and reduce energy consumption by enhancing the thermal performance of buildings external envelopes, as well the wall body (Zhang *et al.*, 2017). Also, (Mohammad *et al.*, 2020) have mentioned that during the operating phase of buildings, 60% of consumed energy is used by ventilation, heating, and air conditioning systems (HVAC). In consequence, decreasing the negative environmental impacts needs to pay more attention to the materials used in buildings construction besides developing better properties of thermal insulation in order to improve buildings energy efficiency (Mohammad *et al.*, 2020). The ability of thermal insulation as a passive solution to reduce undesired heat gain and loss effectively through the building fabric, to achieve energy-efficient design strategies (Asfour and Kandeel, 2016). Also, (Ozel, 2013) in his study aimed to determine the optimum insulation thickness according to the building cooling during the summer period in Antalya for different wall orientations. The insulation material of polystyrene and polyurethane were used in the study (Dombayci *et al.*, 2017). For both different insulation materials, the minimum thicknesses (0.046 m for expanded polystyrene insulation and 0.023 m for polyurethane insulation) were calculated for the warm temperate climate zone. The maximum savings were calculated for the cold climate zone and the minimum savings were for the warm temperate zone (Dombayci *et al.*, 2017). Using thermal insulation also improves buildings' economic aspects due to the increase in awareness and a high electric energy tax (Shahedan *et al.*, 2017). In addition, (Shahedan *et al.*, 2017) have reviewed thermal properties, especially thermal conductivity and the specific heat on different types of concrete, and concluded that a good insulator has a high specific heat capacity which takes time to absorb heat before it can heat up to transfer the heat and the low thermal conductivity and thermal diffusivity can decrease the energy losses and reduce the temperature equivalent through the building concrete.

3.2.2 Optimum Thermal Insulation Thicknesses

Insulation thickness is a significant parameter in the design of exterior walls of buildings. The increasing insulation thickness reduces the heat loss and the heating loads and fuel cost; however, the increase of thickness leads to an increase in insulation investment (Aktemur and Atikol, 2017). Liu et al. (Abdelgadir *et al.*, 2019) have provided in their study literature reviews on determining optimum insulation thickness, insulation materials, using different optimizing and analyzing methods. The impact on the environment and energy-saving in different climates also focused on the degree-time method in the heating and cooling calculation loads and concluded that the optimum insulation thickness affected by wall structure, degree-days, and insulation materials. The performance of the insulated constructions mainly depends on the thickness and properties of the insulation material used (Nematchoua *et al.*, 2015). The thermal properties of materials determine the heat transfer amount inside them, which these properties vary as they depend on the material composition and characteristics (Shahedan *et al.*, 2017). Analytical methods were used in several types of research, one of them calculated in Tunisia in which the climate is mild and temperate; in this study, optimum insulation thickness, saving energy and payback period were calculated for typical wall structure and based on both cooling and heating loads (Daouas, 2011). Other side, (Onan, 2014) in his investigation, has performed calculations (using the P1-P2 method) of the optimum thicknesses of model buildings' insulation, energy savings over 10 years of lifetime, and the payback periods for different climatic regions in Turkey. The results presented the optimum insulation thicknesses of extruded polystyrene foam (XPS), which vary between 3.21 cm and 7.12 cm, and the payback periods also vary between 1 and 8.8 years based on the regions (Onan, 2014). Similarly, in another study, the optimum insulation thickness of the external walls was calculated to be 5.25 cm, the heating energy consumption using this thickness decreased by 17% compared to the previous practice of 3 cm of thermal insulation and the payback period was 2.14 years regardless of the direction of the building walls (Onan *et al.*, 2020). Otherwise, Mohaibesh et al. in their study of evaluating the positive impact of adopting strategies of architectural design and material technologies in residential buildings in two various climatic zones in Palestine to reduce heating and cooling consumption, when using 7 cm of XPS (Mohaibesh *et al.*, 2021).

3.2.3 Optimum Location of Thermal Insulation Layer

The location of thermal insulation has a significant impact on heat transfer through the building wall. A study in Gaza (Aboamir, 2013), mentioned that while three types of external walls used in the study context such as internal insulation, core insulation, and external insulation of wall, and fitting 5 cm expanded polystyrene insulation in the last one leads to 63% of heat fluctuations reduce in arid climates, 10-14% reducing the energy requirements and 8-10% of air conditioning use. Another study on the Mediterranean climate has ensured that external insulation has a significant impact on heating and cooling loads (Serghides and Georgakis, 2012). Also, (Mohaibesh *et al.*, 2021) in their study in Palestine have showed the results of significant thermal effects of the proposed model of the external wall in reducing heating and cooling loads when placing XPS layer towards the exterior as the external wall contains construction materials similar to the study. Moreover, Haj Hussein et al. evaluated the thermal mass effect on the interior thermal environment of residential buildings in Palestine through four different scenarios of typical models according to thermal insulation position in the wall. He showed the impact on the heating and cooling energy demand, for two climatic zones as the outside position of thermal insulation showed better thermal performance for both different climatic zones (Hussein *et al.*, 2021).

Other study has presented the lower effect on the mean daily heating and cooling loads, with a small advantage for external insulation in summer and internal insulation in winter besides that external insulation increases time lag in summer compared to the internal insulation and almost has the same effect on time-lag in winter (Al-Sanea and Zedan, 2011). Another study conducted numerical calculations on determining the effect of insulation of the wall on the heat transfer, as when locating a foamed polystyrene layer of the same thickness and is used external or internal in the wall, the external insulation is more beneficial than internal one, and the study showed the decreasing of heat transferring in external insulation is less by 6.1% under the same thermal conditions (Sobota and Taler, 2018). Moreover, according to Energy Efficient Building Code (Code, 2004), the position of the insulation layer towards the outside or the middle works effectively during the summer period, and the heat storage is lower for the outer layer. On the other hand, as for the internal thermal insulation is more suitable for use in the winter season, where the response is faster and the thermal storage of the inner layer is less (Code, 2004).

3.2.4 Summery

According to the previous studies reviews and the local market, PU, EPS, and XPS insulation materials took a higher impact on building envelope performance. The focus of the research was on types of materials that are installed in the form of boards (rigid insulation panels), which do not require skilled labor or expertise for installation and maintenance. In addition, the fewer prices and affordability, as well as the most common and recommended (*Green buildings Guidelines - State of Palestine*, 2013) in the local environment. Therefore, polyurethane was excluded, as it is less prevalent and requires skill and expertise in installation and maintenance. EPS was also excluded due to its inefficiency impact, higher thicknesses, short life age, and moisture problems. The optimum thicknesses of the insulating layer varied according to the external wall construction, the climatic zone, and the location of the insulating layer within the wall. The position of the insulation layer towards the outside leads to obtaining the most efficient performance of composite walls using conventional materials. The best options depend on the needs and the space function considering life age, moisture resistance, compression strength, R-value, and compatibility, as is seen clearly when using XPS.

3.3 Phase Change Materials (PCMs)

PCM is one of the strategies used for passive cooling and heating for energy efficiency (Rashad *et al.*, 2021). Using PCMs for thermal storage in buildings has been considered since before 1980 (Khudhair and Farid, 2004). Investigations in phase change materials (PCMs) are increasing in recent years as a successful strategy in many thermal energy storage applications. Their use in the building sector improves building efficiency by decreasing heating/cooling loads and promoting renewable energy sources (Q. M. Q. Al-Yasiri and Szabó, 2021). PCMs have a higher latent heat of fusion, which makes them appealing for thermal storage systems (Lee, 2013). The efficiency of building walls depends on PCM layer location within the composite wall, PCM melting temperature, and thickness of PCM layer (Kant, Shukla and

Sharma, 2020). It's important to consider the melting point when selecting PCM, so it significantly impacts energy demand (Rahimpour *et al.*, 2017). The benefits of implementing PCMs on the envelope of building in both active and passive strategies concern basically reducing the heating consumption (active strategy) and reducing discomfort during warm hours (passive strategy) (Carlucci *et al.*, 2021). The incorporation of PCMs can be achieved through the building envelope such as walls (Subbiah, 2017), (Sawadogo *et al.*, 2021), roofs, and windows (Sawadogo *et al.*, 2021). In order to use PCMs widely in the thermal energy storage system, they ought to meet the energy density criteria, cost, and safety, as well as have a convenient phase change temperature (Charles *et al.*, 2019). Phase change materials in thermal energy storage systems are considered an effective bridge for managing heat, as they are flexible to meet the mismatch of energy supply and demand (Yu *et al.*, 2019). Moreover, the implementation of PCMs in building walls is considered a good choice in future scenarios. The main PCMs appropriate and most used for building walls in the Mediterranean climate are paraffin, fatty acid, hydrated salts, and eutectic (Cui *et al.*, 2015). Paraffins and fatty acids are presented as the most used PCM in TES systems, as they have a high phase change enthalpy, and have suitable cycling stability (Barreneche *et al.*, 2017). The most familiar salt hydrates are calcium chloride hexahydrate, sodium sulfate decahydrate, dodecahydrate, sodium phosphate, and magnesium chloride hexahydrate (Xie *et al.*, 2017). Characteristics of PCMs are divided into physical properties, chemical properties, thermal properties, and economic factors (Bland *et al.*, 2017). The desirable characteristics could be considered physically as a low variation of density during phase change, high density, no supercooling and low vapor pressure, chemically: non-inflammable, non-explosive, and non-poisonous, chemically stable, compatibility with material containers, and no chemical decomposition, thermally: high thermal conductivity in solid and liquid phases, high specific heat, suitable phase change temperature, and high latent heat per unit mass, and economically: readily available in large quantity, low cost, and commercially viable (Bland *et al.*, 2017). PCM can be integrated into construction elements and materials by direct incorporation, encapsulation, immersion, and shape stabilization (Cui *et al.*, 2015), and (Rucevskis, Akishin and Korjakins, 2019). The encapsulation of PCMs is preferable as it reduces their reactivity and allows handling with them easier. The small size results in an increase in surface area across in which the heat transfer can occur (Dobri *et al.*, 2021). Encapsulation of PCMs takes some consideration when applied, which affects the performance of the thermal energy storage system (TESS) of PCM. The core-to-coating ratio is a critical parameter in determining the mechanical and thermal stability of encapsulated PCMs, heat storage, and release capacity (Salunkhe and Shembekar, 2012). The PCMs incorporation in the building components enhances the walls thermal performance (Ferster, Shen and Rendall, 2017). According to the research (Cui *et al.*, 2015), the melting temperature range differs between 19 to 28 °C for the organic PCMs and between 25 to 35 °C for inorganic PCMs, in addition, the fusion heat is almost within the scope of 120 to 280 kJ/kg no matter which kinds of PCMs, moreover the thermal conductivity of organic PCMs is close to 0.2 and 0.6 for inorganic PCMs, and the density range of organic PCMs from 700 to 900 kg/m3 and from 1300 to 1800 kg/m3 for the inorganic PCMs. Using PCMs decreases heat transfer to the internal space and temperature fluctuations (Li *et al.*, 2019), (Zhou *et al.*, 2016). It can reduce over-temperatures during summer and temperature fluctuations throughout the day, reducing heating and cooling demands in the building (Rose *et al.*, 2009).

3.3.1 Impact of Using PCMs on Energy Consumption

The thermal energy storage property of PCMs can be utilized for energy efficiency in buildings (Zhu and Yang, 2018). such as a review study (Whiffen and Riffat, 2013) focused on PCM technology and assessing PCMs capability in thermal energy storage (TES) and heat transfer impedance. A wide range of PCMs has been tested concerning indoor comfort temperature zone, and it appeared that organic PCMs, specially paraffin, were be the most viable because of their durability (Whiffen and Riffat, 2013). Previous studies indicated that PCMs' integration in the building components is effective as it decreases the radiant temperatures' fluctuation (Fiorito, 2014). While the surrounding temperature rises, PCM melting begins, and it turns from a solid state to a liquid state as this process absorbs the heat and stops the increase in surrounding temperature (Kamali *et al.*, 2016). But when the temperature goes down below the PCM melting temperature, the solidification operation starts, and it transforms from a liquid state to a solid form. In which this process releases heat to the environment as an exothermic process indeed these processes reduce heating and cooling loads (Kamali *et al.*, 2016). In general, the PCMs melting temperature used for building heating applications ranged between 15 to 30 °C regardless of the type of PCM, while the suggested optimal melting temperatures of PCMs were between 10 to 30 °C), as each category of PCM has various range of melting temperatures which contributes to use in specific applications (Q. M. Q. Al-Yasiri and Szabó, 2021). Another review article showed that the use of paraffin is the broadest as melting temperature varies between 19 to 29 °C and from 120 to 280 kJ/kg (Cui *et al.*, 2017). It is also important to mention that a review study included many previous studies in different climates to clarify the effect of using PCMs as an insulating layer in buildings so that the presence of this layer internally or externally gave the building walls higher thermal properties compared to the previous one and higher thermal performance whether in cooling or heating cases, in addition, to reducing interior temperature fluctuations (H. Akeiber *et al.*, 2016), (Rodriguez-Ubinas *et al.*, 2012). Similarly, models of composite walls with and without PCM material were investigated within three different external climates to evaluate the ability of PCM wallboards. The air temperature fluctuations of the wall surface and in the room were reduced, and using PCM appeared to be essential due to its significant reduction of overheating effect, the temperature of the wall surface is less when PCM wallboard is used, and the natural mixing of the air in which avoiding inconvenient thermal stratifications (Kuznik and Virgone, 2009). A two-dimensional numerical transient heat transfer is investigated in Iraq climatic conditions, using the finite difference method and implementing paraffin in a residential building (H. J. Akeiber *et al.*, 2016). The simulation results revealed the efficiency of PCM and the heat flux inside a room integrated with PCM is lower than a one without PCM (H. J. Akeiber *et al.*, 2016). Using PCM in walls is efficient in maintaining a constant indoor temperature and reducing the electricity demand, as well the study showed through the analytical model and numerical procedure adopted to obtain comfort internal temperature (Ismail and Castro, 1997). While PCMs vary in compositions, characteristics, and performance features, phase change materials should have an appropriate phase change temperature when they are used in buildings, as the melting temperature should also fit the local climatic conditions, depends on temperature, and have a little change in the volume during the phase change process (Sun *et al.*, 2020).

3.3.2 Optimum PCMs Thicknesses

The advantage of using PCMs is in the ability of a thin layer to store a high amount of heat, which improves the thermal performance of the building envelope and minimizes energy consumption (Hussein *et al.*, 2021). The optimal thickness of the PCM layer within building walls is significant for reducing heat transfer and management, which must be carefully chosen (Khedher, 2018). A study has investigated the thermal performance of conventional walls of the buildings in Iran, involved thirteen different phase change materials, as the PCMs were added with three thicknesses: 1, 2, and 4 cm, where a double increase in the PCM thickness leads to less than a twofold decrease in the heat transfer (Younger, 1997). According to results from a study (Zhou, Wong and Lau, 2014), four of phase change materials (PCMs) of different thermal properties were investigated. The results showed that each of the PCMs tested would decrease energy consumption in various efficiencies, in which the highest reduction of energy consumption was obtained when PCM 22 was used (Zhou, Wong and Lau, 2014). However, the reduction avg was 45.35% for heating and 50.75% for cooling purposes, as well the range of energy consumption can be minimized when PCMs thickness increased (Zhou, Wong and Lau, 2014). Similarly, another research examined the application of PCMs in residential buildings in order to decrease energy consumption considering indoor thermal comfort (Sheeja *et al.*, 2020). The optimal thickness of the HCE-SSPCM wallboard ranged between 30 to 60 mm, as the saving of annual energy consumption was 16.2% for heating and 4.53% for cooling, and the reduction rate of indoor temperature fluctuation was 41.3% for heating and 56.2% for cooling, compared to the room without the layer (Sheeja *et al.*, 2020). Furthermore, A wall model incorporated phase change material was tested in winter, using enthalpy method, in which results were obtained of the composite wall under a typical working conditions showed the effects of PCM layer thickness on enhancing thermal behavior of the wall and giving a fewer inner of temperature fluctuations, as the used PCM thicknesses were 0.5, 1, and 3 cm (Nematchoua *et al.*, 2015). Another study revealed the contribution of PCM latent heat, thickness location, and melting temperature to the thermal performance of walls for various climatic conditions in Turkey (Mohaibesh *et al.*, 2021). The obtained results showed that optimized PCM layer thickness and melting temperature vary from 1 to 20 mm and 6 to 34 °C based on climatic conditions. At the same time, the annual optimum thickness of the PCM layer is 20 mm for both layer locations in the wall (Mohaibesh *et al.*, 2021). A numerical investigation was conducted for two PCM materials in the winter and summer months, and which results displayed that the selected PCM layer of 28 °C melting temperature and 20mm thickness could enhance the walls' thermal performance. Asker et al. (Asker *et al.*, 2018) have developed a one-dimensional model in ANSYS FLUENT for a building wall embedded with PCM, in which a transient simulation was conducted for four various envelope designs. Using paraffin wax of two thicknesses 1 cm and 2 cm in Mediterranean climatic conditions showed that implementation of 2 cm inhibits the heat transfer significantly. The effectiveness of incorporating PCM in residential buildings can also be considered from an experimental study that examined the inclusion of a paraffin composite ceiling with 3 different thicknesses 1, 1.5, and 2 cm to find the optimum thickness (Q. Al-Yasiri and Szabó, 2021a) as the results showed the positive impact of using PCM on temperature fluctuation reduction, the time lag (TL), and the decrement factor (DF) (Q. Al-Yasiri and Szabó, 2021a).

3.3.3 Optimum Location of PCM Layer

While previous implementations for different positions of PCM layers had given different results, the optimum location of PCMs is much dependent on conducting the daily melting and freezing cycle, as a complete melting and freezing cycle is achieved (Hussein *et al.*, 2021). An experimental study investigated the impact of PCM on the rate of heat transfer in a building wall, and the results showed that using PCM leads to a significant time delay in heat transfer, and locating the PCM layer near the heat source allows a low-temperature gain compared to other positions (Khan, Bhuiyan and Ahmed, 2020).

The optimal location of the PCM layer could be impacted by its properties (such as heat of fusion, melting temperature, and thermal conductivity), weather conditions, and wall structure. However, when data related to these aspects is determined, PCM optimal location could be found (Cui *et al.*, 2015). The PCM layer placed on the inner side of walls reduces the peak of heat fluxes. It gives better heat transfer and humidity control than the exterior (Cui *et al.*, 2015). And so on. The optimal location for the PCM layer is when it is located from the internal side of the wall (i.e. within the first insulation layer) (Cui *et al.*, 2015). Also, a study aimed to expose the latent heat contribution and other aspects to the wall thermal performance, and to determine the location of the PCM layer, as the findings showed that locating the PCM layer has a significant impact when it's near the interior surface in summer and near the exterior surface in winter (Arıcı *et al.,* 2020). An experimental study showed the effect of incorporating PCM in the external walls towards the internal space of the building helps to significantly improve the thermal performance of the building envelope during continuous air conditioning of the indoor space or even when the air conditioning is turned on intermittently according to the work schedule (Li *et al.*, 2017). The impact of PCM position in the composite wall on heat transfer was analyzed twice: close to the interior and near to the exterior, using the finite volume method to solve nonlinear equations. In addition, when a PCM is installed closer to the external surface, a larger ratio of it melts, allowing it to contribute a better performance in decreasing heat transfer (Younger, 1997). Mohamed (Mohamed, 2011), has mentioned that the thermal insulation layer in the envelope should be in the direction of the heat source. Another study mentioned that many previous studies indicated that the PCM layer is preferable to be closer to the heat source. Such PCM layer position should be to the exterior for cooling and the interior for the heating (Jafri, Bharti and Ahmad, 2015). However, others stated that the middle position gives better annual results for the building performance (Jafri, Bharti and Ahmad, 2015). Similarly, Dashtaki et. al. studied the location of PCM in a composite wall to reach maximum efficiency in Tehran, and the results showed the impact of latent and sensible heat in decreasing the heat flux and thermal loads of the building, as the optimum location was the middle layer. A parametric numerical calculation using FLUENT was carried out to further understand the heat transit law for double PCM layer wallboard and the thermal performance under different conditions, and the results showed that utilization of double PCM layers located in the exterior and interior of building wall has much more performance compared to the single PCM layer (Tong and Xiong, 2018). Thereby the double layers retard the temperature diffusion velocity, and the interior wall temperature can be reduced by more than 10 K (Tong and Xiong, 2018).

3.3.4 Summery

The previous analyses indicate the importance of considering the location, thickness, and the type of material used for thermal insulation. From previous studies reviews, the Paraffin and Hydrated salt insulation materials took a higher impact on building envelope performance. The optimum thicknesses of the insulating layer varied according to the wall components, the climatic zone, and the location of the insulating layer within the wall, as implementing the PCM layer towards the inside leads to obtaining the most efficient performance for composite walls, as well as, paraffin PCM is a better option to be implemented in external walls, due to its characteristics, its high latent heat, its life age, Resistance to weather conditions, and the low phase change temperature.

3.4 Cost of Insulation Materials

Mainly, the newly manufactured materials are of high cost due to their higher thermal properties and lack of availability in the market, but when there are multiple sources of production and spread in the market, their price will be affordable and acceptable. For the extruded polystyrene material (XPS), the cost depends on the density, thickness, form of material, and according to (López-Ochoa *et al.*, 2020), the price of XPS estimated to be 267 €/m3 which almost equals 272 US$/m3. Whereas for phase change materials (PCM), the price of paraffins increases with the percent of purity, The pure paraffin (>99%) is almost 1.88 to 2 $/kg (Kosny, Shukla and Fallahi, 2013). And the Nano-PCM almost costs 0.99 US$/kg (Al-Waeli *et al.*, 2019) and almost 1 US$/kg according to (Hirschey *et al.*, 2021). By comparing the prices, the PCM seem to be higher by almost 3 times than XPS insulation, However, this innovative material with the higher thermal properties could be more affordable in the future. These data are important to estimate the cost of implementing the materials to the building envelope and to find out the saving amount of energy consumed.

3.5 A comparative Study Between the Optimum Choice of Using Insulation Materials

The focus on previous studies of the impact of innovative insulation materials on the efficient use presented aimed to determine the optimum thermal properties, thicknesses, and locations within the composite wall of residential buildings. Several commonly used insulation materials give various results of thermal conduction under different ambient thermal conditions and based on the usage purpose. Installation way of XPS sheets as a layer in the wall is considered easy due to the use of rigid sheets or panels that stand stable or can be glued to the wall layers or even fitting panels to the wall configurations, see the figure below. Designers present flexible XPS panels concerning the aesthetic features, dimensions, size, anchoring systems, and installation execution. Like some cases, installation of the XPS panels needs applying adhesive mortar and preceding preparation of the substrate in order to ensure the permanent bond of insulation panels to the wall structure, in addition, to guaranteeing structural safety in service and resistance of extreme conditions (Masera, Iannaccone and Salvalai, 2014).

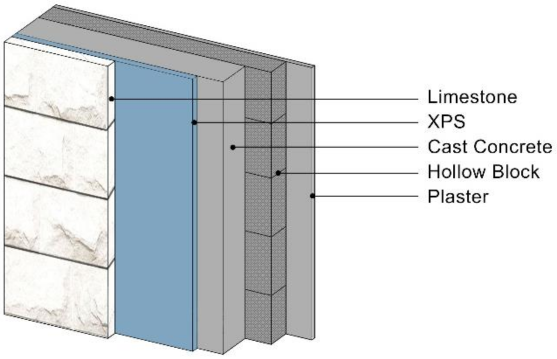


Figure 13 Installation of XPS in the wall section, Researcher.

In addition to the role of thermal insulation in preventing heat transfer and fluctuations in the internal temperatures, the innovative materials (PCMs) are distinguished from traditional materials by their properties in improving the thermal performance of the building envelope, the high ability to insulate through heat storage and release by changing its physical state during the heat transfer process, dealing with normal and abnormal climate conditions more effectively. Its optimal thickness is less and therefore useful for existing and limited spaces in residential buildings. Compared to conventional materials used in buildings, PCMs provide a large heat capacity in a limited temperature range, which is acts as an isothermal container of heat (Soares *et al.*, 2017). Thermal Energy Storage (TES) of PCMs can be used to decrease buildings' dependence on fossil fuels, reduce the energy demand for heating and cooling, decrease the air conditioning loads needed in heating/cooling, improve heat capacity and thermal resistance of building's envelope, and improve the indoor thermal comfort (Soares *et al.*, 2017). Incorporating PCMs into buildings is an innovative technological solution that could be used in both existing buildings and new buildings (Reda *et al.*, 2013). As in Mediterranean climate contexts, most benefits are clearly found in the summer period, in which their use contributes significantly to the reduction of pollution produced by the residential sector. As a result of phase change, the material requires a container that protects it from the environment and harmful interaction, ensures structural stability, easy handling, corrosion resistance, and strength flexibility (Bland *et al.*, 2017). Integration of PCM into wall construction can be via direct incorporation, encapsulation, immersion, and shape stabilization (Rucevskis, Akishin and Korjakins, 2019). As the encapsulation of PCMs is better in reducing their reactivity and allowing handling them easier. Also, the small size increases the surface area across in which the heat transfer can occur (Dobri *et al.*, 2021). Encapsulation of PCMs takes some consideration when applied, which affects the performance of Thermal Energy Storage System (TESS) of the PCM. While melting and solidification processes are controlled by convection and conduction, respectively, the high thermal conductivity, lower temperature of the external surface, and smaller capsule diameter reduce the total solidification time of encapsulated PCM (Salunkhe and Shembekar, 2012). One of the recommended implementation systems is applying the material (encapsulation of PCM) and integrating it via wall panels in order to be effective and more practical in the installation process. These sheets or boards can be divided into small honey cells (honeycomb structures) that are used in different geometrical cores (Duan, Xiong and Yang, 2019), and each cell contains an appropriate amount of the material. See the figure below:

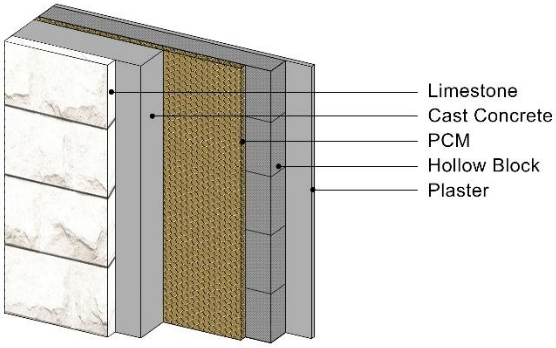


Figure 14 Installation of PCM in the wall section, Researcher.

Through previous studies, thermal performance of the walls depends on the wall construction, the type of thermal insulation used, its thickness, and its location within the division. The thermal resistance of the wall is assumed to be constant, but there is a change in the thermal performance of the wall based on these parameters. Therefore, the insulating materials used within the climatic environment of the study were analyzed to find the best among them and their sustainability over time, life age, and efficiency in energy conservation. Moreover, examining the thermal performance of the models based on the previous parameters. The new feature of this research is to assess the useful usage of the PCMs in Middle East region generally and in Palestine particularly, in terms of thermal performance, energy consumption and efficiency, cost, and payback period. For this purpose, the study will enable engineers and designers to select the best insulation system for a given application, as well as helping the researchers forward more innovative research works in this field.

3.6 Commonly Used Model Walls in The Context of Study (Construction and Materials)

A group of commonly used composite walls (typical models) in the study area. For the intent of this study, ten models of composite walls are selected to clarify the wide range of thermal characteristics of the wall systems. As the selected walls contain Limestone, cast concrete, hollow block, and internal plaster (Dawoud, 2015) (Code, 2004), in addition to thermal insulation (Code, 2004), where its type, location and thickness vary, and their thermal characteristics are shown and listed in Table 4. The data was collected based on the researcher's practical experience and oral interviews with specialists and contractors in the construction field. The first case of composite walls is the basic case consisting of limestone, cast concrete, hollow blocks and internal plaster without an insulation layer as shown in the figure below. The Second case of composite walls contains limestone, cast concrete, hollow blocks, and interior plaster with an air layer that works as an insulator.

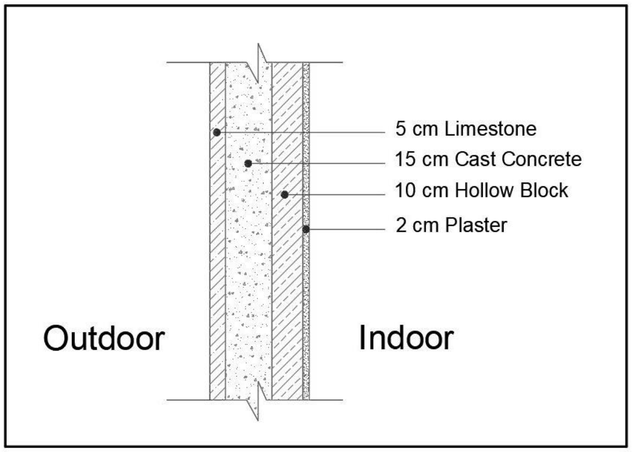


Figure 16 shows the first wall of common walls in the study region.

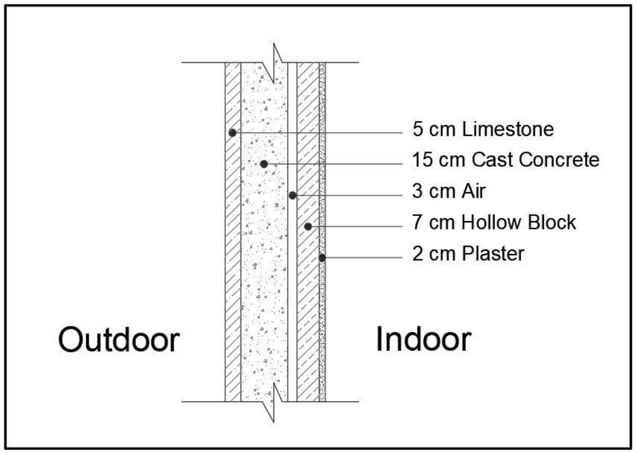


Figure 16 shows the second wall of common walls in the study region.

The Third case consists of cast concrete, hollow blocks, a middle air layer, and two layers of plaster, outer and inner. The Fourth case consists of two layers of hollow blocks, a middle air layer, and two layers of plaster, outer and inner, as it's shown in the next figures:

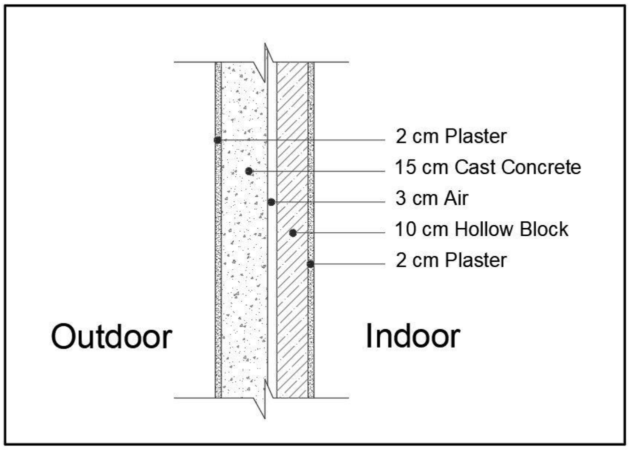


Figure 20 shows the third wall of common walls in the study region.

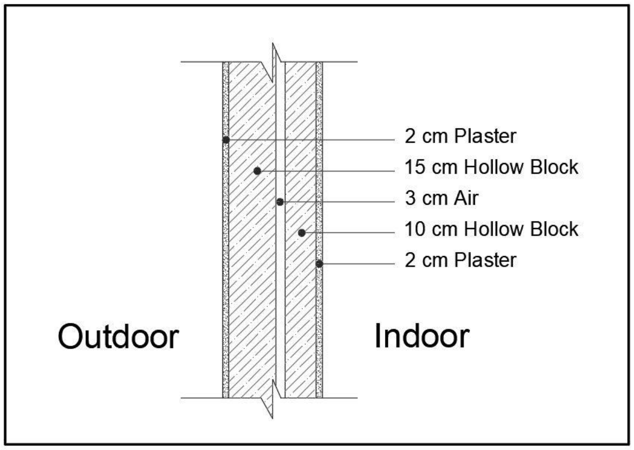


Figure 20 shows the fourth wall of common walls in the study region

The Fifth wall contains two layers of hollow blocks, a middle insulation layer, and two layers of plaster, outer and inner. The Sixth wall consists of cast concrete, hollow blocks, a middle insulation layer, and two layers of plaster, outer and inner, as it’s seen in the figures below:

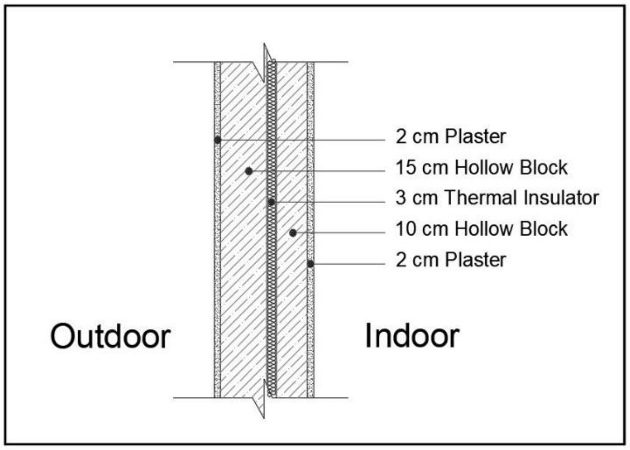


Figure 18 shows the fifth wall of common walls in the study region.

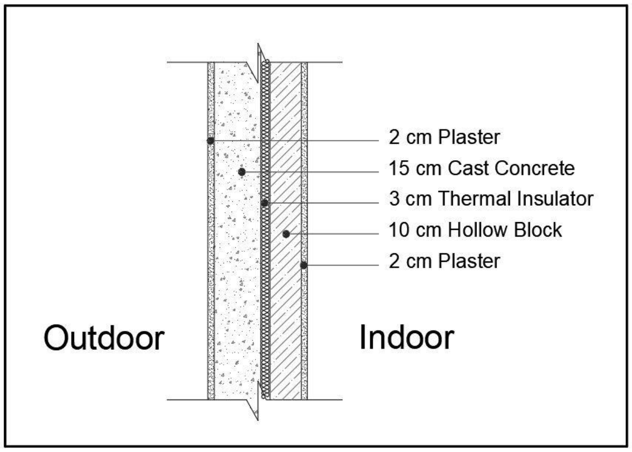


Figure 18 shows the sixth wall of common walls in the study region.

The Seventh wall consists of limestone, cast concrete, a middle insulation layer, hollow blocks, and plaster. The Eighth wall consists of limestone, cast concrete, hollow blocks, an inner insulation layer, and plaster, as it’s seen in the figures below:

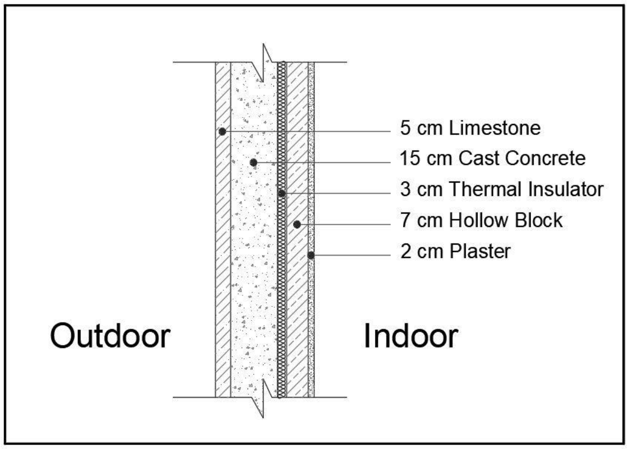


Figure 24 shows the seventh wall of common walls in the study region.

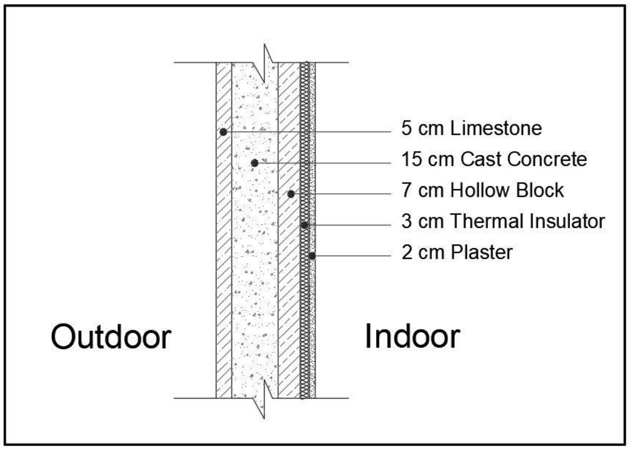


Figure 24 shows the eighth wall of common walls in the study region.

The Ninth wall contains limestone, cast concrete, an inner insulation layer, and plaster. The Tenth wall has limestone, an outer insulation layer, cast concrete, hollow block, and inner plaster layer, as it’s shown in the next figures.

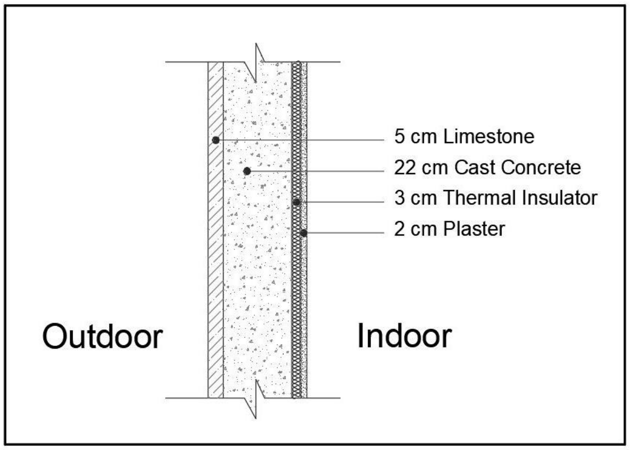


Figure 22 shows the ninth wall of common walls in the study region.

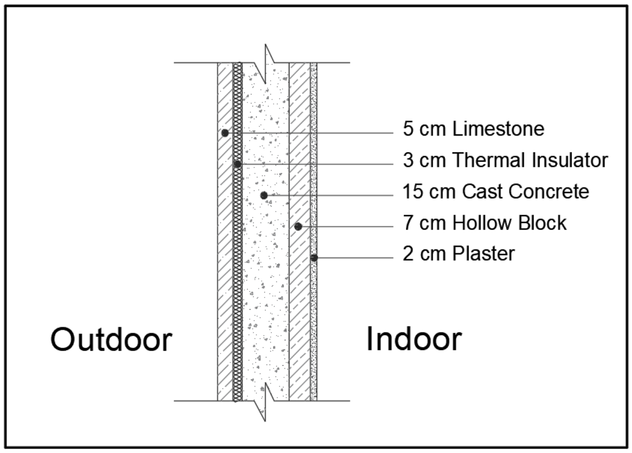


Figure 22 shows the tenth wall of common walls in the study region.

There are multiple construction methods of the composite walls that are common and used in the study area, and for the insulation, it is noticed from the previous figures that there are two widely used methods, namely, internal insulation and middle insulation, and external insulation. Although external insulation has been less used, it’s acclaimed for its thermal efficiency in the different climatic environments.

3.7 Base Case Study (Reference Case Model)

The base case expresses the standard practice in the construction field at the beginning of the concrete revolution. A large proportion of the existing buildings still contain it in all different climate regions in the study area. And since a large percentage of residential buildings share the same exterior wall structure, this model has been adopted as a reference model and is enhanced with a thermal insulation layer using different materials to obtain the best thermal performance.

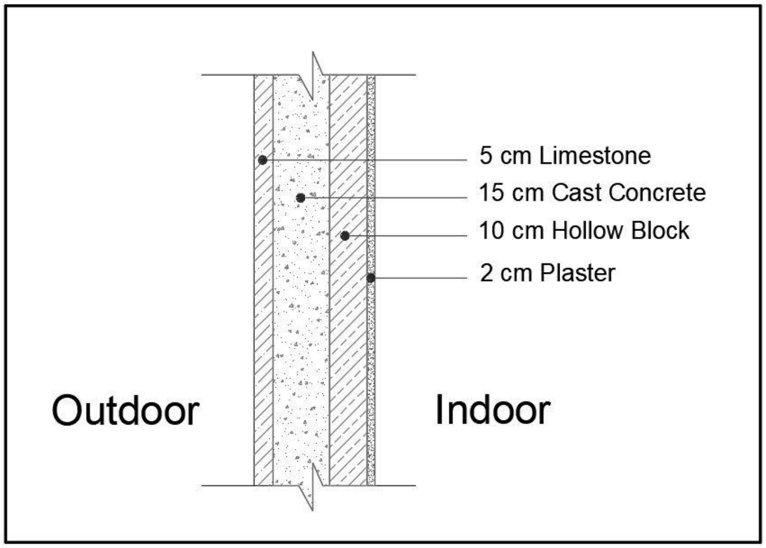


Figure 25 shows the reference model wall.

3.8 Conclusion

This chapter has provided a comprehensive literature review on types of thermal insulating materials used in the study area's climate and their role in influencing the performance of building walls in reducing building energy consumption and a comparative study of the optimum choice of using insulating materials. Moreover, clarifies the commonly used models in the context of the study.

Chapter Four

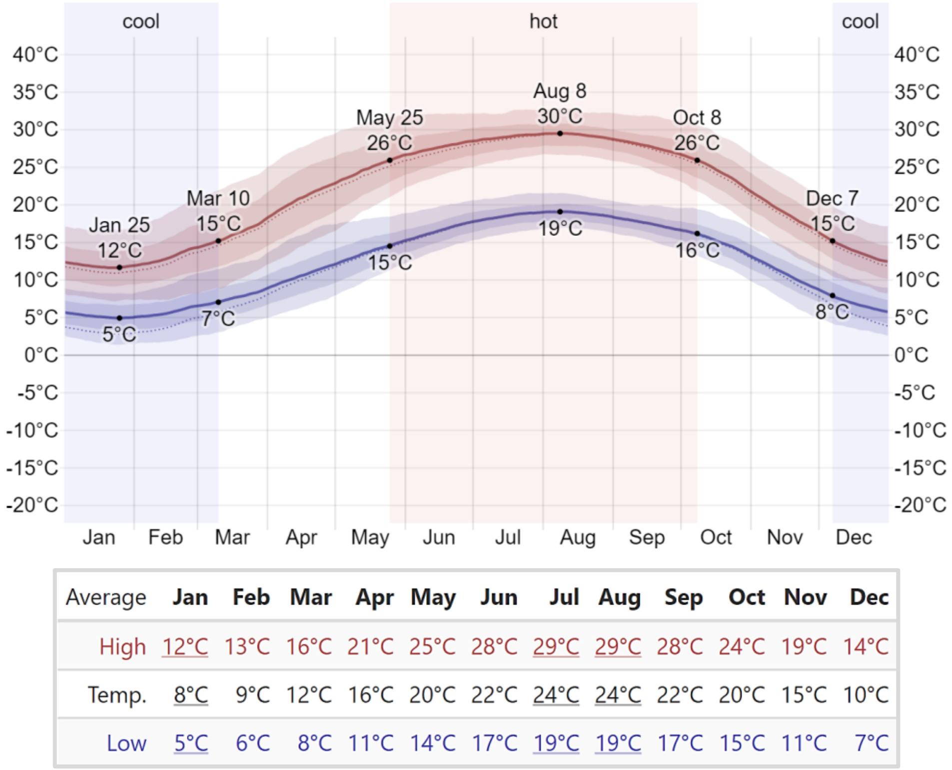
Chapter Four: Energy and Heat Transfer

4.1 Introduction

The importance of architecture lies in achieving human coexistence with its surroundings through the building and providing a comfortable environment for building users as the person spends a long time in the dwelling, so the designer should achieve integration and linkage between inside and outside the building in order to improve the thermal performance and thermal comfort of the building following the principles of sustainability. This study highlights the importance of using passive design principles to improve the quality of the interior environment for residential buildings to provide the greatest comfort and stability to the users. Braungart and McDonough suggest in their book that Humans have a design problem, not a pollution one. When they can manage products and buildings intelligently from the start, then waste, contamination and scarcity couldn't happen (Onan, 2014). As sustainable design concerns three linked components: society, economy, and environment, Design-related decisions affect sustainable development and the abundance of the needs of future generations (Onan, 2014). Moreover, the definition of basic mechanisms of heat transfer was explained and carried out. In addition to the theoretical aspect of each process, several practical cases are intended to present heat transfer mechanisms that were developed, as in parallel learning how to develop them in ANSYS (FLUENT). The researcher in this study showed it is fundamental for developing this study to analyze heat transfer and how thermal insulation impacts the amount of energy consumption in different climatic conditions. This work has been carried out from February 2021 to November 2022.

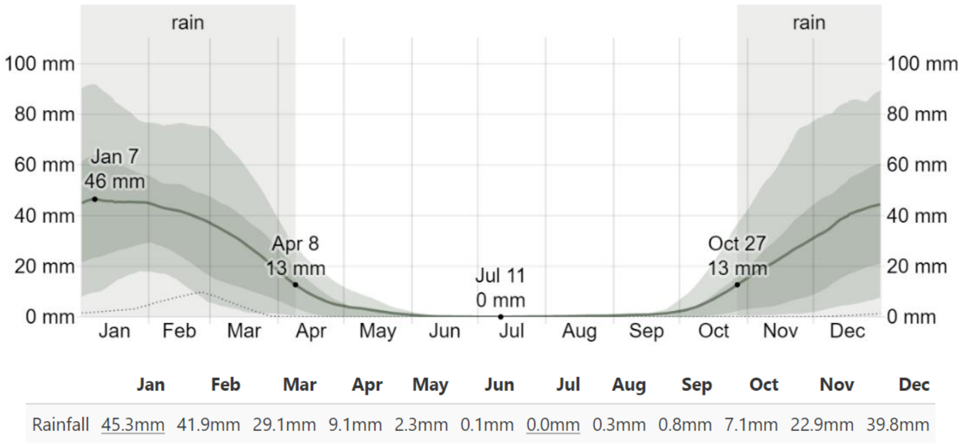
4.2 Case Study Area: Jerusalem

Palestine’s location gives it an advantage in the Koppen climate classification (Kottek *et al.*, 2006), as the study Mediterranean region contains hot-summer Mediterranean (Csa), to the hot semi-arid (BSh) and the hot desert climate (BWh) (Zoccatelli *et al.*, 2019). A simulation-based optimization methodology in a study is presented to define the optimum PCM peak of melting temperature. Choosing the PCM melting temperature is a key factor for improving the energy performance in the building in different climate conditions (Saffari *et al.*, 2017). The results show the best PCM melting temperature is nearly 26 ℃ (melting range of 24–28℃) a dominant cooling climate, whereas the melting temperature of 20 ℃ (melting range of 18–22℃) in heating dominant climates. While in climates with energy demands for both heating and cooling, the optimum PCM melting point ranges between maximum and the minimum peak of melting temperatures (Saffari et al., 2017). Jerusalem which is located at latitude 31°46'5.95"N (jerusalem-latitude-longitude, 2022), and longitude 35°12'49.36"E (jerusalem-latitude-longitude, 2022) has a long, arid, warm, and clear summer, while the winter is cold and generally clear. Throughout the year, temperatures typically vary from 5 to 30 °C and are rarely below 1 °C or above 33 °C (Average Temperature in Jerusalem, 2022). The average temperature in Jerusalem in both winter and summer is clarified as follows: the winter season continues for 3.1 months (from December, 7th to March, 10th , with the lowest average temperature of 5 °C, and the summer season holds for 4.5 months (from May, 25th to October, 8th), as the highest average daily temperature is 30 °C as shown in the figure below (Average Temperature in Jerusalem, 2022).



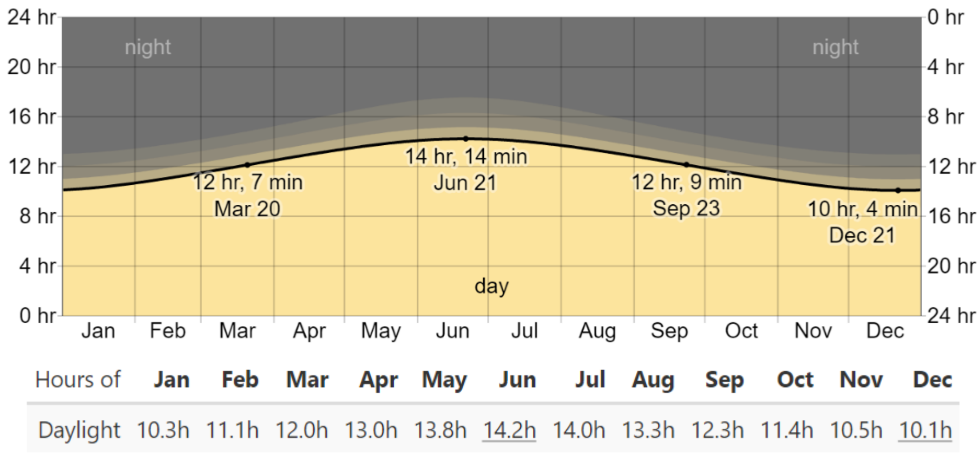
Average	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
High	12°C	13°C	16°C	21°C	25°C	28°C	29°C	29°C	28°C	24°C	19°C	14°C
Temp.	8°C	9°C	12°C	16°C	20°C	22°C	24°C	24°C	22°C	20°C	15°C	10°C
Low	5°C	6°C	8°C	11°C	14°C	17°C	19°C	19°C	17°C	15°C	11°C	7°C

Figure 26 The daily average high (red line) and low (blue line) temperature, with 25th to 75th and 10th to 90th percentile bands. The thin dotted lines are the corresponding average perceived temperatures (*Average Temperature in Jerusalem*, 2022).



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	45.3mm	41.9mm	29.1mm	9.1mm	2.3mm	0.1mm	0.0mm	0.3mm	0.8mm	7.1mm	22.9mm	39.8mm

Figure 27 The average rainfall (solid line) accumulated over the course of a sliding 31-day period centered on the day in question, with 25th to 75th and 10th to 90th percentile bands. The thin dotted line is the corresponding average snowfall (Average Temperature in Jerusalem, 2022).



Hours of	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Daylight	10.3h	11.1h	12.0h	13.0h	13.8h	14.2h	14.0h	13.3h	12.3h	11.4h	10.5h	10.1h

Figure 28 The number of hours during which the Sun is visible (black line) (Average Temperature in Jerusalem, 2022).

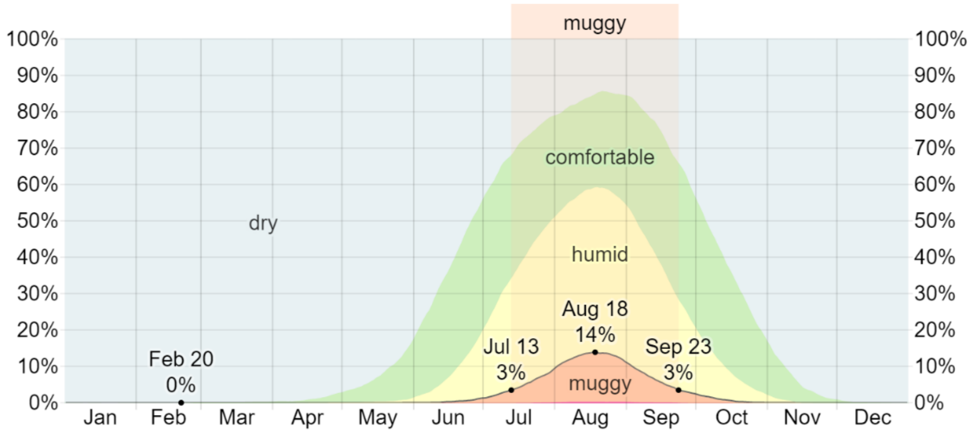


Figure 29 The percentage of time spent at various humidity comfort levels, categorized by dew point (*Average Temperature in Jerusalem*, 2022).

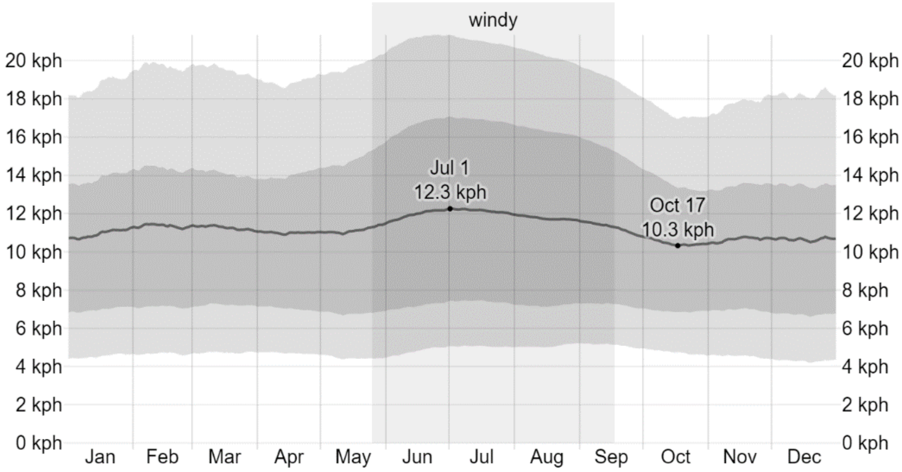


Figure 30 The average of mean hourly wind speeds (dark gray line), with 25th to 75th and 10th to 90th percentile bands (*Average Temperature in Jerusalem*, 2022).

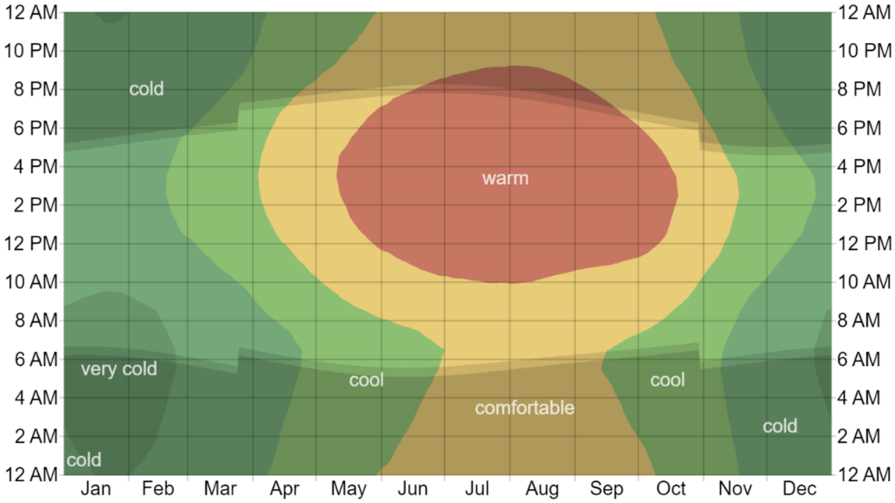


Figure 31 The average hourly temperature. The shaded overlays indicate night and civil twilight (Average Temperature in Jerusalem, 2022).

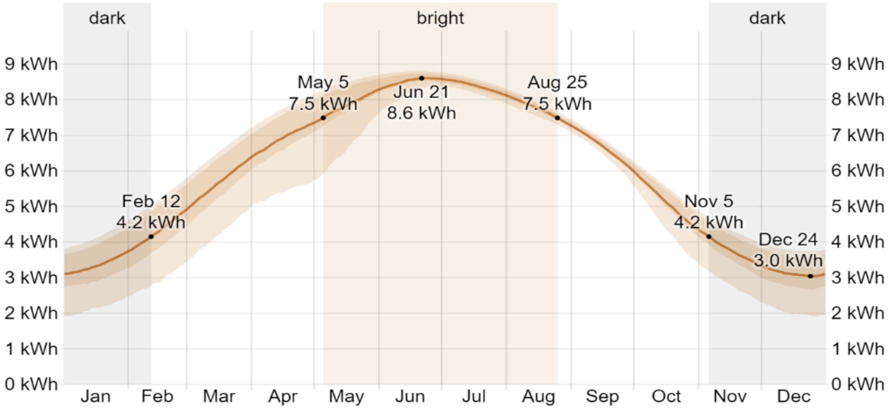


Figure 32 The average daily shortwave solar energy reaching the ground per square meter (orange line), with 25th to 75th and 10th to 90th percentile bands (Average Temperature in Jerusalem, 2022).

4.3 Data Analysis / Data processing

The selected materials used for analytical simulation and considered as recommended materials for construction are shown in the table below:

Table 4 Represents Materials Properties

Building envelope	Components (From outside to inside)	Thickness (cm)	Thermal Conductivity (W/m.K)	Density (kg/m³)	Specific Heat Capacity (J/kg·K)	Source
External Wall (Structure)	Limestone	5	1.53	2200	1000	(Code, 2004).
	Cast Concrete	15	1.75	2300	1000	(Muallem, 2020), & (Code, 2004).
	Hollow Block	10	0.77	1200	1000	(Code, 2004).
	Plaster	2	1.2	2000	1000	(Muallem, 2020).
	XPS Insulation	varying	0.034	22	1280	(Oktay *et al.*, 2016).
	Paraffin wax (28 °C) melting point	varying	0.2	770 liquid 880 solid	Specific Heat Capacity =2000 (J/kg·K) Heat of fusion = 245 (kJ/kg)	(Q. M. Q. Al-Yasiri and Szabó, 2021), & (Sun *et al.*, 2019).

4.4 Validation Study

Several validation studies that were use PCMs are mostly carried out on CFD models and the heat transfer of walls. In this study, a 2D geometry was chosen. A transient analysis under conduction /and convection heat transfer has been applied to measure the time dependency of the heat transfer in the models' system, which enable to solve of conduction and convection equations within the applied boundaries and initial conditions. Among five models used in the study, the fourth model was chosen for the validation study. The layers of Model 4 include Stone, concrete, block, PCM (paraffin), and plaster. The wall length is 100 cm, and the width of each layer is 6 cm for Stone, 2 cm for PCM, 15 cm for concrete, 7 cm for block, and 3 cm for the plaster layer. The model has been investigated numerically using the ANSYS FLUENT 13.0 software, as various grid sizes and time steps were examined in the preliminary simulations to get computational grid convergence. The 2D computational grid was constructed using (282504) hexahedral elements. The transient simulation was run using the k-epsilon turbulence model, and the time step used in calculations was set to 0.1 s. The solidification/melting model was enabled to describe the phase change phenomena in n-Octadecane. The first-order upwind spatial discretization and the pressure solver with the PRESTO algorithm for pressure-velocity coupling were selected to obtain a converged solution. The convergence criteria were set by setting the absolute residual values to 10-6 for energy and 10-3 for other variables. Zero heat flux boundary conditions were set on the upper and bottom sides of the wall. The outside wall was held at a constant temperature of 305K, and the inside wall was held at a constant heat transfer coefficient of 4 W/ m^2. The Liquid fraction in the next figure shows the path of the fraction liquid compared to time of the study.

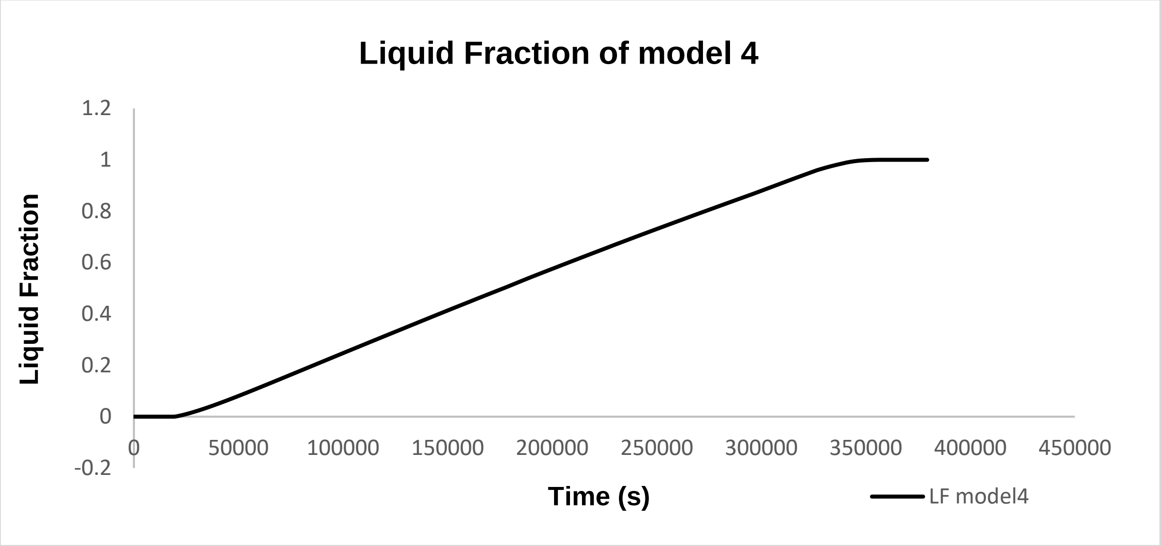


Figure 33 shows liquid fraction of model 4. Source: (Maghalseh, M. et al., 2022).

Three points at different heights were chosen to clarify the temperature (k) track compared to time (s) within the wall section, which is at heights of 25, 50, and 75cm.

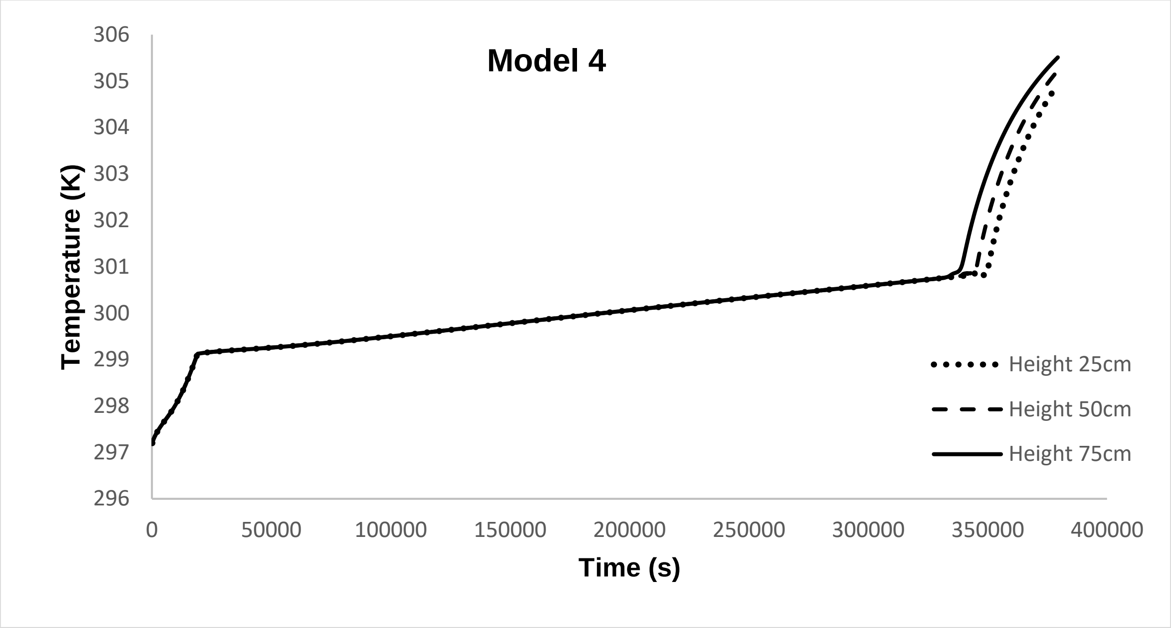


Figure 34 shows Variation of the temperature at different height in Model 4 as function of time. Source: (Maghalseh, M. et al., 2022).

Using ANSYS FLUENT R2 2022, the 2D computational grid was reconstructed and transient simulation was run using the k-epsilon turbulence model. The time step used in calculations was set to 0.1 s. The solidification/melting model was enabled to describe the phase change phenomena in n-Octadecane, which is appeared in the liquid fraction graph in the next figure which shows the path of the fraction liquid compared to time of the study.

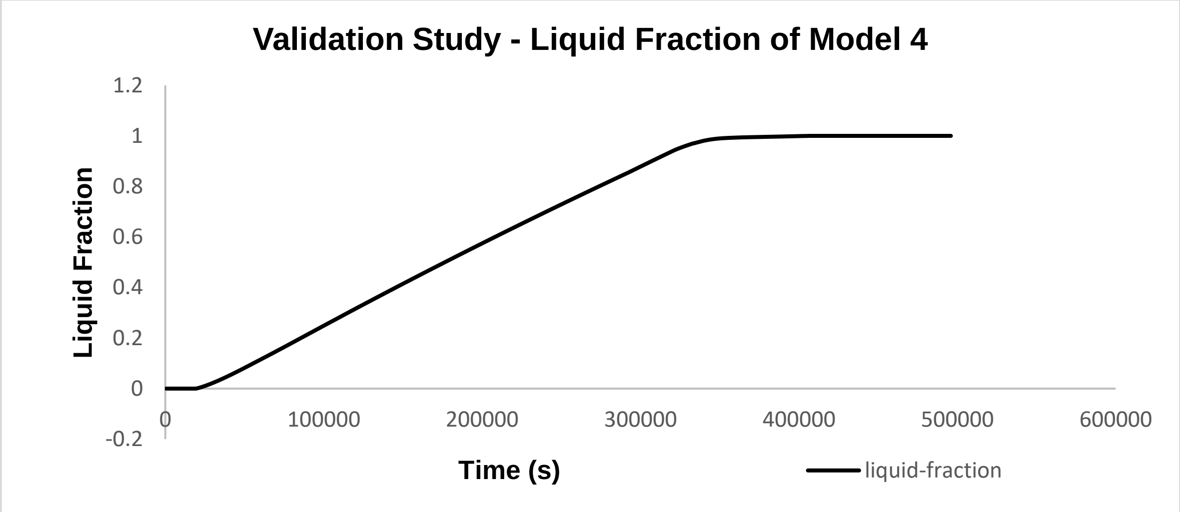


Figure 35 shows the path of the fraction liquid compared to time of the study, Researcher.

Similarly, the same heights and locations of the three points were compared with the previous study, which is at heights 25, 50, and 75cm.

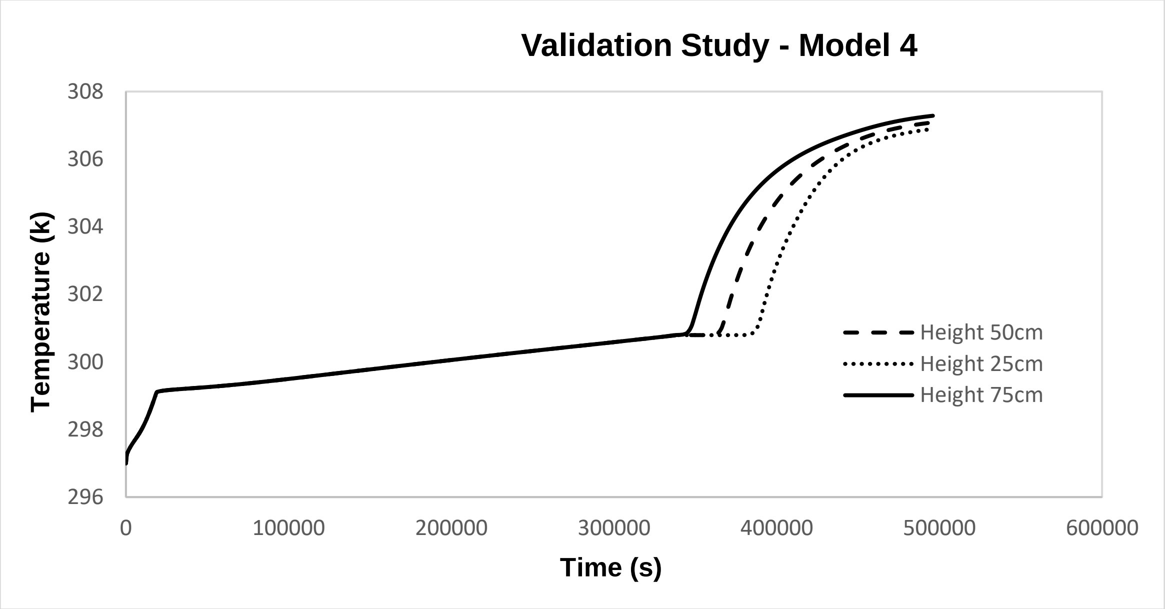


Figure 36 shows Variation of the temperature at different height in Model 4 as function of time, Researcher.

The Liquid fraction model was compared between the previous model and the modern one that was created, the results showed a matching of more than 95%, so this ensures that the validation study is approved. Also, when the three points at the same heights and locations were compared between the two models, the results showed a matching between both two simulations for more than 90%, which means that the results are valid. Although the percentage of matching between points taken at the same height and location exceeded 90%, there is some disparity in determining the temperature of melting with time. This disparity is due to the difference in years of versions between the programs and nature of reading the data.

4.5 Identifying Design Parameters and Input Values

As a result of climate change and significant temperature differences in the past few years, the research reveals the importance of using thermal insulation materials and their performance in preventing heat transfer through walls. In addition, the study focused on highlighting the best practices for the use of external walls in the local environment of Palestine in particular. According to the previous reviews, the research found the best thermal performance for walls with the same wall section thickness section containing local materials, that the main factors affect significantly the thermal performance of the walls were thermal specifications of the insulation layer, thickness, and its location within the wall.

Table 5 shows simulation parameters and their references

Parameter	Reference
Temperature (Out /In), (Winter/Summer)	Palestinian Code (EEBC) (Code, 2004)
U-Value	Literature Reviews
Layer Thicknesses (optimum/Avg)	Literature Reviews & Assumption
Location of Layers	Literature Reviews & Previous Practices & Results of simulation
Software	ANSYS (FLUENT)

4.6 Heat Transfer Calculations (FLUENT)

4.6.1 Evaluation Criteria

In this section, principles of physics' fundamental dominance presented how the heat is transferred via a building envelope. The equations describing the heat transfer allow for the evaluation of heat losses via wall components. The evaluation is carried out following the procedures from guide standards and the building regulations in Palestine. The thickness and thermal conductivity of materials affect the overall heat transfer coefficient when heat is ed. The larger the coefficient, the more heat is easily transferred from the source (Aboamir, 2013). The relation between the coefficient of overall heat transfer (U) and the rate of heat transfer (Q) can be explained by the equation (Aboamir, 2013):

$$q = U \text{ A } \Delta \text{TLM} \qquad (3)$$

Where, Q refers to heat transfer rate, W=J/s [btu/hr] A expresses heat transfer surface area, m^2 [ft2] U is the coefficient of overall heat transfer, W/(m^2°C) [Btu/(hr-ft2°F)] ΔTLM is a logarithmic mean temperature difference, °C [°F]. When considering an exposed wall to a hot fluid (A) on a side and a cooler fluid (B) on the opposite side, the heat transfer can be expressed by (Serghides and Georgakis, 2012):

$$q = h_1 A\,(T_A - T_1) = \frac{kA}{\Delta x}\,(T_1 - T_2) = h_2 A\,(T_2 - T_B) \qquad (4)$$

The heat loss related to the building envelope is straight dictated by the outdoor and indoor temperature difference, environmental conditions, and thermal quality. The next figure presents a scenario where indoor air temperature (Ti) is higher than external one (Te) as a result of the temperatures difference between the indoor (Tsi) and external surfaces (Tse) of components of the building envelope.

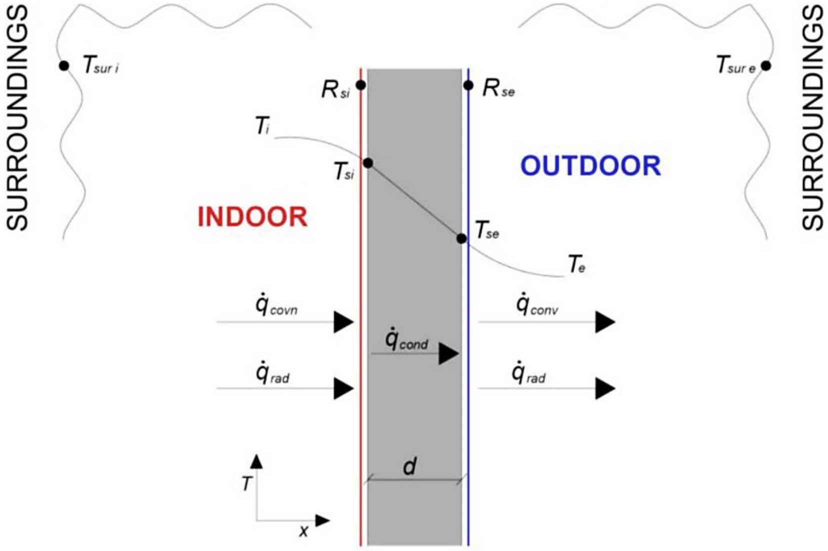


Figure 37 shows Heat loss through building envelope component, source: (O'Grady, 2018).

The heat loss via building envelope is intricate and the heat is transferred in three modes: conduction, radiation, and convection. The heat transfers by conduction when there is a temperature difference, which involves the energy transport from high energetic parts to the less energetic ones in the component. On the other hand, the heat flows from a higher temperature region (T*si*) to a lower temperature region (T*se*) (O'Grady, 2018). Several numerical calculations in previous studies have been performed to analyze the heat transfer during charging and discharging considering the PCMs' latent thermal energy storage, in which transient state was selected for heat transfer since the phase-change is non-linear for the heat transfer (Kottek *et al.*, 2006). The melted paraffin amount increases when the boundaries temperature increases, that while increasing thickness, the heat transfer rate decreases because of increasing thermal resistance, and as a result the melting rate decreases (Akhavan, Zarei and Izadpanah, 2018).

4.6.2 Numerical Approach for Building Walls Assessment and Thermal Calculations

Before using ANSYS to calculate the heat transfer through model walls, the following questions were set to be answered:

- What are the main objectives of this type of analysis?

- What are the determinants to be set in calculations?
- How many details must be included in the model?

when answering like questions accurately, ANSYS finite elements software should be employed efficiently, considering typical Modeling and simplifications. Moreover, ANSYS software is potent for thermal analysis. It addresses sundry different thermal matters, such as primary heat transfer, steady-state /or transient conduction, radiation, and convection.

Several Computational Fluid Dynamic (CFD) tools that used previously for numerical investigation of application PCMs, both in the system scale and for the whole buildings. CFD models are used to predict airflow and temperatures in the indoor environment by numerically solving partial differential equations for mass, momentum, and energy. The equations are linearized and applied to finite volumes to obtain a particular numerical solution. In the PCMs applications, CFD investigation is often combined with ANSYS FLUENT, one of the specialized CFD tools used for thermal calculations of building envelopes enhanced with PCM (Boostani and Mirzapour, 2015). The ANSYS software was used in this study due to the most accurate and frequently used in studies of calculations and numerical simulation of the heat transfer mechanisms, according to (Jiménez, 2013). In order to find out the optimum thickness of thermal insulation, Nyers and Komuves in their study applied a developed mathematical model, methods and a steady-state mathematical model to reach the energy-economic optimum for thermal layer thickness (Nyers and Komuves, 2015). Unlike previous studies, Zedan and Mujahid in their study developed an analytical solution for heat transfer in composite walls where the solar radiation in the study is considered explicitly with not through sol-air temperature (Zedan and Mujahid, 1993). The transient study showed the utility of this method as providing an efficient way to purely numerical calculations (Zedan and Mujahid, 1993). Transient heat study can be conducted accurately through ANSYS-FLUENT, which allows a numerical simulation model to validate the capacity of simulating temperature development of a model containing PCM and understanding the PCM contribution to energy efficiency (Kheradmand *et al.*, 2016). Models can be solved in ANSYS-FLUENT numerically using transient steady-state in one or two dimensions (Akhavan, Zarei and Izadpanah, 2018).

4.6.3 Simulation Procedure and Models

For the study purposes, a 2D geometry model was chosen, and transient simulation analysis was applied under conduction and convection heat transfer to account for the time dependency of the study problem and heat transfer in the entire system that enables to solving the equations of conduction and convection under the applied boundary conditions. Nine composite wall models were used and calculated in this study in two phases. Each wall consists of different combined materials, one of which is Extruded Polystyrene (XPS) and Paraffin layer as a phase change material (PCM), these materials used in the study as thermal insulations with different locations and thicknesses based on the study methodology. The different constituent layers include: for the first and second phases (single insulation layer): Model 1: Stone, concrete, block, and plaster without insulation layer. Model 2: Stone, concrete, block, XPS (4th layer) and plaster. Model 3: Stone, XPS (2nd layer), concrete, block, and plaster. Model 4: Stone, concrete, XPS (3rd layer), block, and plaster. Model 5: Stone, concrete, block, PCM (4th layer) and plaster. Model 6: Stone, PCM (2nd layer), concrete, block, and plaster. Model 7: Stone, concrete, PCM (3rd layer), block, and plaster. Phase three (double insulation layers), is developed based on the phase one and two, Model 8: Stone, XPS (2nd layer), concrete, PCM (4th layer), block, and plaster. And Model 9, in the phase four, which is developed also based on the previous cases: Stone, XPS (2nd layer), concrete, PCM (4th layer), block, and plaster. In this case, the insulations thicknesses were reduced to 50%. The wall height is 100 cm, and the length of each layer is 5 cm for the Stone, 15 cm for the concrete, 4 cm for the XPS, 2 cm for the PCM, 10 cm for the block, and 2 cm for the plaster layer. A set of points was taken to measure temperatures within the walls models located at three different heights at 25 cm, 50cm, 75cm. The phase change process can be explained by partial differential equations, which can be solved by applying analytical or numerical methods. However, numerical approaches can predict more accurate results efficiently (H. Akeiber *et al.*, 2016). Moreover, the numerical approach is an efficient solution for heat transfer troubles, as it is widely used for thermal bridge assessment of building envelopes. In addition, two common numerical methods are the Computational Fluid Dynamics (CFD) and Finite Element (FE) approaches (O'Grady, 2018). Furthermore, CFD could be used for optimization procedures, in which they can save cost and considerable time for researchers (H. Akeiber *et al.*, 2016). While ANSYS FLUENT is the most used and useful software in such problems, multiple CFD codes can be chosen, such as Star CCMT, ANSYS-CFX, and COMSOL Multiphysics (H. Akeiber *et al.*, 2016). Software tools that can anticipate heating and cooling energy demand effectively support improving the energy efficiency of buildings, leading to valid predictions of the demand of energy in dynamic conditions in lower computational costs (De Rosa *et al.*, 2016). The phase change can be considered in the heat equation using the method of effective heat capacity or the enthalpy method (Kuznik *et al.*, 2011). Numerical studies concerning PCM integrated into building walls can be categorized as the unidirectional heat equation, and two or three-dimensional heat equation, in the single wall, in which studies that involve the unidirectional heat equation take into account the phase change temperature, thickness of the PCM and place (Kuznik *et al.*, 2011).

For predicting the conduction and the convection heat transfer, the following equation is used in FLUENT in the energy conservation (Ansys, 2011), (Al-Maghalseh, 2014):

$$\frac{\delta}{\delta t}(\rho E)+\nabla.\left(\vec{u}\left(\rho E+p\right)\right)=-\nabla.\left(k_{eff}\nabla T-\sum_{j}h_{j}\vec{J}_{j}+\left(\overline{\overline{\tau}}_{eff}.\vec{u}\right)\right)+S_{h} \tag{6}$$

As the first three terms on the second part of the equation present the heat conduction, species diffusion and viscous dissipation respectively.

$$E=h-\frac{p}{\rho}-\frac{u^{2}}{2} \tag{7}$$

where sensible enthalpy is defined for ideal gases as:

$$h=\sum_{j}Y_{j}h_{j} \tag{8}$$

And for incompressible flow:

$$h=\sum_{j}Y_{j}h_{j}+\frac{p}{\rho} \tag{9}$$

$$h_{j}=\int_{T_{ref}}^{T}C_{p},jdT \tag{10}$$

Natural convection could be modelled in the FLUENT using two methods: the Boussinesq model and the Prewsise model. In the Prewsise model, the user can input the change in density experienced as a function of temperature in the fluid, if it is a polynomial or a set of data points that describe the difference in density. While the Boussinesq model handles a density as a constant value in the equations, except for the buoyancy term in momentum equations (Ansys, 2011), (Al-Maghalseh, 2014):

$$\left(\rho-\rho_{o}\right)g\approx-\rho_{o}\beta\left(T-T_{o}\right)g \tag{11}$$

Reynolds' analogy concept in ANSYS FLUENT is adapted to model turbulent heat transport for turbulent momentum transfer, so the modelled energy equation is explained (Ansys, 2011):

$$\frac{\partial}{\partial t}(\rho \mathrm{E})+\frac{\partial}{\partial x_{i}}\left[u_{i}(\rho \mathrm{E}+p)\right]=\frac{\partial}{\partial x_{j}}\left(k_{eff}\frac{\partial T}{\partial x_{j}}+u_{i}(\tau_{ii})_{eff}\right)+S_{h} \tag{12}$$

where E means the total energy and $\left(\tau_{ii}\right)_{eff}$ is the deviatoric stress tensor, which is defined in (Ansys, 2011) as:

$$\left(\tau_{ij}\right)_{eff} = \mu_{eff}\left(\frac{\partial u_j}{\partial x_i}+\frac{\partial u_i}{\partial x_j}\right)-\frac{2}{3}\mu_{eff}\frac{\partial u_k}{\partial x_k}\delta_{ij} \tag{13}$$

And to represent viscous heating, the term of $\left(\tau_{ij}\right)_{eff}$ is used, computed in the density-based solver. Otherwise, effective thermal conductivity for the standard and realized *k*-*ε* models is given (Ansys, 2011) as:

$$k_{eff} = k+\frac{c_p\mu_t}{\mathrm{Pr}_t} \tag{14}$$

where *k*, is the thermal conductivity and the default value of the turbulent Prandtl number is 0.85. An enthalpy-porosity method is used for modelling the solidification/melting process (Ansys, 2011). This technique is described in detail in (Voller and Prakash, 1987). The energy conservation equation for this case is written as:

$$\frac{d}{dt}(\rho H)+\nabla.(\rho\vec{v}H)=\nabla\ .(k\nabla T)+S \tag{15}$$

The enthalpy of the material is calculated represented as the sum of the sensible heat, *h*, and latent heat, *ΔH*:

$$H = h+\Delta H \tag{16}$$

The sensible heat is calculated as:

$$h = h_{ref}+\int_{T_{ref}}^{T} c_p dT \tag{17}$$

And latent heat is also calculated as:

$$\Delta H = \beta_l L \tag{18}$$

While the liquid fraction β_l, can be calculated as:

$$\begin{aligned}
&\beta_l = 0, when T < T_{solid}\\
&\beta_l = 1, when T > T_{solid}\\
&\beta_l = \frac{T-T_{solid}}{T_{liquid}-T_{solid}}\ if\ T_{solid} < T < T_{liquid}
\end{aligned} \tag{19}$$

Also, solid, and liquid temperatures are calculated as:

$$T_{solid} = T_{melt}+\sum_{solutes} K_i m_i Y_i \tag{20}$$

$$T_{liquid} = T_{melt} + \sum_{solutes} m_i Y_i \tag{21}$$

where, K_i represents the partition coefficient of solute *i*, which is the ratio of the concentration solid to that in the liquid at the interface; and Y_i is the mass fraction of solute *i*, and m_i is the slope of the liquid surface with respect to Y_i (Ansys, 2011).

The source term in the momentum equation (Ansys, 2011) can be written as:

$$S = \frac{(1-\beta)}{\left(\beta_l^3 + \partial\right)} A_{mush} \left(\vec{v} - \vec{v}_p\right) \tag{22}$$

Due to the Darcy's law damping terms as a source term are added to the momentum equation because of the effect of phase change on convection, whereas ϵ is a small constant number (0.001) used to prevent division by zero, A_{mush} is the mushy zone constant. Values between 10^4 and 10^7 are recommended for most computations (Ansys, 2011). In the present study, the mushy zone was set to 10^8. $\vec{v}_p$ is the solid velocity due to pulling solidification materials out of the domain; in the present study, pull velocities are not included in the solution and so $\vec{v}_p$ is set to zero.

The liquid velocity can be calculated by the following equation (Ansys, 2011):

$$\vec{v}_{liq} = \frac{\left(\vec{v} - \vec{v}_p\left(1-\beta_l\right)\right)}{\beta_l} \tag{23}$$

The models were recreated numerically using the ANSYS FLUENT 2022 R2 software. Different grid sizes and time steps were carefully examined in preliminary simulations to obtain computational grid convergence. 2D computational grid was constructed using hex-dominant elements. Transient simulations were conducted using the k-epsilon turbulence model. The time step used in calculations was adjusted to obtain a fast and accurate result. The solidification/melting model was enabled to describe the phase change phenomena. The second-order upwind spatial discretization and the pressure solver with the PRESTO algorithm for pressure-velocity coupling were selected to obtain a converged solution. Convergence criteria were established by setting the absolute residual values to 10-6 for all variables. Zero heat flux boundary conditions were set on the upper and bottom sides of the wall. Due to the climate change in the last few years and the subsequent thermal changes and weather fluctuations, the average temperatures considered in the research for the external environmental conditions of Jerusalem city are 1 °C for winter and 34.3 °C for summer as extreme environmental conditions. According to ASHRAE handbook-Fundamentals (*ASHRAE Handbook-Fundamentals SI UNIT*, 2021), the heating dry bulb temperature (DB) is 2 ℃ and the cooling dry bulb temperature (DB) is 33.1 ℃. In contrast, the temperatures of internal conditions for thermal comfort are: 21 ℃ for winter and 23 ℃ for summer.

4.6.4 Results of Heat Transfer Calculations

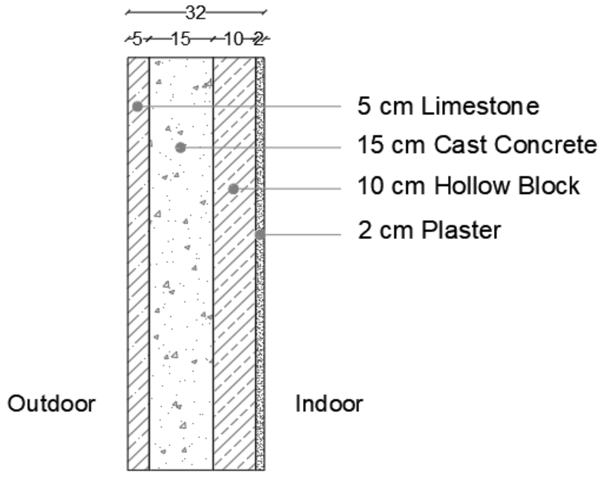
Numerical calculations are carried out for the different models including: a wall without insulation layer (Reference Case), walls with XPS layer, walls with a PCM layer, and walls with both XPS and PCM layers based on the first part of results (using a single layer). Numerical simulations investigate the impact of using conventional insulation XPS layer and PCM layer on the temperature distribution inside the composite walls as well as finding the best behavior of composite walls based on the thermal behavior of the insulation layer, its thickness, and location inside the composite walls.

Phase one: contains model 1, model 2, model 3, and model 4 in summer and winter

Model 1 (Reference Case)

The model contains four layers of materials: stone, concrete, block, and plaster without insulation layer.

In Summer: The simulation results showed that the average temperature of the internal wall surface in summer is almost 27.3 ℃, as is seen in the figure below which is outside the comfort zone temperature. In this case, heat flux is high due to the absence of a thermal insulation layer.



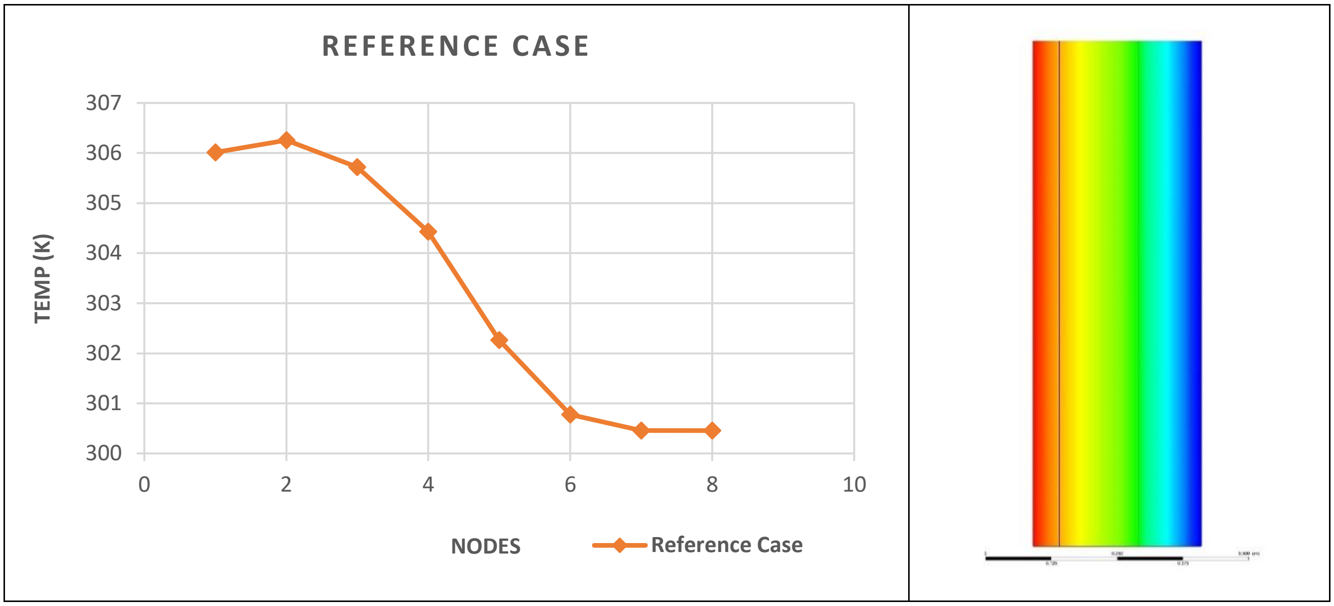


Figure 38 shows Model 1 (Reference Case) configurations and simulation results in summer

In Winter: The simulation results showed that the average temperature of the interior wall surface in winter is almost 13 °C as shown in the next figure, which is below the comfort zone temperature.

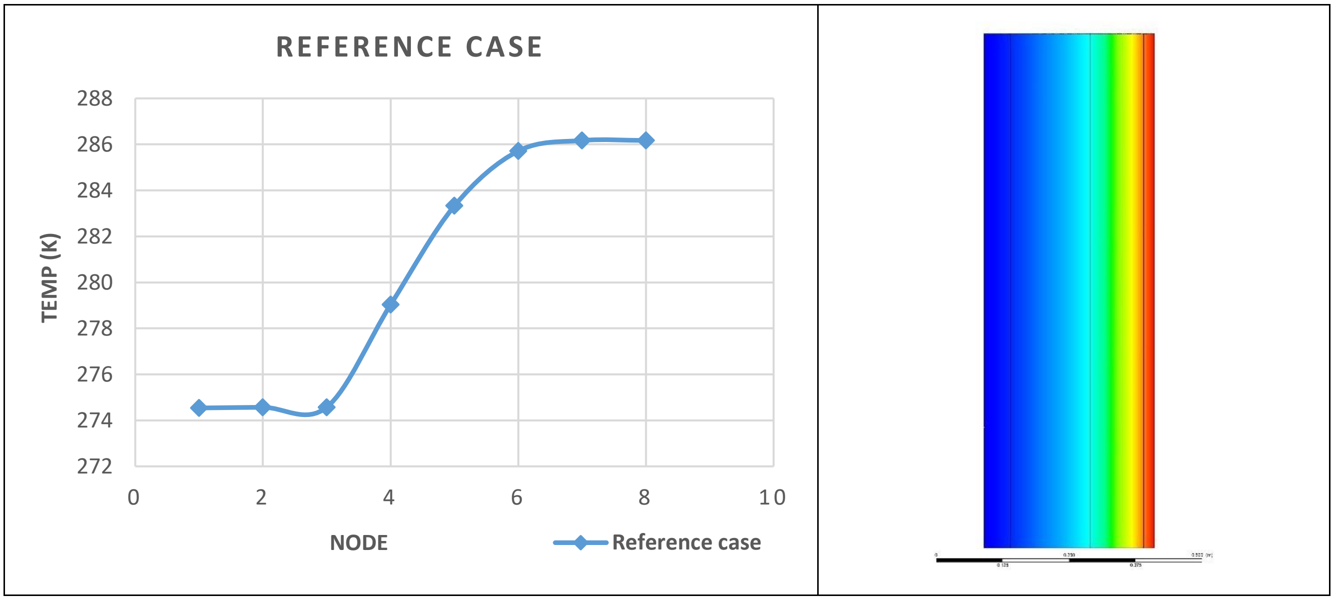


Figure 39 shows Model 1 (Reference Case) simulation results in the winter.

Model 2 (enhanced with XPS)

Contains five layers of materials: stone, concrete, block, XPS (4th layer) and plaster.

In summer: The average temperature of the internal wall surface in summer was 24.6 °C which is close to the thermal comfort zone but still out of the zone. The insulation layer of XPS located towards interior. In this case, the temperature difference compared to the reference case is almost 2.7 degrees.

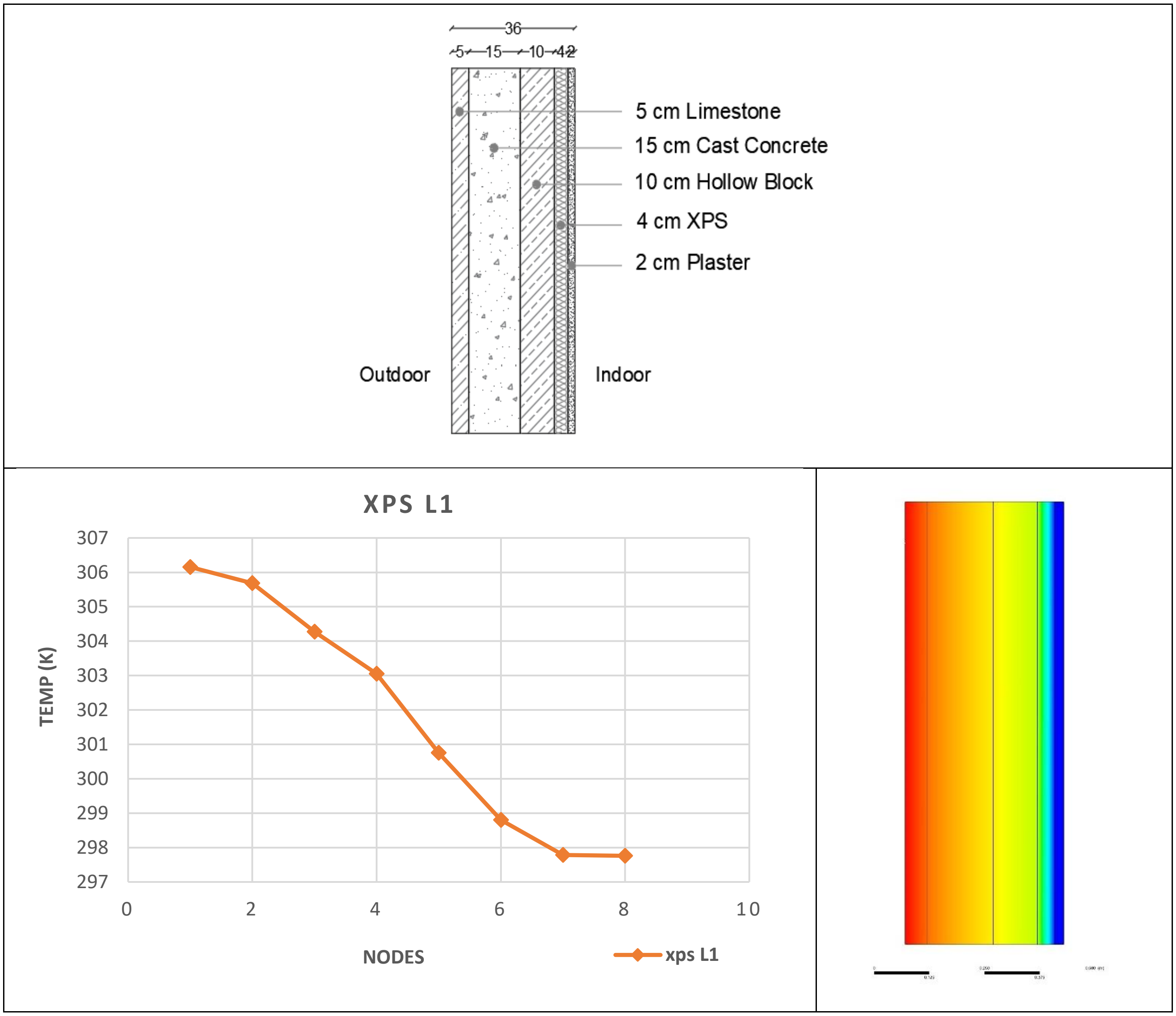


Figure 40 shows Model 2 (enhanced with XPS) configurations and simulation results in summer.

In winter: The average temperature of the internal wall surface in winter was 17.1 ℃ which is a bit close to the thermal comfort zone but still below the zone. In this case, the temperature difference compared to the reference case is almost 4.1 degrees.

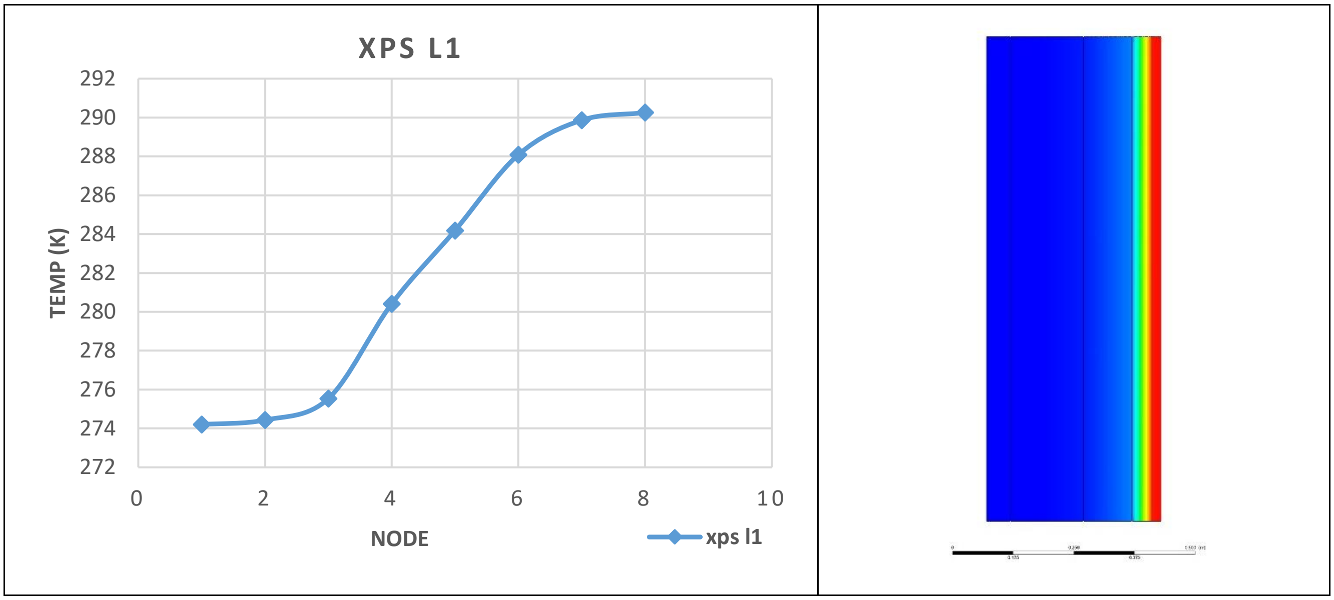
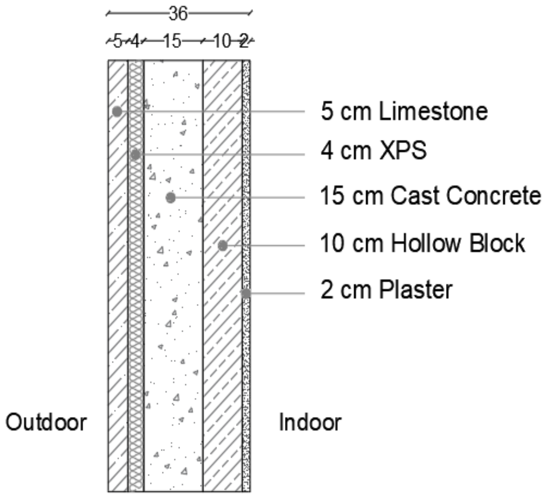


Figure 41 shows Model 2 (enhanced with XPS) simulation results in winter.

Model 3 (enhanced with XPS)

It consists of five materials layers: stone, XPS (2nd layer), concrete, block, and plaster. The insulation layer of XPS located towards the exterior.

In summer: The average temperature of the internal wall surface in summer was 24.4 °C, which is closer to the thermal comfort zone, but still out of the zone. The insulation layer of XPS located toward the exterior gives an advantage to obtaining a better result. In this case, the temperature difference compared to the reference case is almost 2.9 degrees.



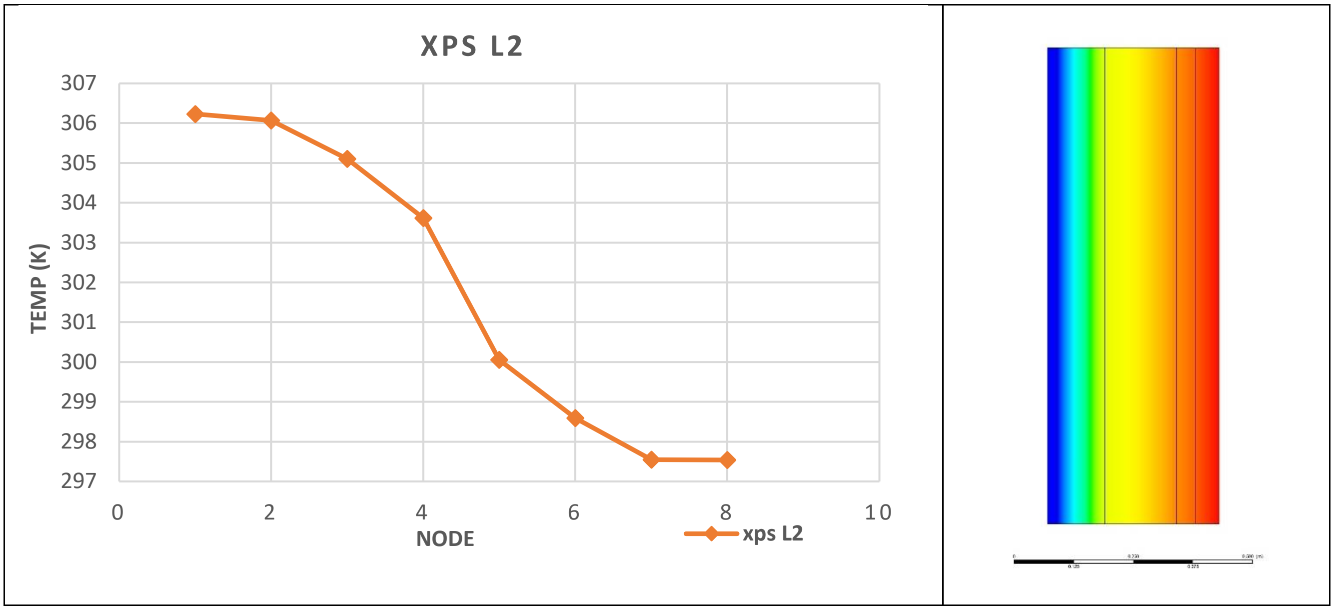


Figure 42 shows Model 3 (enhanced with XPS) configurations and simulation results in summer.

In winter: The average temperature of the internal wall surface in winter was 17.6 °C which is closer to the thermal comfort zone, but still under the zone. The insulation layer of XPS located toward the exterior gives the advantage to obtain a better result. In this case, the temperature difference compared to the reference case is almost 4.6 degrees.

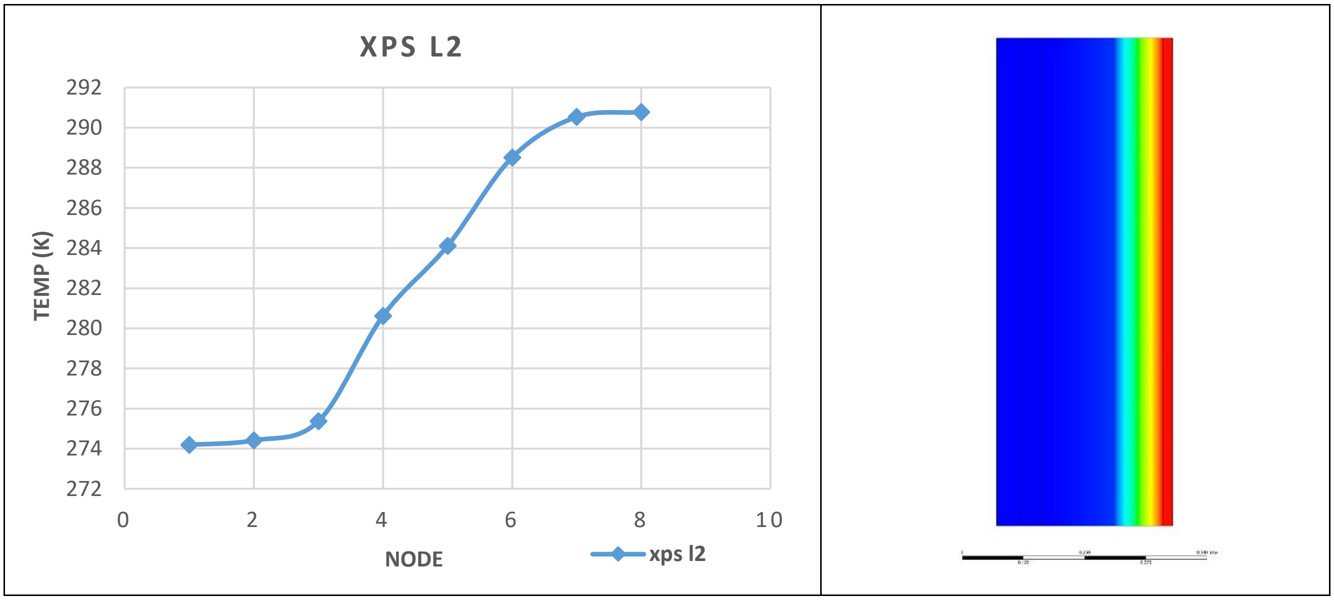


Figure 43 shows Model 3 (enhanced with XPS) simulation results in winter.

Model 4 (enhanced with XPS)

Contains five layers of materials: Stone, concrete, XPS (3rd layer), block, and plaster.

In summer: The average temperature of the internal wall surface in summer was 24.9 °C. It is closer to the thermal comfort zone, but still out of the zone. The insulation layer of XPS located in the middle of the wall section. In this case, the temperature difference compared to the reference case is almost 2.4 degrees.

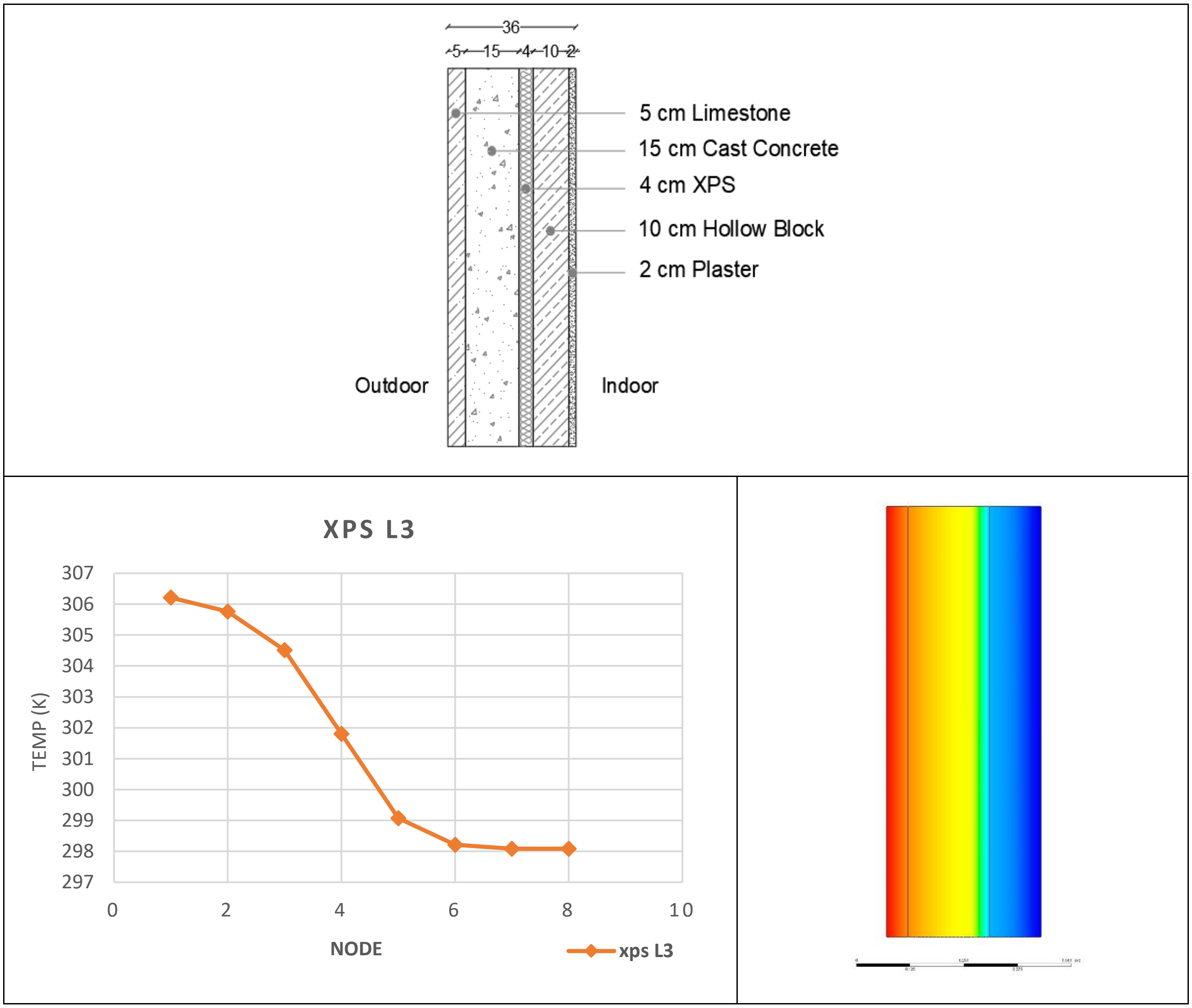


Figure 44 shows Model 4 (enhanced with XPS) configurations and simulation results in summer.

In winter: The average temperature of the internal wall surface in winter was 15.1 °C which is far from the thermal comfort zone. The temperature difference compared to the reference case is almost 2.1 degrees.

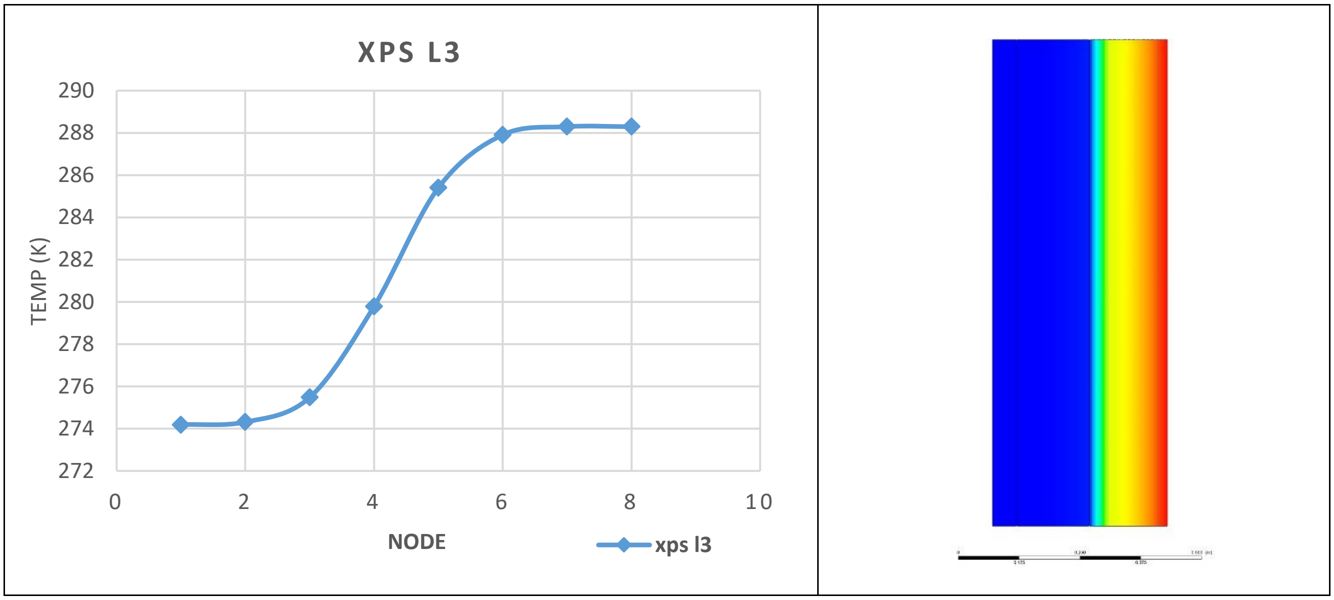


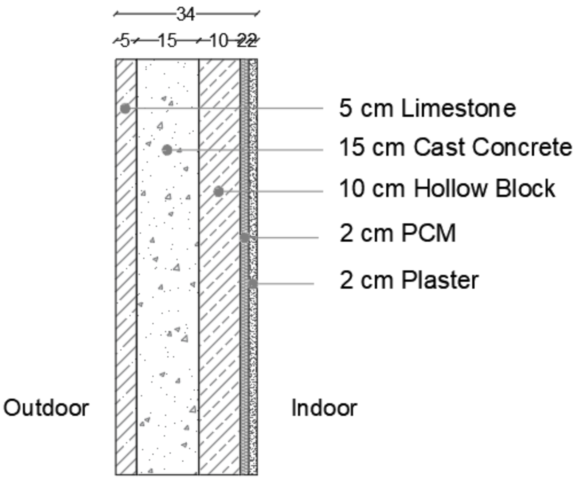
Figure 45 shows Model 4 (enhanced with XPS) simulation results in winter.

Phase two: contains model 5, model 6, and model 7 in summer and winter

Model 5 (enhanced with PCM)

It consists of five layers: stone, concrete, block, PCM (4th layer) and plaster.

In summer: The average temperature of the internal wall surface in summer was 25.6 °C, which is out of the comfort zone. This is because the insulation layer of PCM is located towards the interior. In this case, the temperature difference compared to the reference case is almost 1.7 degrees.



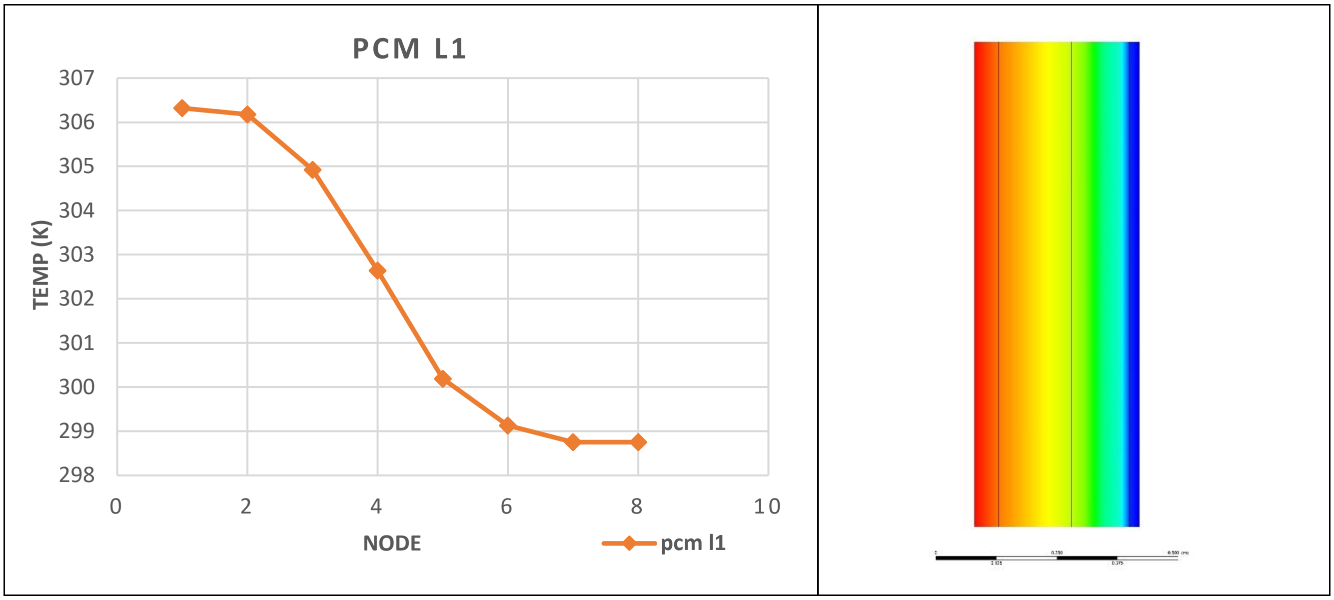


Figure 46 shows Model 5 (enhanced with PCM) configurations and simulation results in summer.

In winter: The average temperature of the internal wall surface in winter was 16.1 °C, which is below the comfort zone. Compared to the reference case, the temperature difference, is almost 3.1 degrees.

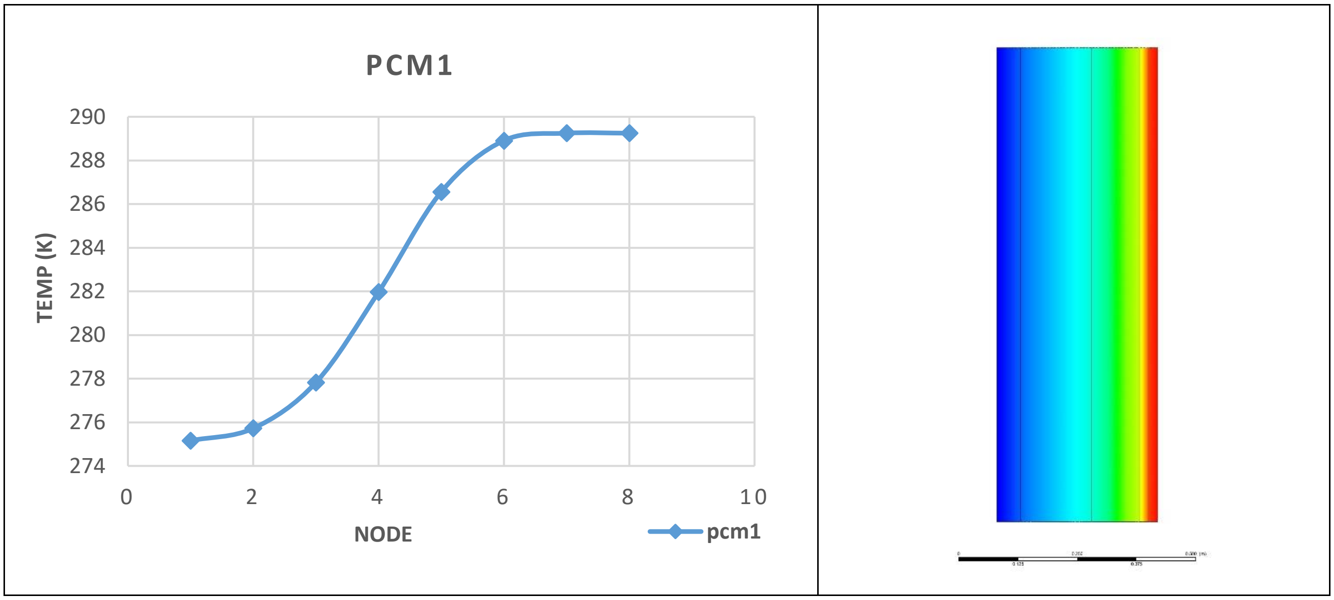


Figure 47 shows Model 5 (enhanced with PCM) simulation results in winter.

Model 6 (enhanced with PCM)

It consists of five layers of materials: stone, PCM (2nd layer), concrete, block, and plaster.

In summer: The average temperature of the internal wall surface in summer was 25.9 °C, which is out of the comfort zone temperature range. The insulation layer of PCM is located towards the exterior, giving a temperature difference compared to the reference case of almost 1.5 degrees.

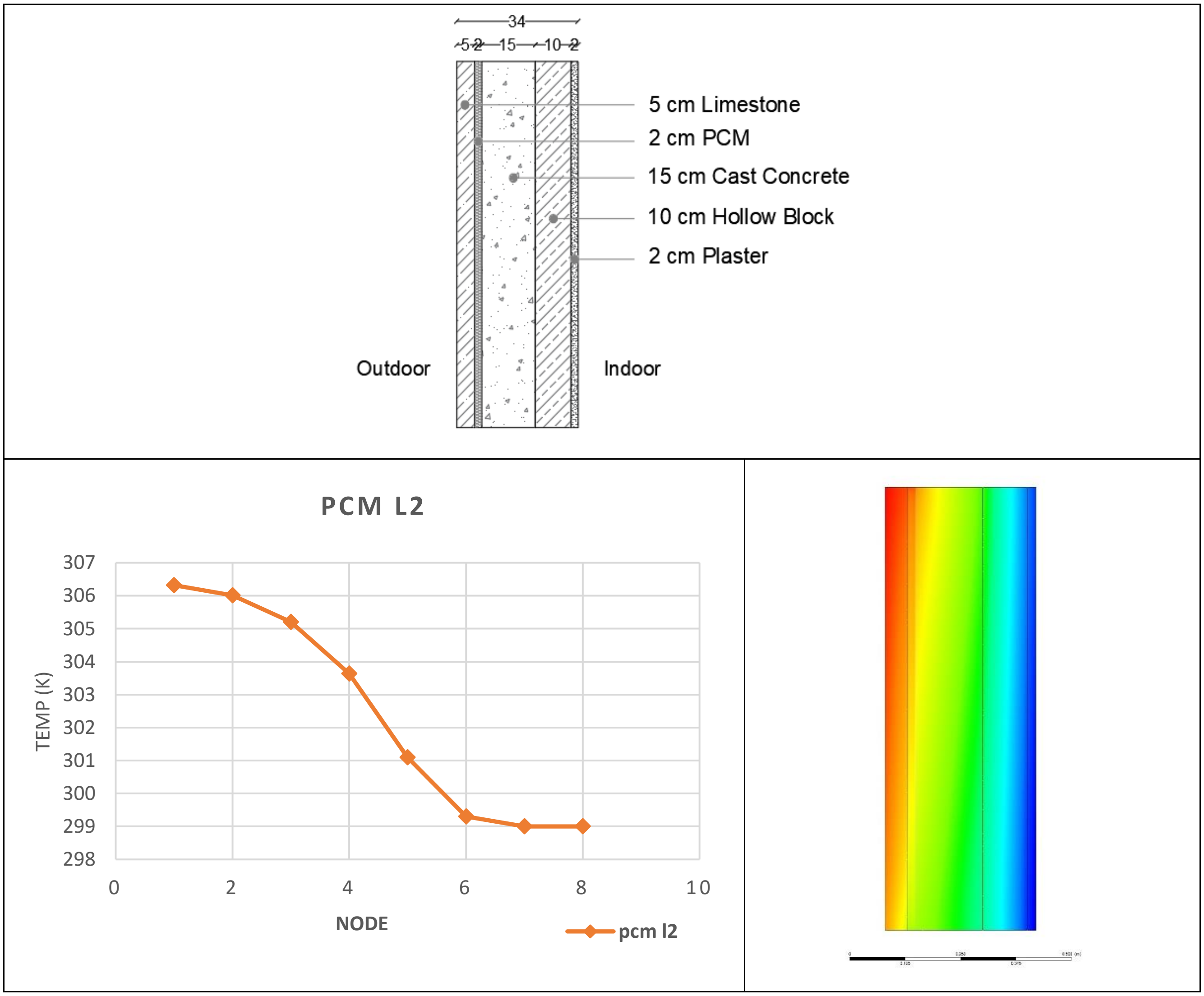


Figure 48 shows Model 6 (enhanced with PCM) configurations and simulation results in summer.

In winter: The average temperature of the internal wall surface in winter was 15.6 °C, which is far from the comfort zone range. In addition, the insulation layer of PCM is located towards the exterior, which makes PCM less efficient. In this case, the temperature difference compared to the reference case is almost 2.6 degrees.

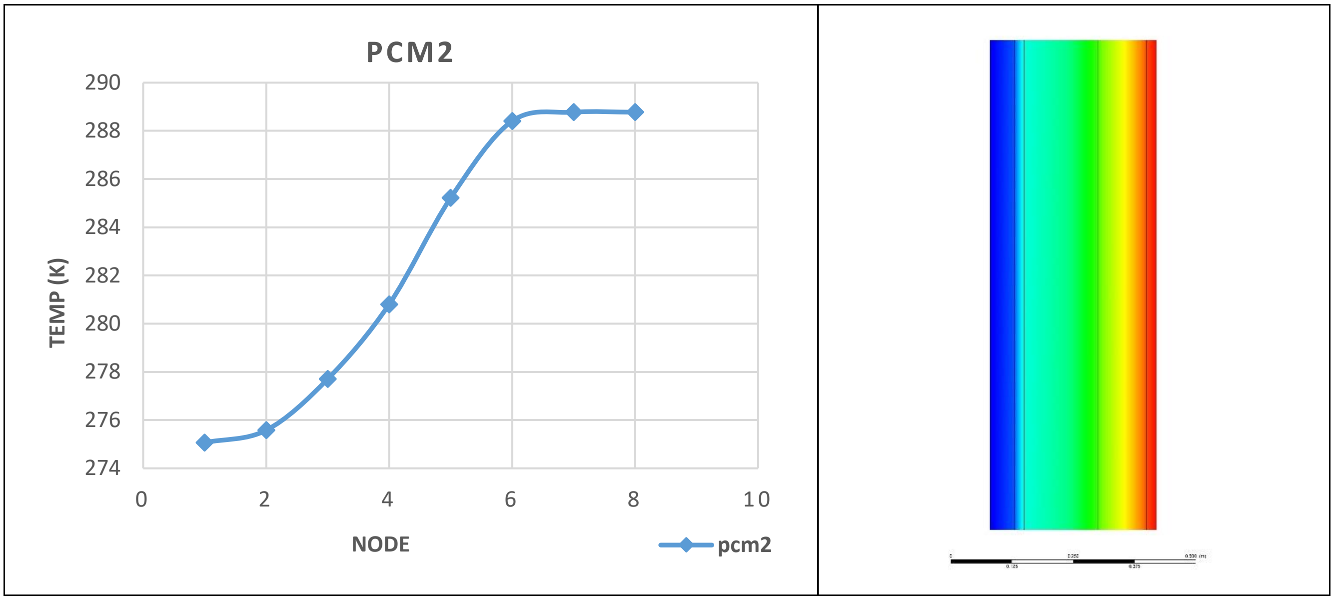
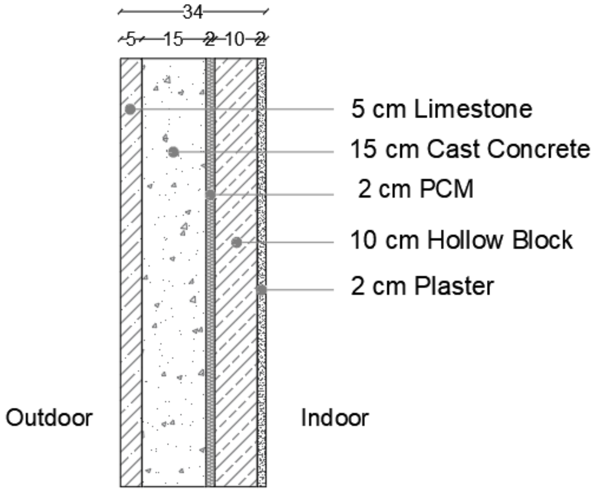


Figure 49 shows Model 6 (enhanced with PCM) simulation results in winter.

Model 7 (enhanced with PCM)

Consists of five layers: stone, concrete, PCM (3rd layer), block, and plaster.

In summer: The average temperature of the internal wall surface in summer was 25.0 °C. It is closer to the thermal comfort zone but still out of the zone. The insulation layer of PCM is in the middle of the wall section. In this case, the temperature difference compared to the reference case is almost 2.3 degrees.



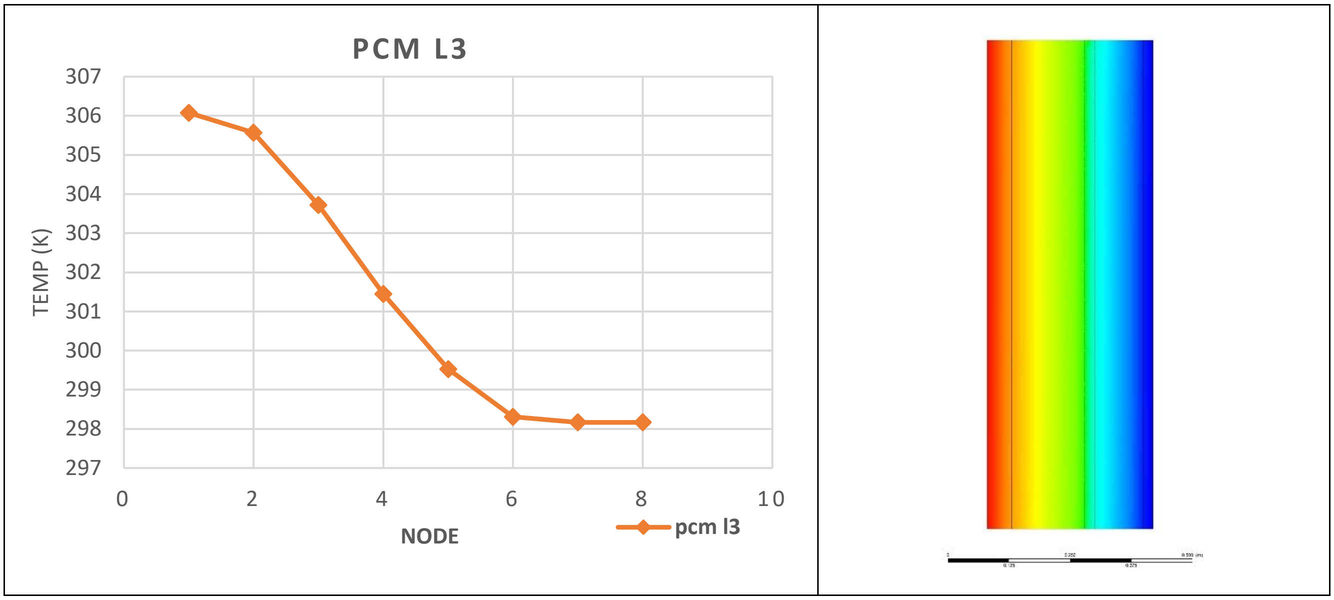


Figure 50 shows Model 7 (enhanced with PCM) configurations and simulation results in summer.

In winter: The average temperature of the internal wall surface in winter was 16.1 °C, which is far from the thermal comfort zone. The temperature difference compared to the reference case is 3.1 degrees.

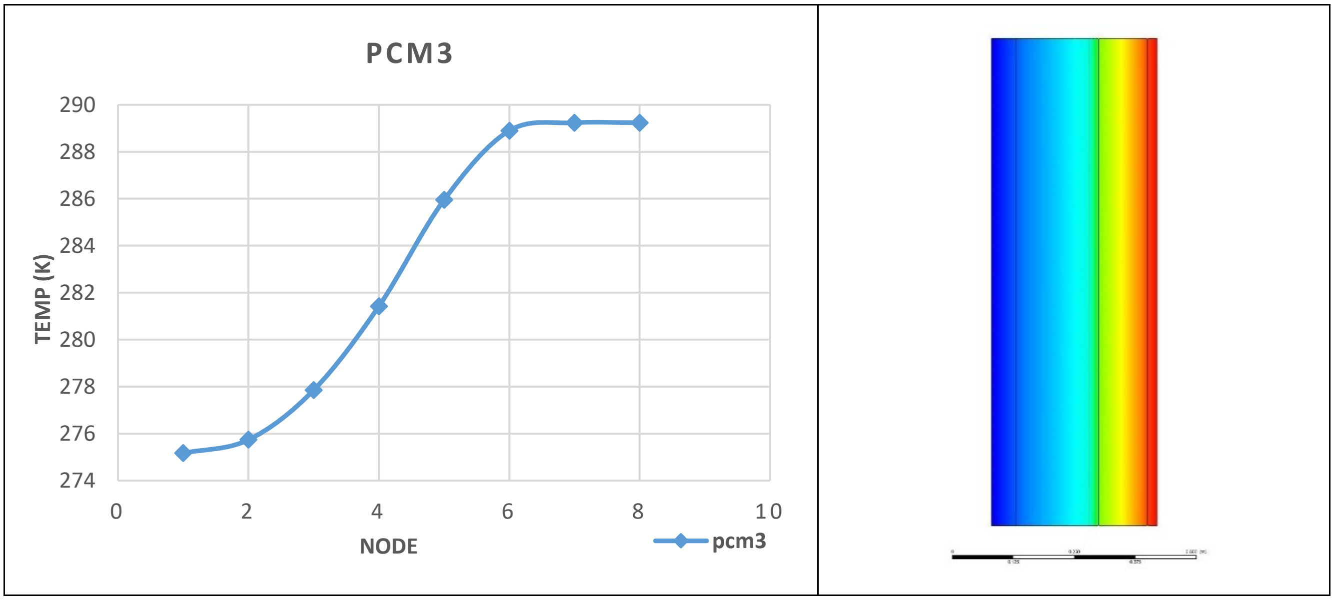


Figure 51 shows Model 7 (enhanced with PCM) simulation results in winter.

Phase three (Double insulation layers): contains model 8 in summer and winter

Model 8 (enhanced with XPS & PCM)

This model consists of six layers: stone, XPS (2nd layer), concrete, PCM (4th layer), block, and plaster.

In Summer: The average temperature of the internal wall surface in summer was 23.7 °C, that it is closer to the thermal comfort zone. The insulation layers of XPS and PCM are located towards the exterior and in the middle of the wall section. In this case, the temperature difference compared to the reference case is almost 3.6 degrees which consider the best value obtained.

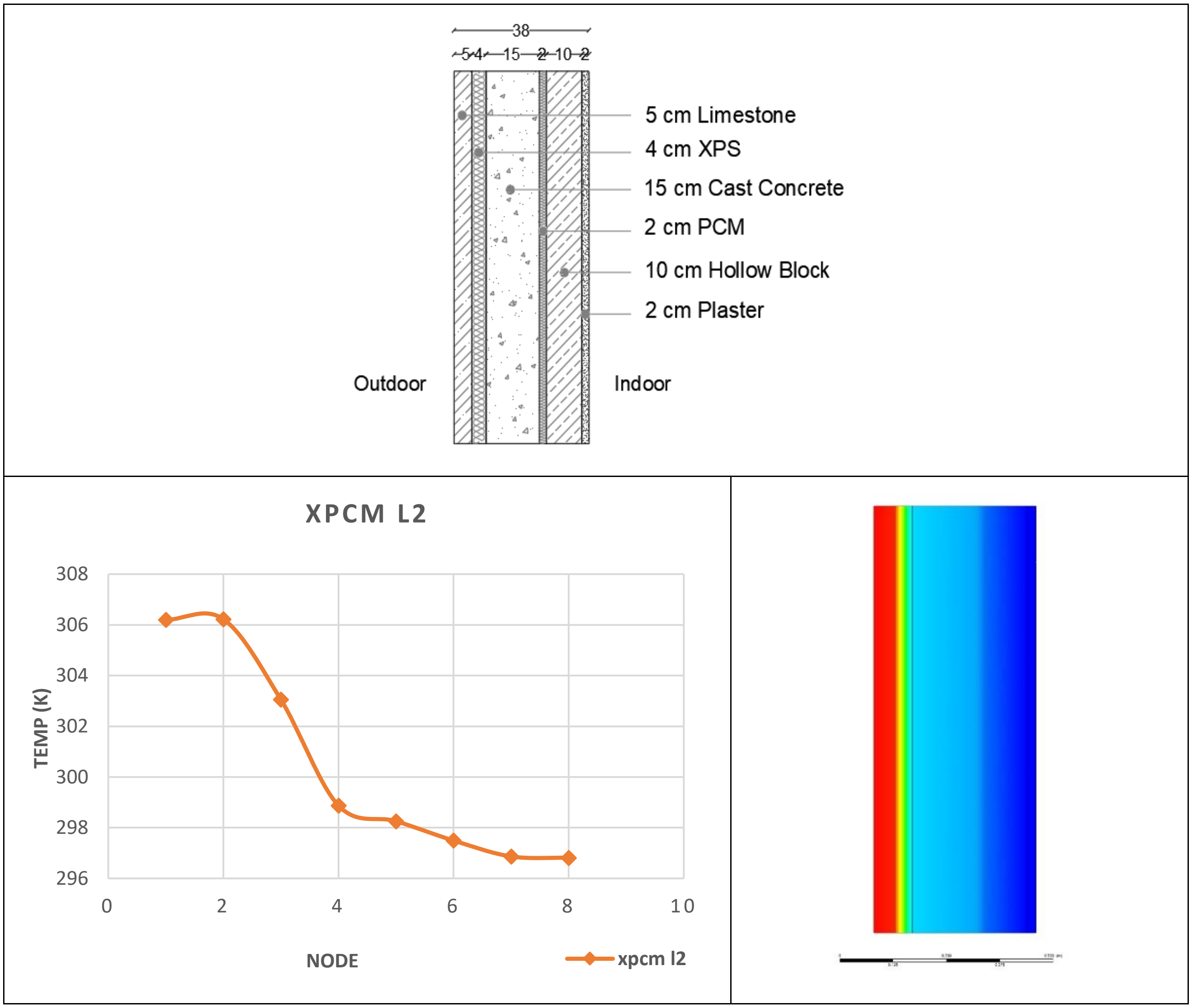


Figure 52 shows Model 8 (enhanced with XPS &PCM) configurations and simulation results in summer.

In winter: The average temperature of the internal wall surface in winter was 19.5 °C, which is within the thermal comfort zone. Therefore, the temperature difference compared to the reference case is almost 6.5 degrees, as it is the best difference between other cases.

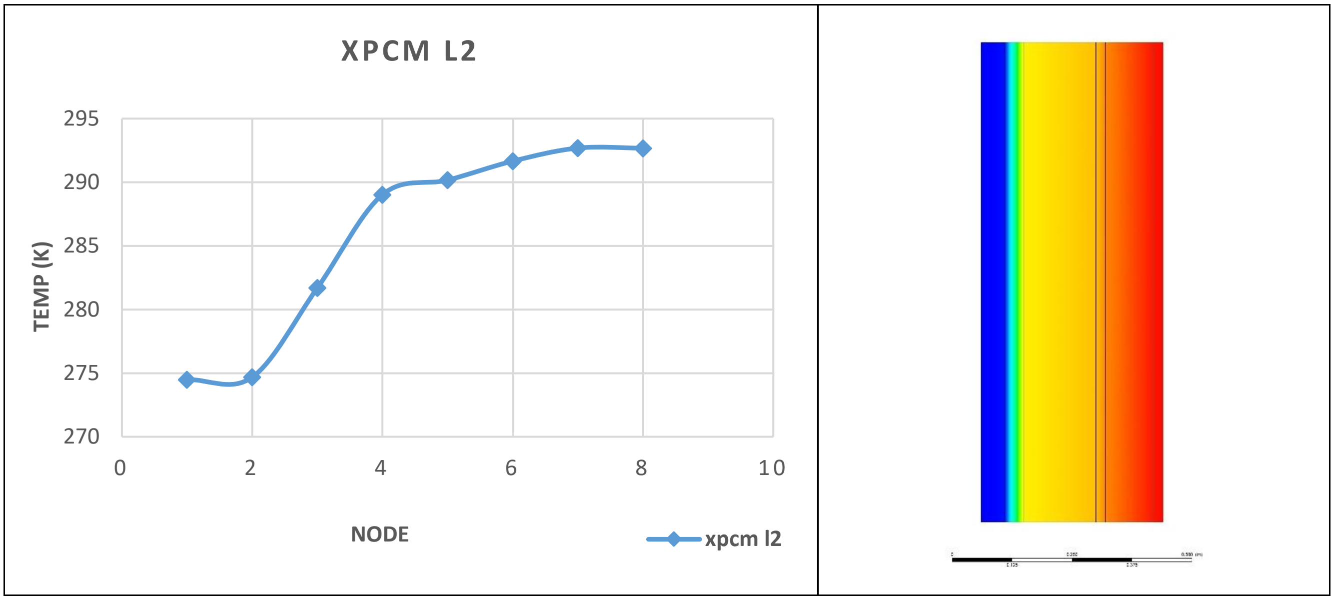


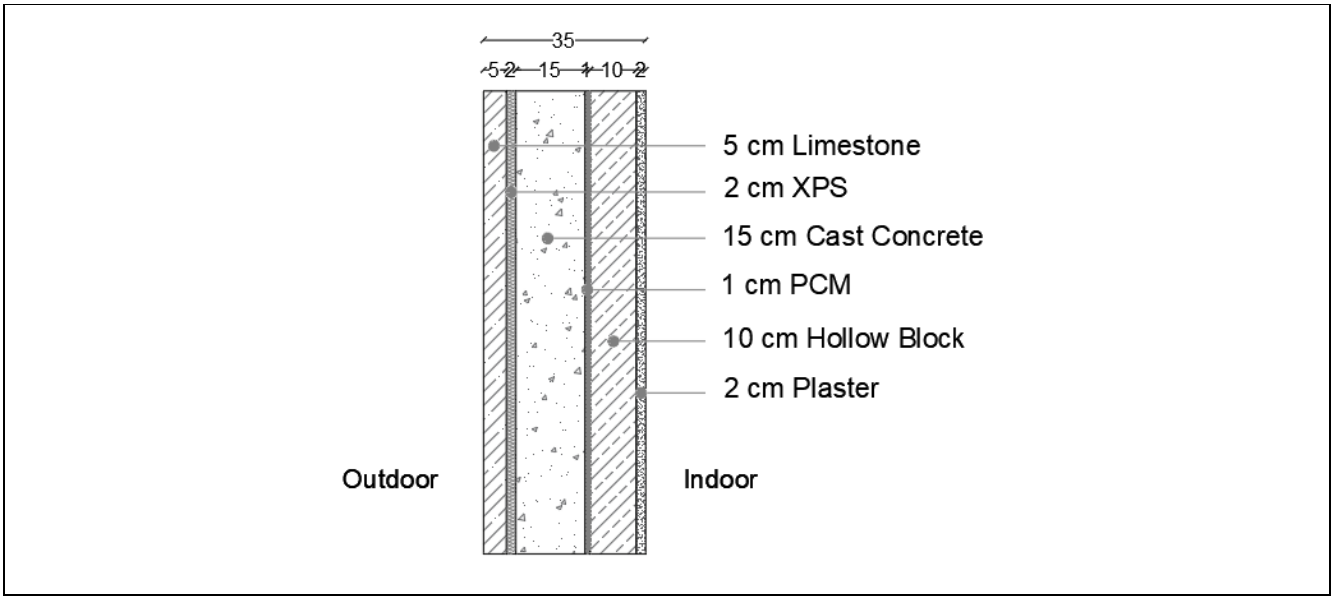
Figure 53 shows Model 8 (enhanced with XPS &PCM) simulation results in winter.

Phase four: contains Model 9

Model 9 (enhanced with XPS & PCM, 50% thickness)

It consists of six layers: stone, XPS (2nd layer), concrete, PCM (4th layer), block, and plaster.

In summer: The average temperature of the internal wall surface in summer was 24.2 °C. It is closer to the thermal comfort zone. The insulation layers of XPS and PCM are located towards the exterior and in the middle of the wall section and have half thickness. The temperature difference compared to the reference case is almost 3.1 degrees.



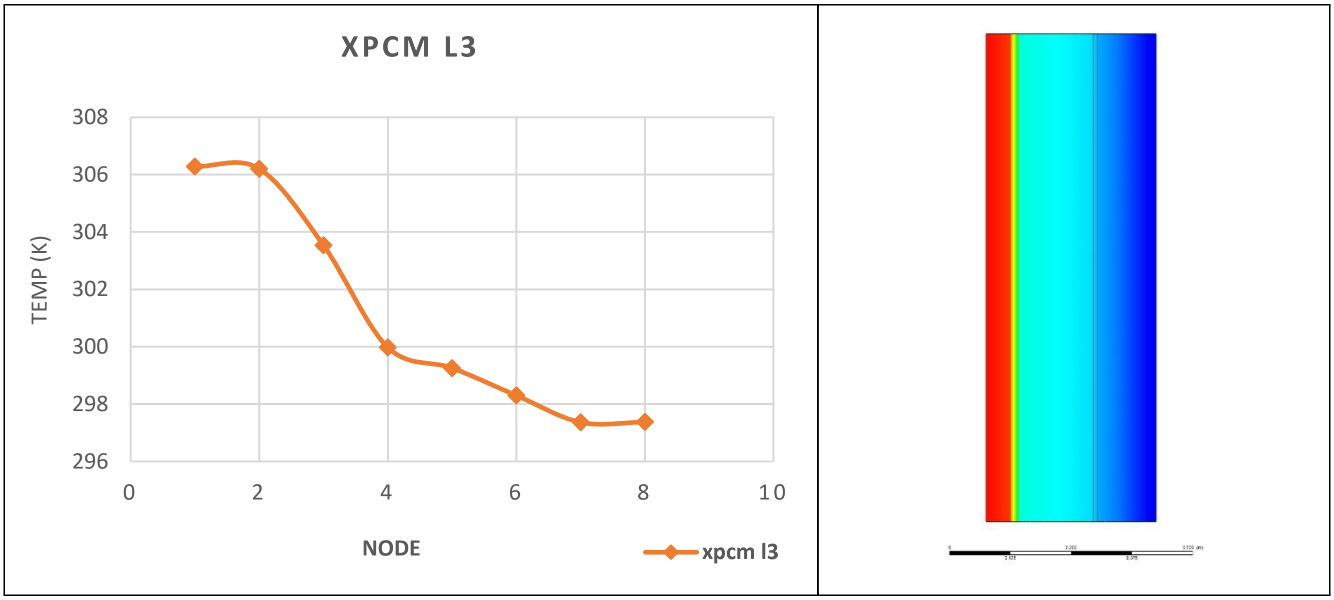


Figure 54 shows Model 9 (enhanced with XPS &PCM) configurations and simulation results in summer.

In winter: The average temperature of the internal wall surface in winter was 18.7 ℃, which is within the thermal comfort zone. Therefore, compared to the reference case, the temperature difference is almost 5.7 degrees.

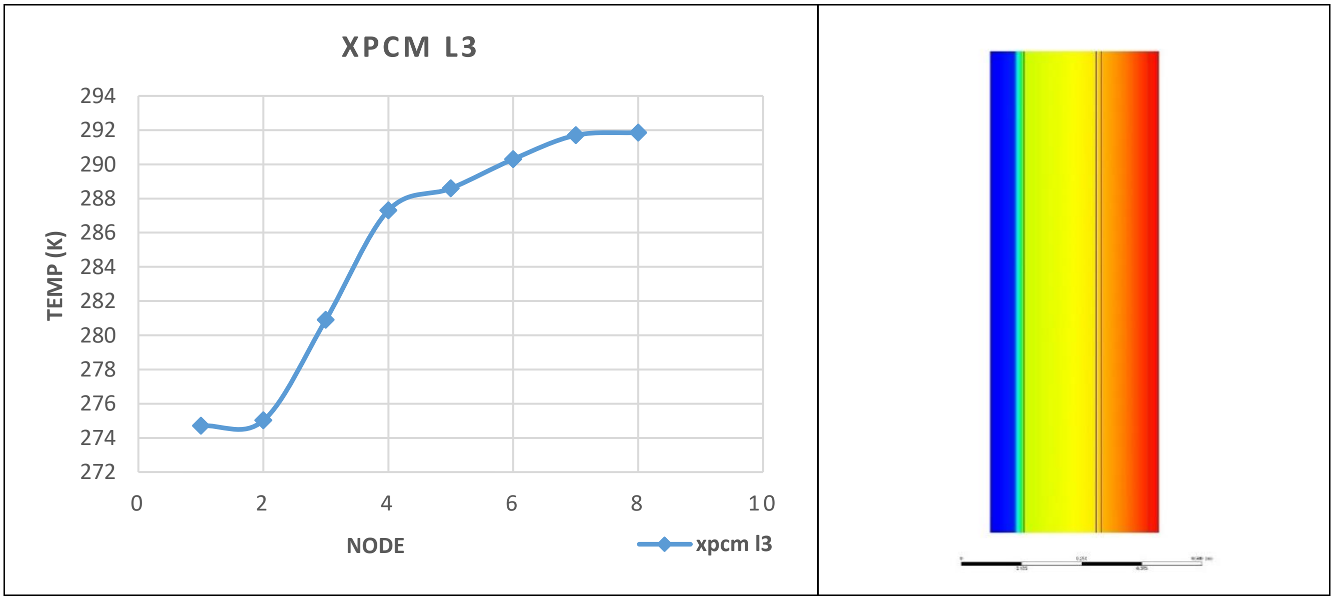


Figure 55 shows Model 9 (enhanced with XPS &PCM) simulation results in winter.

4.6.5 Wall Models Comparison

The thermal comparison of the wall models was made based on the heat transfer results, that is seen in the table below:

- Phase One and Two: The best behavior for the wall models enhanced with XPS was **Model 3** in summer and winter. The average temperature of the inner wall surface in summer is 24.4 ℃. The temperature difference compared to the reference case is almost 2.9 degrees. While in winter, the average temperature of the internal wall surface in winter was 17.6 ℃, and the temperature difference compared to the reference case was almost 4.6 degrees. Phase Two: For the models enhanced with PCM, the best behavior was **Model 7** in summer and winter. The average temperature of the internal wall surface in summer is 25.0 ℃, and the temperature difference compared to the reference case is almost 2.3 degrees. While in winter, the average temperature of the internal wall surface was 16.1 ℃, and the temperature difference in this case compared to the reference case is almost 3.1 degrees.
- Phase Three and Four: For the wall model enhanced with both XPS and PCM (**Model 8),** the average temperature of the internal wall surface in summer was 23.7 ℃, and the temperature difference compared to the reference case is almost 3.6 degrees. However, the average temperature of the internal wall surface in winter was 19.5 ℃, and the temperature difference compared to the reference case is nearly 6.5 degrees. However, when the thickness of insulations reduced by 50% in **(Model 9),** the average temperature of the internal wall surface in summer was 24.2 ℃, with difference of almost 3.1 degrees in summer, and the average temperature of the internal wall surface in winter was 18.7 ℃, with a temperature difference of almost 5.7 degrees.

Table 6 shows the comparison between the wall models.

Wall Models Comparison							
		Average temperature of internal surface in summer ℃	Temperature difference in summer compared to ref case	Average temperature of internal surface in winter C	Temperature difference in winter compared to ref case	Best thermal performance	Ranking
Phase 1	Ref Case	27.3	-	13.0	-	-	9
	XPS L1	24.6	2.7	17.1	4.1		4
	XPS L2	24.4	2.9	17.6	4.6	▨	3
	XPS L3	24.9	2.4	15.1	2.1		5
Phase 2	PCM L1	25.6	1.7	16.1	3.1		7
	PCM L2	25.9	1.5	15.6	2.6		8
	PCM L3	25.0	2.3	16.1	3.1	▨	6
Phase 3	XPCM L2	23.7	3.6	19.5	6.5		1
Phase 4	XPCM 3	24.2	3.1	18.7	5.7		2

Overall Models Comparison

By comparing the all models that wither enhanced with single layer (XPS or PCM) or enhanced with double layers of thermal insulations (XPS & PCM), the results showed that Model 8 comes first in thermal performance (two layers of insulation), then Model 9 (two layers of insulation with half thickness). After that, Model 3 (one layer of XPS) comes and then Model 2 and Model 4. Following Model 7, Model 5 and finally Model 6. See figures below:

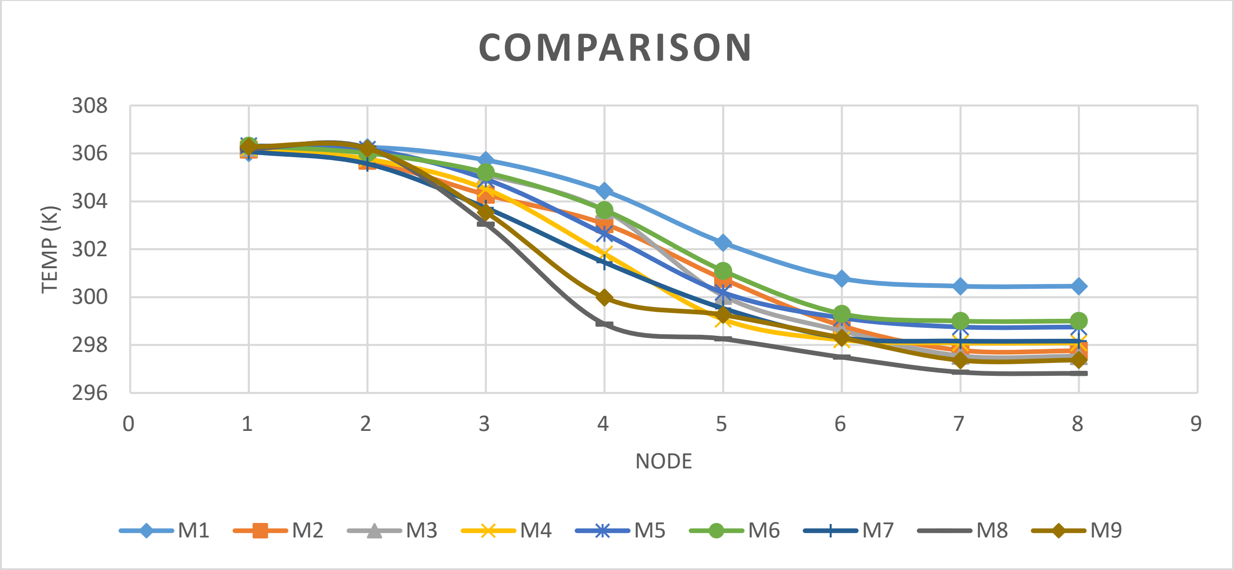


Figure 56 shows the overall models comparison used in the study in summer.

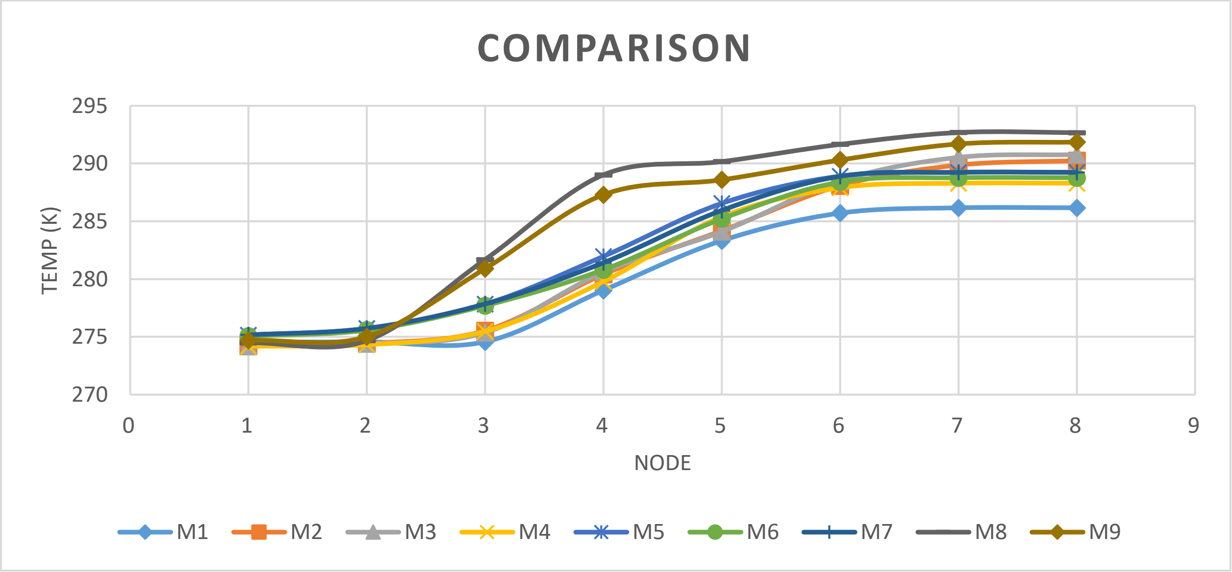


Figure 57 shows the overall models comparison used in the study in winter.

The figure below shows the walls models graph and the best behavior of models in each phase and the process of simulation;

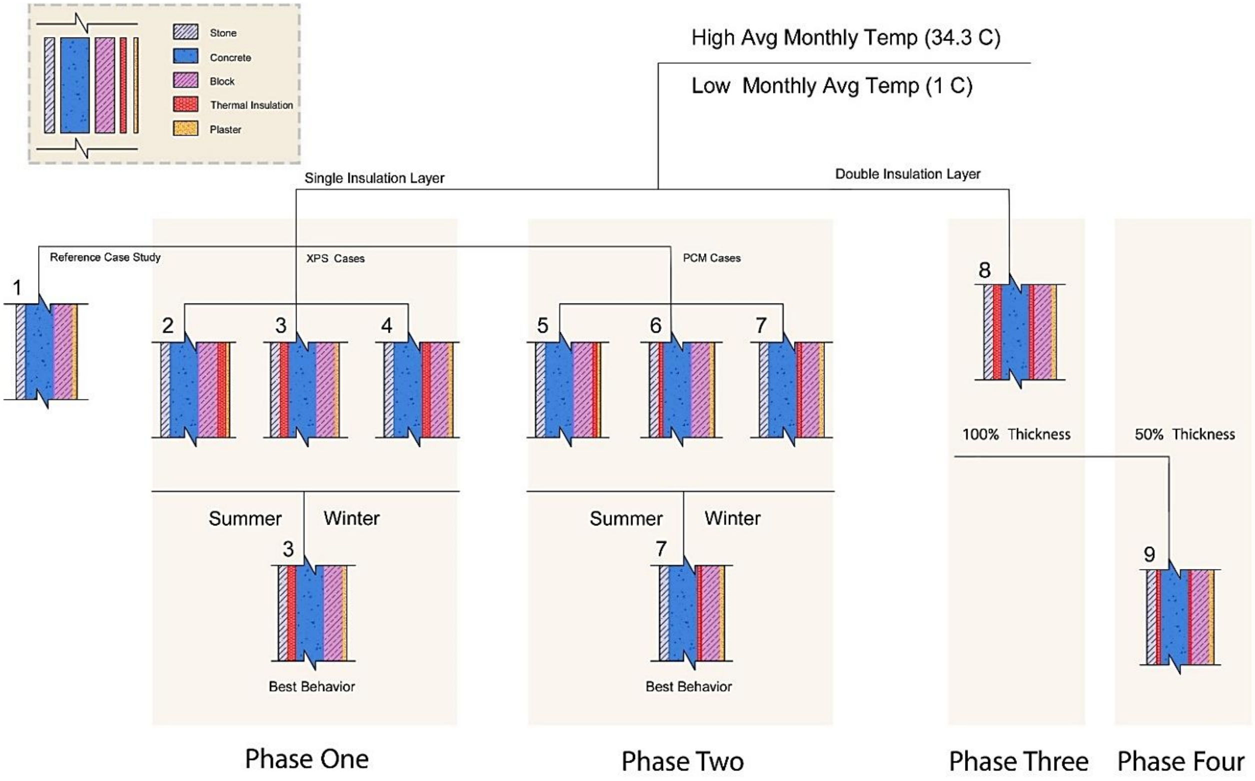


Figure 58 shows the walls models graph and the best behavior of each phase, researcher.

4.6.6 Summary

A numerical investigation is conducted in order to observe the heat transfer of wall models for the selected models including models without insulation (Reference Case), models with XPS insulation, models with PCM insulation, and the model with both XPS and PCM layers. The calculations investigated the impact of using various insulation layers on the temperature distribution inside the composite that helped find the best behavior of composite walls based on the thermal behavior of the insulation layer, its thickness, and location inside the composite walls. The best behavior for the wall models enhanced with XPS was Model 3 in summer and winter. However, for the models enhanced with PCM, the best behavior was Model 7.

4.7 Energy Calculations of Heating and Cooling

Generally, using insulation material of higher properties is a good alternative to improve sustainable urban areas by decreasing energy consumption, air pollution, and CO2 emissions, and saving energy. The thermal conductivity of the applied materials being an important factor in energy consumption, the internal energy loads can play a significant role, specifically the heating and cooling loads. The contribution of using a new material (PCM) is being shown in affecting the amount of building heating and cooling demands. The energy demand was calculated for the month of January and August as being the months with the highest demand for energy.

4.7.1 Case Study Design Parameters

The specific data flow needed in this analysis determined; The physical data includes the apartment within a residential building (Multistory building) located in Jerusalem's climatic zone (31°46'5.95"N, 35°12'49.36"E). The practical experience and Palestinian Code were relied on in the specifications of building construction in terms of interior spaces, ceiling height, and matters related to the building characteristics and its orientation that are based on the recommended design standards. Using the DesignBuilder software and the Energy Plus engine, calculations were made for three periods of time; Annually (Heating and Cooling), January (Heating), and August (Cooling) under normal climatic conditions based on the ASHRAE database. The plan area of 171.8 m2, while the plan with closed walls measured 140.5 m2. The conditioned zones are guestroom, bedrooms, living, and kitchen. However, the unconditioned zones are the bathrooms and staircase as it’s seen in the next figures.

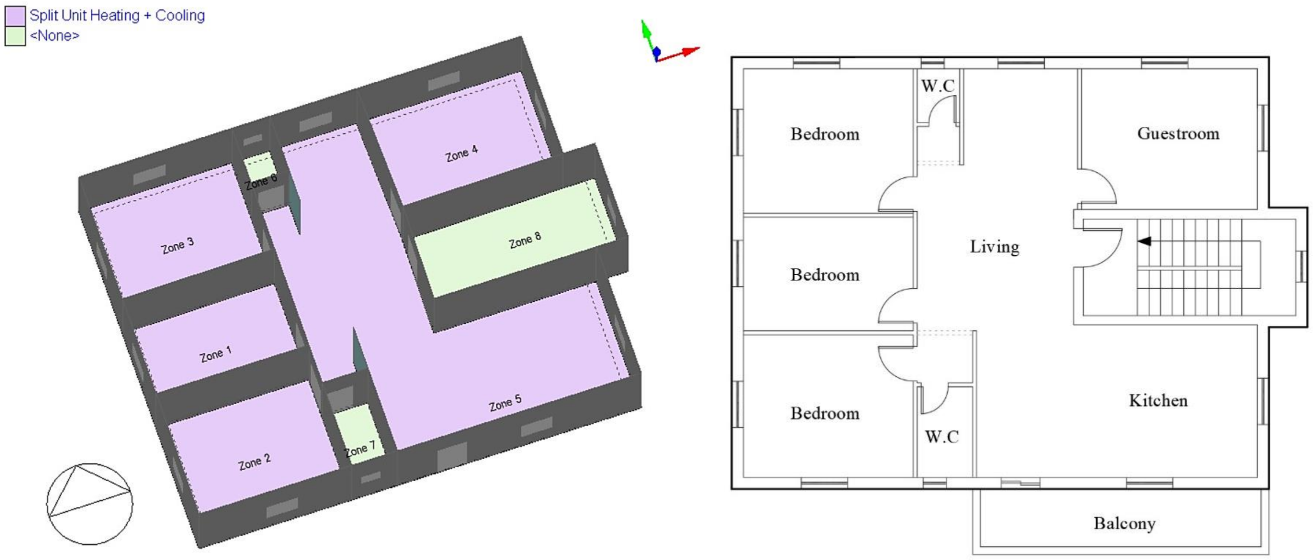


Figure 59 case study plan, functions, and zones.

The layout settings were set based on ASHRAE (ASHRAE Handbook-Fundamentals SI UNIT, 2021) and literature reviews such (Monna *et al.*, 2021), and (Haj Hussein *et al.*, 2022). The next table contains some of used simulation parameters:

Table 7 DesignBuilder Simulation Parameters

Parameters		**Value**
Construction	Ext. Wall Configuration	According to the case study, Figures 66 and 67
Activity	Occupancy density (people/ m^2)	0.039
	Schedule	Living Bed Kitchen_occ
	Clothing: Winter, Summer (clo)	1, 0.5
	Metabolic Factor	0.9
Floor Area (m^2)	Conditioned Area of PCM Case (m^2)	115.0
	Conditioned Area of Ref. Case (m^2)	115.9
Openings	Window to Wall Ratio up to (%)	20
	Glazing Type	Dbl Clr 6mm/13mm Air
	Window Frame Type	Aluminum (with thermal break)
	Shading	N/A
	Natural Ventilation	Inactive
	Mechanical Ventilation	Active
	HVAC System	Active
HVAC	Heating system	Electricity from the grid
	Cooling System	Electricity from the grid
	Split Unit	Heating & Cooling
	Seasonal CoP (Cooling)	4
	Seasonal CoP (Heating)	4
Environmental control	Heating Set Point (℃)	21
	Cooling Set Point (℃)	25
	Air infiltration (ac/h)	0.25

The ocuupancy density is 0.039 people/ m^2. The factor of metabolic rate per person set to be 0.9. The schedule of clothing was set for generic summer and winter clothing which is 0.5 clo for summer and 1 clo for winter clothing. The occupancy data also are collected for residential spaces, and the activities in the zones were set as guestroom, bedrooms, living and kitchen. The Scheduled Heating and Cooling Day Profiles of (Living Bed Kitchen_occ) Activity were (from 6:00 to 7:30, and from 18:00 to 23:00) for the working days and with 30 days of Holidays in the year. The heating and cooling set points are set as 25 ℃ for summer and 21 ℃ for winter. The multi-split unit air conditioning was the proposed HVAC system for the apartment. The average Coefficient of Performance (CoP) of heating and cooling systems seasonal used was 4.0 CoP according to the datasheet of the manufactured unit of the system, which falls under the ASHRAE Standards. The air velocity for comfort calculations is set according to the occupied times and based on ASHRAE database in the software. The results of calculations are conducted just for the occupied zones. The ceiling and floors for both cases were highly insulated to prevent any effect on the thermal calculations and to focus on studying the performance of the external walls only.

Walls Structure and Materials Properties

Referring to Figure 38 which showed the composition of the external wall of the reference case, and Figure 50 presented the composition of the wall in the PCM case. Additionally, Table 4 contains the thermo-physical parameters of materials used in the two cases. The reference case is when Model 1 is applied in the apartment, which contains four layers of materials: stone, concrete, block, and plaster without an insulation layer as shown in the figure below. In this case, the conditioned area of the Reference case is 115.9 m2, and the net height is 2.8 m for both cases.

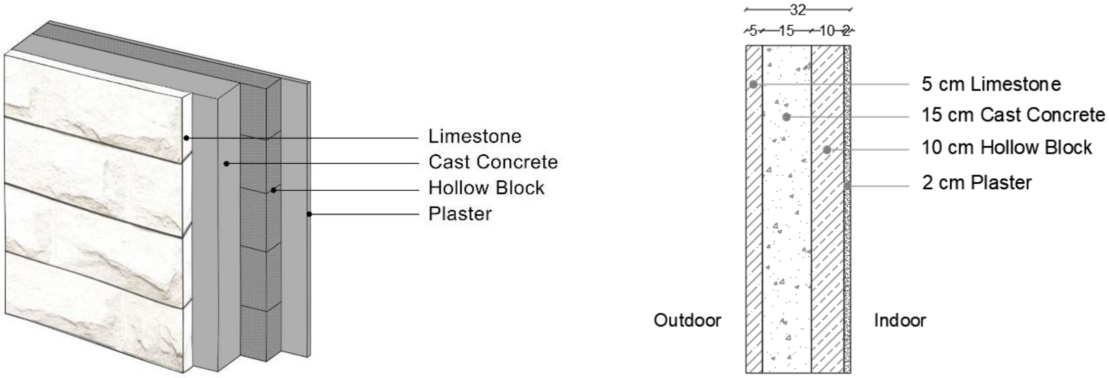


Figure 60 Reference wall configuration, Researcher.

The PCM case is when Model 7 is applied in the apartment, which consists of five layers: stone, concrete, PCM (3rd layer), block, and plaster as it’s seen in the figure below. The conditioned area of the PCM case is 115 m2. The difference in thickness is due to the additional layer of insulation.

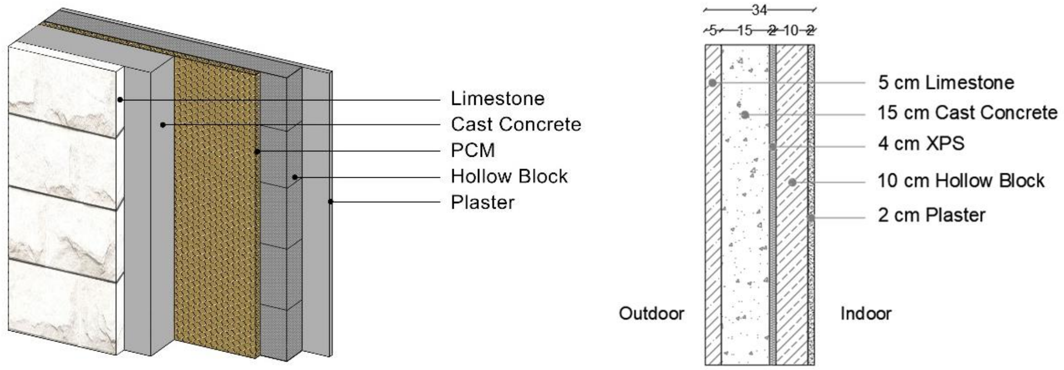
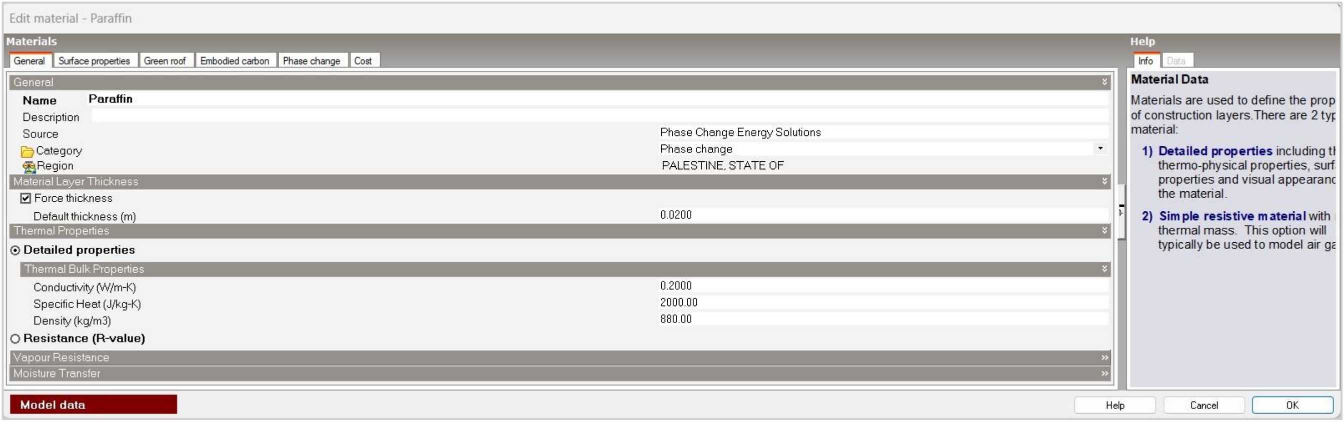


Figure 61 Installation of PCM in the wall section and wall configuration, Researcher.

The properties of Paraffin (28 °C) includes 0.2 W/m.K of the thermal conductivity, 880 kg/m³ of density, and 2000 J/kg·K of specific heat capacity based on (Q. M. Q. Al-Yasiri and Szabó, 2021) and (Sun *et al.*, 2019) that are presented in the next figure.



Edit material - Paraffin

General

Name	**Paraffin**
Description	
Source	Phase Change Energy Solutions
Category	Phase change
Region	PALESTINE, STATE OF

Material Layer Thickness

☑ Force thickness

Default thickness (m)	0.0200

Thermal Properties

● **Detailed properties**

Thermal Bulk Properties

Conductivity (W/m-K)	0.2000
Specific Heat (J/kg-K)	2000.00
Density (kg/m3)	880.00

○ **Resistance (R-value)**

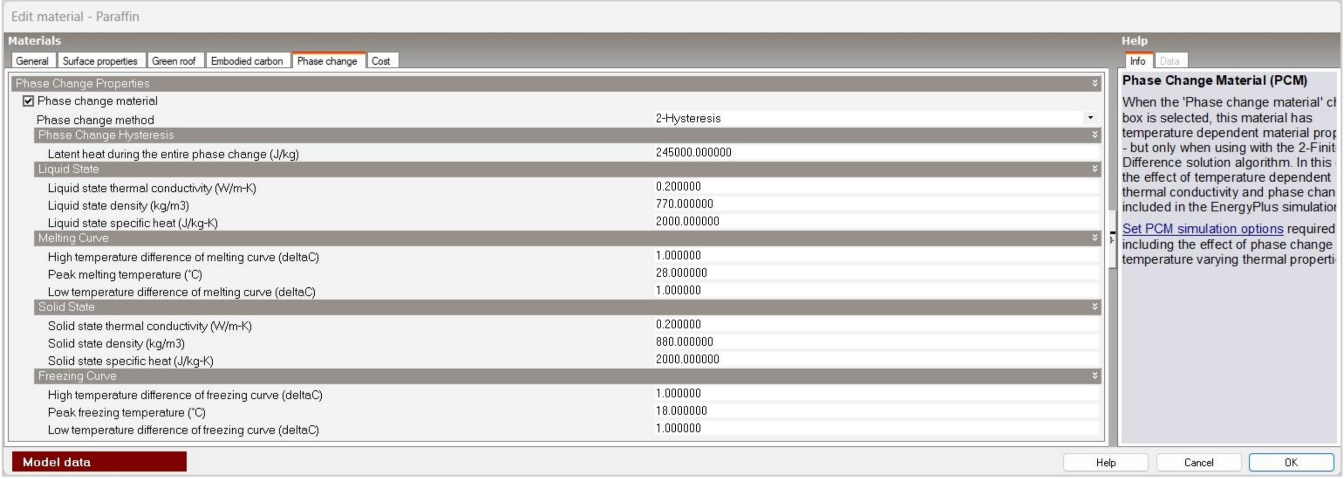
Material Data

Materials are used to define the prop of construction layers.There are 2 typ material:

1) **Detailed properties** including tl thermo-physical properties, surf properties and visual appearanc the material.
2) **Simple resistive material** with thermal mass. This option will typically be used to model air ga

Figure 62 shows the properties of paraffin material.

When the insulation layer is defined and the check box is selected as a phase change material, this material is simulated considering the melting/freezing process based on the temperature-dependent material properties of paraffin which is mentioned in Table 4. The Hysteresis method of modeling paraffin is used which allows the process of melting /freezing to follow different temperature /enthalpy curves to present the effect of the material in the actual building envelope applications, see the figure below:



Edit material - Paraffin

Phase Change Properties

☑ Phase change material

Phase change method	2-Hysteresis
Phase Change Hysteresis	
Latent heat during the entire phase change (J/kg)	245000.000000
Liquid State	
Liquid state thermal conductivity (W/m-K)	0.200000
Liquid state density (kg/m3)	770.000000
Liquid state specific heat (J/kg-K)	2000.000000
Melting Curve	
High temperature difference of melting curve (deltaC)	1.000000
Peak melting temperature (°C)	28.000000
Low temperature difference of melting curve (deltaC)	1.000000
Solid State	
Solid state thermal conductivity (W/m-K)	0.200000
Solid state density (kg/m3)	880.000000
Solid state specific heat (J/kg-K)	2000.000000
Freezing Curve	
High temperature difference of freezing curve (deltaC)	1.000000
Peak freezing temperature (°C)	18.000000
Low temperature difference of freezing curve (deltaC)	1.000000

Phase Change Material (PCM)

When the 'Phase change material' c
box is selected, this material has
temperature dependent material pro
- but only when using with the 2-Finit
Difference solution algorithm. In this
the effect of temperature dependent
thermal conductivity and phase chan
included in the EnergyPlus simulatio

Set PCM simulation options required
including the effect of phase change
temperature varying thermal properti

Figure 63 shows the paraffin properties and simulation settings.

4.7.2 Heating, Cooling Loads, and Comfort Calculations

First, the heating and cooling loads during January and August:

Heating loads calculations

- The apartment using Model One (Reference Case): The first step of simulation was studying the apartment with no insulation applied into external walls. Using Design Builder, the result of energy loads of the heating during January month was as follows:

Table 8 The results of Energy load of the heating during the January, researcher.

Simulated Case	Heating Energy Per Conditioned Building Area [kWh]
Reference Case	1337.69

And the graph below presents the obtained results of the apartment heating loads for the same month.

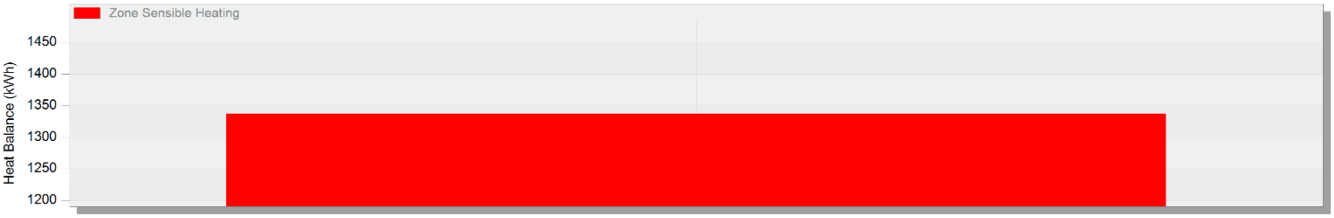


Figure 64 Heating loads results of the apartment (Reference Case).

- The apartment using Model Seven (PCM Case): The second case of simulation was for the apartment with PCM insulation applied into external walls. The result of energy loads for the heating during January was as follows:

Table 9 The results of Energy loads of the heating during the winter period, researcher.

Simulated Case	Heating Energy Per Conditioned Building Area [kWh]
PCM Case	862.77

And the next graph shows the obtained results of the apartment heating loads for the same period.

Figure 65 Heating loads results of the apartment (Enhanced with PCM).

Cooling loads calculations

- The apartment using Model One (Reference Case): For the first case simulation of apartment with no insulation applied, the result of energy loads of the cooling during August was as follows:

Table 10 The results of Energy load of the cooling during the summer period, researcher.

Simulated Case	Cooling Energy Per Conditioned Building Area [kWh]
Ref Case	612.46

The obtained result of the apartment cooling loads for August is shown in the graph below.

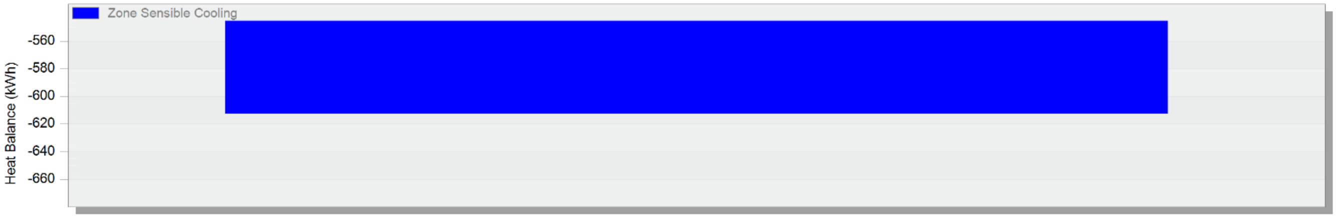


Figure 66 Cooling loads results of apartment (Reference Case).

- Apartment using Model Seven (Enhanced with PCM): For the second case, the result of energy loads for cooling loads of apartment with PCM during the August was as follows:

Table 11 The results of Energy load of the cooling during the summer period, researcher.

Simulated Case	Cooling Energy Per Conditioned Building Area [kWh]
PCM Case	355.64

The obtained result of the apartment cooling loads during August is shown in the graph below.

Figure 67 Cooling loads result of the apartment (Enhanced with PCM).

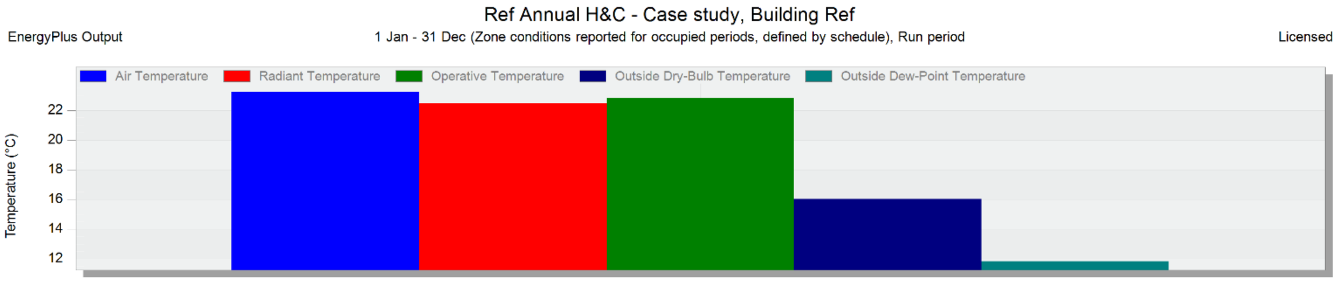
Second, the annual heating and cooling loads:

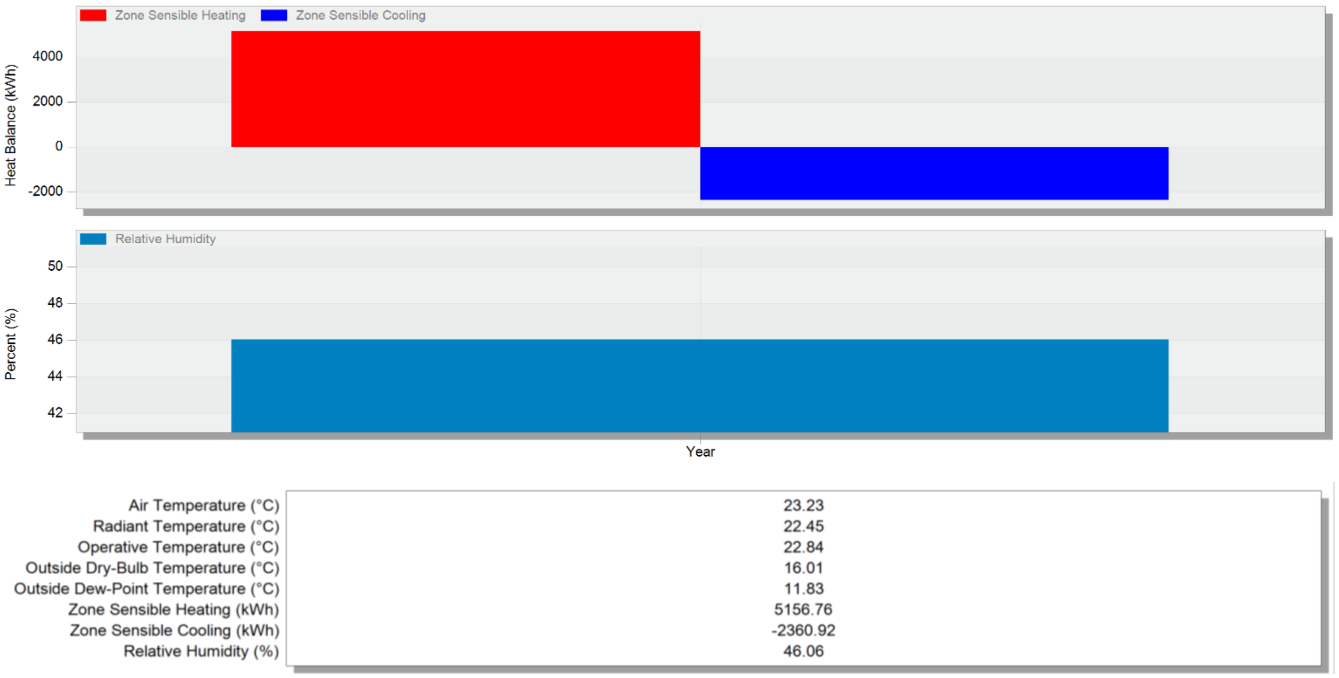
❖ Apartment using Model One (Reference Case): The annual heating and cooling calculations were conducted for the apartment with no insulation applied, the results were as follows:

Table 12 The results of energy load of the annual heating and cooling, researcher.

Simulated Case	Annually Energy Per Conditioned Building Area [kWh]
Ref Case	7517.68

The results obtained showed that the annual heating load was 5156.76 kWh, the annual cooling load was 2360.92 kWh, the relative humidity was 46.06%, and the operative temperature was 22.84℃.





Air Temperature (°C)	23.23
Radiant Temperature (°C)	22.45
Operative Temperature (°C)	22.84
Outside Dry-Bulb Temperature (°C)	16.01
Outside Dew-Point Temperature (°C)	11.83
Zone Sensible Heating (kWh)	5156.76
Zone Sensible Cooling (kWh)	-2360.92
Relative Humidity (%)	46.06

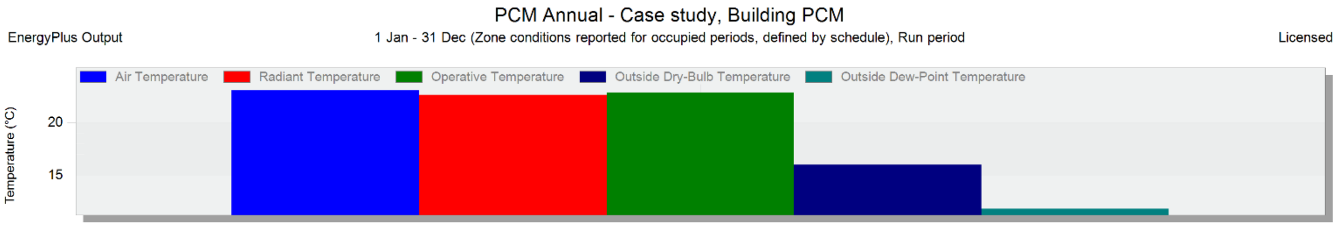
Figure 68 The annual heating & cooling loads, and comfort calculations results of (Reference Case).

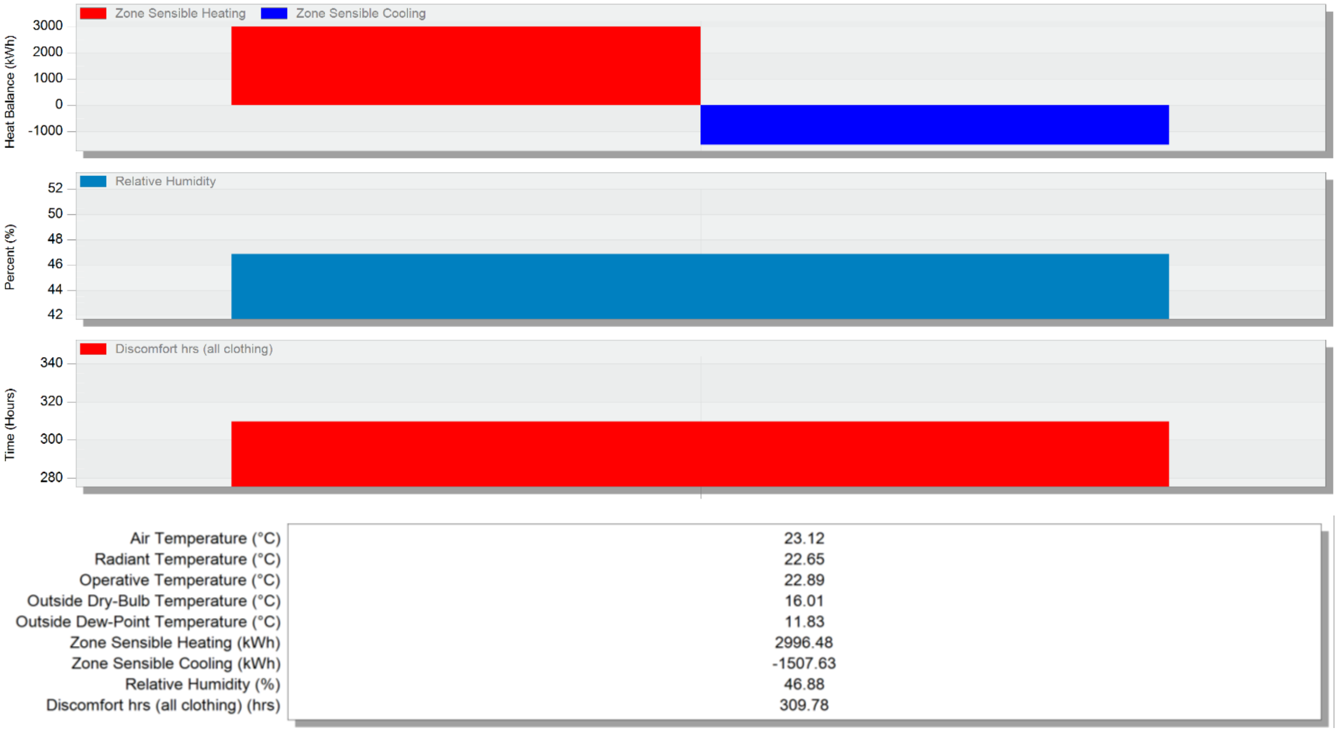
- Apartment using model seven (Enhanced with PCM): The annual heating and cooling calculations were conducted for the apartment enhanced with PCM and the results were as follows:

Table 13 The results of energy load of the annual heating and cooling, researcher.

Simulated Case	Cooling Energy Per Conditioned Building Area [kWh]
PCM Case	4504.11

The results obtained showed that the annual heating load was 2996.48 kWh, the annual cooling load was 1507.63 kWh, the relative humidity was 46.88%, and the operative temperature was 22.89°C. The annual discomfort hours of the PCM case were 309.78 hrs. The operative temperature, outside dry-bulb, outside dew-point temperature, and relative humidity were done as they’re seen in the next figure.





Air Temperature (°C)	23.12
Radiant Temperature (°C)	22.65
Operative Temperature (°C)	22.89
Outside Dry-Bulb Temperature (°C)	16.01
Outside Dew-Point Temperature (°C)	11.83
Zone Sensible Heating (kWh)	2996.48
Zone Sensible Cooling (kWh)	-1507.63
Relative Humidity (%)	46.88
Discomfort hrs (all clothing) (hrs)	309.78

Figure 69 The annual heating & cooling loads, and comfort calculations results of (PCM Case).

4.7.3 Condensation Calculations

Condensation calculations are conducted to observe if there is any condensation in the wall layers which leads to monitoring and controlling the moisture transfer through the wall layers and validating the best thickness and location chosen for paraffin in the wall. This aims to protect the wall from moisture and mold growth and contributes to elongating the life age of the wall. Interstitial condensation occurs as a result of the transfer of water vapor in winter due to the difference in water vapor pressure across the structural elements from the inner (warm) side to the outer (cold) side, where the water vapor pressure inside is higher than outside (Code, 2004). Interstitial condensation happens where temperatures are equal to or below dew point as water vapor travels through building elements (Code, 2004). The calculations for Model 7 have been done manually based on the Glaser-Method Model for one-dimensional transfer for a steady state condition. It’s a simple method to calculate condensation in building elements, which can be calculated without software. The required data settings were collected based on ASHRAE Handbook, Palestinian Energy Efficient Building Code, and DesignBuilder database. The calculations are conducted for January month 31 days and 744 hours. According to the Palestinian Energy Efficient Building Code (Code, 2004), The design temperature of the climatic zone of the city of Jerusalem in winter (T_e) is 4.7 °C. The Inside temperature (T_i) is 20 °C. The maximum design value of relative humidity for winter is 71.7%. The next table shows the results of calculations:

Table 14 Material specifications, required values and results of condensation calculations

N	Layer	Thick-ness (d)	Vapor resistivity (μ)	Vapor resistance (sd)	Thermal Conduct-ivity (λ)	Thermal resistance (R)	Interface	Temp. (T)	Saturation pressure (*Ps*)	Actual vapor pressure (*P*)
		m	-	m	W/m.K	m^2.K/W		°C	Pa	Pa
	Outside	0				0.04		4.7	1122.4	683.2
1	Limestone	0.05	40	2	1.53	0.03268	out/5	9.5623	1853.235	817.515
2	Cast Concrete	0.15	15	2.25	1.75	0.085714	3/4	10.497	1987.515	968.58
3	Paraffin	0.02	100	2	0.2	0.1	2/3	12.949	2138.58	1102.86
4	Hollow Block	0.1	6	0.6	0.77	0.12987	1/2	15.809	2272.86	1143.144
5	Plaster	0.02	20	0.4	1.2	0.01667	in/1	19.523	2313.144	1170
	Inside	0				0.13		20	2340	1170
			Sum	7.25		0.534931				
					U	1.869401	W/m^2 K			

Where T is temperature in °C, q is heat flux in W/m^2, λ is thermal conductivity, and R is thermal resistance in m^2K/W. The condensation calculations have been done through temperature heat transfer calculations and vapor pressure calculations as follows:

a) Temperature Heat Transfer Calculations:

$q = U (T_i - T_e) = 1.8694 (20-4.7) = 28.602$ W/m^2

$T_{si} = T_i - qR_{si} = 19.523$ °C

$T_{1/2} = T_{si} - qR_1 = 15.809$ °C

$T_{2/3} = T_{1/2} - qR_2 = 12.949$ °C

$T_{3/4} = T_{2/3} - qR_3 = 10.497$ °C

$T_{se} = T_{3/4} - qR_4 = 9.5623$ °C

b) Vapor Pressure Calculations:

$P_i = P_{i/1} = 0.5. P_{si} = 0.5 . 2340$ Pa $= 1170$ Pa, where P_a at 20 °C is 2340 Pa.

$P_e = 0.8 P_{se} = 0.8 . 854$ Pa $= 676$ Pa, where P_e at 4.7 °C is 854 Pa.

The water vapor permeability (g) can be found as: $g = \frac{pi - p\,e}{1.5\,.\,10^6.\,Sd} = \frac{1170-683.2}{1500\,.\,7.25}$ kg/m.h.Pa = 0.04476 g/m^2.h

g: Moisture transfer rate [kg/(h m²)], δ: water vapor permeability of the air with respect to partial, μ: water vapor resistance factor [-], and d: thickness of the material [m].

$P_{1/2} = P_{i/1} - gZ = P_{i/1} - g\,.\,\frac{1}{\delta}.S_{d1}$, where Z the resistance to water vapor diffusion, and $\frac{1}{\delta air} = 1500$ m.h.Pa/g

$P_{1/2}$ = 1143.144 Pa

$P_{2/3}$ = 1102.86 Pa

$P_{3/4}$ = 968.58 Pa

$P_{4/e}$ = 817.515 Pa

Furthermore, q, P_i, P_s, g and Z were found as follows:

Table 15 shows the values of *q, Pi, Ps, g* and *z*

q = 28.602 W/m^2	Pi = 1170 Pa	Ps = 2340 Pa	g = 0.04476 g/ m^2.h	Z = 1500 m.h.Pa/g

Based on the results in table 13, The next diagram of Glaser-Method presents the saturation pressure (*Ps*) and partial pressure (*P*) for each layers' surfaces. Thus, the results show there is no condensation occurs among the layers, and the Paraffin layer can be useful for protection against interstitial condensation.

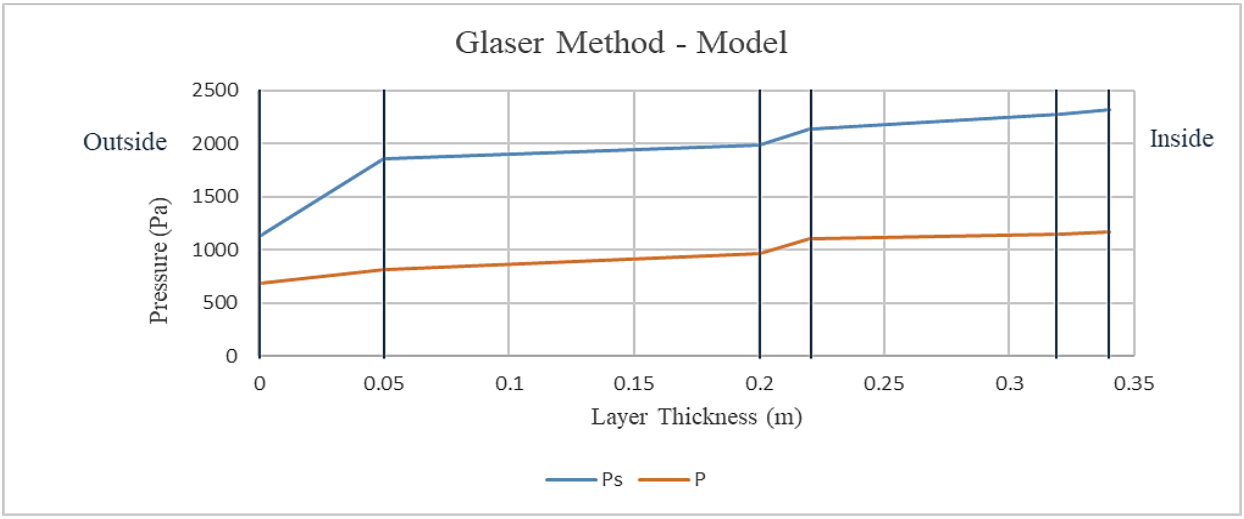


Figure 70 Glaser-Method Model

There is no condensation in the wall, as the partial vapour pressure is at every point lower than the possible saturated vapour pressure. Thus, the construction build-up is physically acceptable under the given climate conditions.

4.7.4 Cost of Implementing PCM (Paraffin)

The required volume of PCM insulation to be implemented into external walls was almost 1.31 m3. The density of solid paraffin was 880 kg/m3, so the total mass of the material counted to be 1152.8 kg. Since the price of paraffin is 1 $/kg, the cost of PCM material used for the apartment equals 1152.8 US$.

4.7.5 Summery

This study presented the amounts of energy demand for the month of January and August which are the months with the highest demand for energy. The energy calculations of heating and cooling loads obtained showed a reduction in heating energy per conditioned building when using PCM in January was 474.92 kWh, with a saving of 35.5%, whereas the reduction in cooling energy per conditioned area in August was 256.82 kWh, with a saving of 41.9%. However, the reduction of annual energy loads was 3013.57kWh with a saving of 40.1%, as they’re seen in the next table.

Table 16 Heating and cooling loads: results, saving and payback period.

	August (Cooling) (kWh)	January (Heating) (kWh)	Annually (kWh)
Reference Case	612.46	1337.69	7517.68
PCM Case	355.64	862.77	4504.11
Reducing (kWh)	256.82	474.92	3013.57
Saving (%)	41.9	35.5	40.1
Payback Period (yrs)			2.5

The exchange rate of the shekel to the dollar reached 0.30 US$ on the date of 1-8-2022 (Xe Currency Converter, 2022). The price of electricity per kilowatt hour was 0.5138 Nis for the prepaid electric meters (‘JDECO’, 2022), which equals 0.5138*0.3 = 0.15414 US$. The annual cost of saving electricity is 3013.57* 0.15414 = 464.51 US$. The equation of Payback Period equals Initial Cost / Annual Saving. The Initial cost of PCM was 1152.8 US$, and the annual saving was 3013.57* 0.15414 = 464.51 US$. So, the payback period equals 1152.8 US$ / 464.51 US$ = 2.48 years which is almost 2.5 years.

4.8 Discussion

This study is aimed to find the best behavior of common models used in the residential buildings within the Mediterranean climatic region, a case study of Jerusalem. Nine insulated models have been investigated with selected insulation materials in addition to the reference case for comparison. The models were exposed to the same boundary conditions in the simulation system. The heat transfer calculations of models have been done under extreme conditions in winter and summer as worst-case scenarios to observe the material's ability to isolate in extreme conditions without a system collapse, in addition to the marked climate change and temperature fluctuations in recent years. As well as to obtain the best practices of wall models to reach the energy efficiency of residential buildings compared with common practices in the local environment of Jerusalem.

Firstly, the study's methodology is based on analyzing the models and evaluating the most effective thermal performance of the standard models and the developed ones using ANSYS FLUENT software by changing the location of the insulation layer, thickness, and thermal behavior. The study clarifies that using insulation materials of better thermal properties in the building wall composition can positively affect the thermal performance of the building envelope as well thickness and suitable location of the material layer within the wall section have a significant impact on thermal heat transfer, heating and cooling calculations and distributing temperatures compared to the local practices in Palestine. The climatic zone of Jerusalem was taken as a case study and not for Palestine as a whole, as there is more than one climatic zone, so that the readings and results are effective, realistic, and logical, as each climatic design depends on the type of climatic zone in which the building is located. Since the surrounding conditions affect the cases equally along the wall, the points at different heights are exposed to the same effect and have the same temperatures. Thus, the thermal effect is linear and has the same results for thermal conductivity, and therefore the points at the height of 50 cm were taken for all models and compared. In summer, the results of cases containing PCM are taken when the state of PCM is liquid due to the melting point of PCM ranging between (27 ℃ and 29 ℃). While in winter, PCM's state is solid and the phase change of PCM has not occurred. However, the PCM impact on heat transfer is clear. The study investigated the heat transfer in composite walls through analytical simulation models with boundary conditions in the extreme weather in the summer and winter seasons, considering the software inputs and based on scientific references. Temperatures (the highest and lowest design temperature based on ASHRAE 2021) were taken for the Jerusalem region as a case study and not for the Palestine region. The study aims to obtain results closer to reality.

In the first phase, wall models enhanced with a single conventional material layer (XPS) were investigated in addition to the reference case, which is essential to be compared based on it. For the reference case (Model 1): in summer & winter, the results agreed with a study (Monna et al., 2019) mentioned that indoor temperatures in residential buildings with no thermal insulation always remain outside the comfort zone in summer and winter despite using electric fans in summer and portable electric and gas heaters in winter. The results showed that the reference case gave 27.3 ℃ in summer and 13.0 ℃ in winter within extreme conditions which is outside the comfort zone. In Model 2, the XPS located towards the interior showed an average temperature of the internal wall surface in summer that was 24.6 ℃. This result is close to the thermal comfort zone but still out of the comfort zone. The temperature difference compared to the reference case is almost 2.7 degrees. However, the average temperature of the internal wall surface in winter was 17.1 ℃, which is a bit close to the thermal comfort zone but still below the zone. In this case, the temperature difference compared to the reference case is almost 4.1 degrees. But in Model 3, the insulation layer of XPS is located toward the exterior, which gives the advantage to obtain a better result. The summer result of the average temperature for the internal wall surface was 24.4 ℃, which is closer to the thermal comfort zone but still out of the zone. The temperature difference compared to the reference case is almost 2.9 degrees. While in winter, the average temperature of the internal wall surface in winter was 17.6 ℃ which is closer to the thermal comfort zone but still under the zone. In this case, the temperature difference compared to the reference case is almost 4.6 degrees. Otherwise, Model 4, in which the XPS layer locates in the middle of the wall section, gave the worst results among the models enhanced with XPS, as the average temperature of the internal wall surface in summer was 24.9 ℃ out of the zone. In this case, the temperature difference compared to the reference case is almost 2.4 degrees. On the other hand, in winter, the average temperature of the internal wall surface was 15.1 ℃, which is far from the thermal comfort zone, and the temperature difference compared to the reference case is almost 2.1 degrees.

The second phase contains the investigated wall models enhanced with a single layer of paraffin (PCM). Compared to conventional materials, PCMs are distinguished from traditional materials by their properties in improving the thermal performance of the building envelope, the high ability to insulate through heat storage, and release by changing its physical state during the heat transfer process, dealing with normal and abnormal climate conditions more effectively. On the other hand, its optimal thickness is less useful for existing and limited spaces in residential buildings, as it’s seen in the study results.

In Model 5, the insulation layer of PCM is located toward the interior and has an average temperature of an internal wall surface of 25.6 °C in summer, which is out of the comfort zone. In this case, the temperature difference compared to the reference case is almost 1.7 degrees. While in winter, the average temperature of the internal wall surface in winter was 16.1 °C, which is below the comfort zone, and the temperature difference compared to the reference case is almost 3.1 degrees. But for Model 6, due to the insulation layer of PCM being located towards the exterior, the results were the worst among the models enhanced with XPS, which makes it inefficient, as the average temperature of the internal wall surface in summer was 25.9 °C which is out of the comfort zone temperature range. And the temperature difference compared to the reference case is almost 1.5 degrees. While in winter, the average temperature of the internal wall surface in winter was 15.6 °C, which is far from the comfort zone range. In this case, the temperature difference compared to the reference case is almost 2.6 degrees. The results of Model 5 and Model 7 were a bit close, indicating that PCM is more efficient in that the PCM is more efficient when it is located toward the interior. As for Model 7, the average temperature of the internal wall surface in summer was 25.0 °C, which is closer to the thermal comfort zone but still out of the zone. The insulation layer of PCM is in the middle of the wall section, thus the temperature difference compared to the reference case is almost 2.3 degrees. While in winter, the average temperature of the internal wall surface in winter was 16.1 °C, which is far from the thermal comfort zone. Therefore, the temperature difference compared to the reference case is almost 3.1 degrees. However, through the year months, Model 7 takes the best behavior as well the heat transfer during charge and release of the heat energy is less close to the entire space. In addition, PCM layer in Model 5 is closer to the internal surface which makes a risk to heat transfer to the indoor space when releasing heat energy. In this phase, solutions were found to install PCM layer in the wall; In general, the preferable solution for PCM installation is to install the material by encapsulating it in small capsules that are fixed on the panels (Dobri *et al.*, 2021). So, in Model 5, plaster panels can be dynamic installed on rails behind the PCM layer, or even alternatives to plaster such as gypsum boards, wood or other mixed materials can be used. In Model 6, PCM panels can be dynamic installed after the stone, so that they are installed on the rails behind the cladding stone, while keeping enough ventilation space behind the stone to prevent moisture. And in Model 7, the panels can be static fixed in the middle. And since the volume of the material changes little (Sun *et al.*, 2020) during the phase change period (decreases with melting and increases with solidification), when designing the material envelope, this change is taken into account and the material encapsulation is designed at the maximum volume that the material reaches. Thus, there is no effect on the wall design.

The third phase contains the investigated wall model enhanced with double layers (XPS and PCM). The results for the model with two different materials of insulation layers gave a higher quality of thermal resistance. Such as in Model 8, the insulation layers of XPS and PCM are located towards the exterior and in the middle of the wall section. Thus, the average temperature of the internal wall surface in summer was 23.7 ℃, which is closer to the thermal comfort zone. In this case, the temperature difference compared to the reference case is almost 3.6 degrees, considering the best value obtained. And in winter, the average temperature of the internal wall surface in winter was 19.5 ℃, which is within the thermal comfort zone. Compared to the reference case, the temperature difference is almost 6.5 degrees, as it is the best difference between other cases.

The fourth phase contains the last wall model, which is Model 9. In this case, the thickness of the double layers of thermal insulation were decreased to half the assumed thickness. As the average temperature of the internal wall surface in summer was 24.2 ℃. The insulation layers of XPS and PCM are located towards the exterior and in the middle of the wall section and have a half thickness. The temperature difference compared to the reference case is almost 3.1 degrees. While in winter, the average temperature of the internal wall surface in winter was 18.7 ℃, which is within the thermal comfort zone. The temperature difference compared to the reference case is almost 5.7 degrees.

From the previous results, the best behavior of models that were enhanced with conventional material (XPS) in phase one was Model 3, as the insulation layer of XPS is located towards the exterior. While the best behavior of the models enhanced with PCM in phase two was Model 7, as the location of PCM is in the middle of the wall section. It's important to mention that while XPS thickness is double compared to the PCM layer, PCM models gave good results and can work efficiently in buildings envelopes. Also, PCM can outperform in the impact when it is used with the same thickness as XPS, as the use of material with higher physical and thermal properties has an advantage in results if it is used with the same thickness of local materials with lower properties. Moreover, the time of simulation took a very long time compared to XPS cases when extracting the results of models in the PCM and especially XPS-PCM models, as a result of heat storage in the material and the transformation from solid-state to liquid in the summer. Thus, the time flow is more significant.

The second main part of the simulation emphasized the energy study of heating and cooling calculations. The heating and cooling loads of the residential building have been examined through a case study of an apartment in the city of Jerusalem under normal climatic conditions. Thermal calculations of the heating and cooling loads have been conducted for the Reference Case without insulation layer and for the PCM

Case when Paraffin insulation layer was applied. Practical experience and Palestinian code were relied on in the building construction specifications in terms of interior spaces, ceiling height, and matters related to the building characteristics and its orientation that are also based on the recommended design standards. The calculation results are conducted for the occupied zones. The ceiling and floors for both cases were highly insulated to prevent any effect on the thermal calculations and to focus on studying the performance of the external walls only. This approach allowed the evaluation of energy demand consumption in the building and addresses an integral comparison for similar periods before and after the installation of PCMs, in which their integration into the building can reduce the operating costs of the building in consuming monthly heating/cooling loads. The energy calculations of heating and cooling loads obtained showed a reduction in heating energy per conditioned building when using PCM in January was 474.92 kWh, with a saving of 35.5%, whereas the reduction in cooling energy per conditioned area in August was 256.82 kWh, with a saving of 41.9%. However, the reduction of annual energy loads was 3013.57 kWh with a saving of 40.1%. The required volume of PCM insulation to be implemented into external walls was almost 1.31 m3. Since the price of paraffin is 1 $/kg, the cost of PCM material used for the apartment equals 1152.8 US$. The annual cost of saving electricity is 3013.57* 0.15414 = 464.51 US$. The equation of Payback Period equals Initial Cost / Annual Saving. The Initial cost of PCM was 1152.8 US$, and the annual saving was 3013.57* 0.15414 = 464.51 US$. So, the payback period equals 1152.8 US$ / 464.51 US$ = 2.48 years which is almost 2.5 years.

Chapter Five

Chapter Five: Conclusion & Future Works

5.1 Introduction

In this study, two simulation processes have been conducted that set a start of heat transfer investigation using the phase change materials (PCMs) and the comparison between the thermal insulation materials based on the determinants. And the energy investigation of heating and cooling loads using DesignBuilder software, that helps engineers, designers, and researchers to verify any current, future applied, or theoretical studies related to the study climate, and thermal performance of walls, energy consumption, heat transfer, and a comparison of their effect on heating and cooling loads.

5.2 Research Limits and Limitations

The extent of the research is limited to the following:

- Heat transfer simulation of external walls enhanced with XPS or /and PCM under extreme conditions.
- Energy simulation of heating and cooling loads under normal conditions for a case of an apartment.
- Comparison between the implemented insulation materials of Paraffin and XPS based on criteria.
- The climate zone in the city of Jerusalem in Palestine: A Mediterranean climate, with hot summers and rainy winters.

However, the research has encountered several limitations and challenges such:

- The limited time available for the research led to the limit of selected conventional and new insulation materials not used in the local environment.
- The search was limited to a specific type of building (residential) based on statistics on the largest energy consuming sector (Njore, 2016) and (Monna *et al.*, 2020), and the most significant envelope elements which is the external wall (Salameh, 2012) and (Mohaibesh *et al.*, 2021).
- Assumption of the PCM thickness used in the cases within thickness ranges of previous studies.
- Using the recommended Installation technique for the PCM layer within wall configuration.
- Implementing new material to one apartment in the middle high of the multistorey buildings.
- The new learning of software that is used for calculations, in addition to the long duration time of simulation for each case (Transient Simulation), and the use of two different programs.

5.3 Conclusion

Residential apartments are the largest in the urban environment and have the highest expenditures on electric energy. As well people suffer from a high amount of energy consumption and electric expenditures for heating and cooling needs. Energy consumption is also expected to increase due to urbanization, population growth, and climate change. New studies are needed on an appropriate isolation mechanism in the climatic region of the study using new materials. the contribution of the study is in using a new material (PCM) in affecting the thermal performance of the building envelope, thermal heat transfer, temperature distribution, and on heating and cooling loads.

The research framework is divided into two main parts; the first part concerns the heat transfer study that is emphasized studying conventional insulation materials used within the local climatic environment through literature reviews, experience, and local market, as well the phase change materials as new insulation materials. Parallely, a simulation study using FLUENT software was conducted to find the best practices and behavior of the insulated wall models used as well as ensure the results through a validation study. The heat transfer calculations have been done under extreme conditions in winter and summer as worst-case scenarios to monitor the ability of the material to isolate in extreme conditions without a system collapse, as well due to the marked climate change and temperature fluctuations in recent years. In addition to obtaining the best practices of wall models to reach the energy efficiency of residential buildings compared with common practices in the local environment of Jerusalem. The thermal performance of the building envelope has been studied to determine the most significant element in energy consumption through previous studies, in order to improve the thermal performance of residential buildings in Palestine since a numerical investigation for selected wall models was conducted to observe the temperatures distribution through the walls sections at different heights by selecting points in the middle of each layer in addition to the internal and external surfaces.

Locations of the insulation layer within walls sections are assumed to be towards the exterior, in the middle, and towards the interior. Thicknesses of insulation layers in this study are also assumed 4cm XPS and 2cm PCM for the full thickness applied cases, as the use of material with higher physical and thermal properties has an advantage in results if it is used with the same thickness of local materials with lower properties, in addition to relying on some close numbers in the use of the material from previous studies, and adopting a correct ratio between the two materials for comparison. The numbers decreased to 2cm, and 1cm for the last case to see the difference in the effectiveness of the materials in a less thickness of double layers wall compared to a wall with a single layer of XPS material, also to observe the thermal behavior, compare the cases to find the best practices and conclude recommendations of using insulations. Based on the numerical investigation of cases and the heat distribution within walls sections, the temperature average of the internal surface of the walls is examined and compared with other models in hot summer and cold winter (extreme conditions). these calculations have been verified by a selected similar case that used the same software. By comparing the all models that wither enhanced with a single layer (XPS or PCM) or enhanced with double layers of thermal insulations (XPS & PCM), the results showed that the best behavior for the wall models enhanced with XPS was Model 3 in summer and winter. The average temperature of the inner wall surface in summer is 24.4 °C. The temperature difference compared to the reference case is almost 2.9 degrees. While in winter, the average temperature of the internal wall surface in winter was 17.6 °C, and the temperature difference compared to the reference case was almost 4.6 degrees. For the models enhanced with PCM, the best behavior was Model 7 in summer and winter. The average temperature of the internal wall surface in summer is 25.0 °C, and the temperature difference compared to the reference case is almost 2.3 degrees. While in winter, the average temperature of the internal wall surface was 16.1 °C, and the temperature difference in this case compared to the reference case is almost 3.1 degrees. For the wall model enhanced with both XPS and PCM (Model 8), the average temperature of the internal wall surface in summer was 23.7 °C, and the temperature difference compared to the reference case is almost 3.6 degrees. However, the average temperature of the internal wall surface in winter was 19.5 °C, and the temperature difference compared to the reference case is nearly 6.5 degrees. However, when the thickness of insulations was reduced by 50% in (Model 9), the average temperature of the internal wall surface in summer was 24.2 °C, with a difference of almost 3.1 degrees in summer, and the average temperature of the internal wall surface in winter was 18.7 °C, with a temperature difference of almost 5.7 degrees.

The second part is concerned with studying the energy of heating and cooling calculations, and comfort calculations. The heating and cooling loads of the residential building have been examined through a case study of an apartment in the city of Jerusalem under normal thermal boundary conditions. Energy demand was calculated for the month of January and August as being the months with the highest demand for energy. In addition to seeing the extent to which the heating and cooling loads are reduced. The percentage of energy saving in the case of applying PCM thermal insulation was examined based on the results of calculations of heating and cooling loads for the residential building. The energy calculations of heating and cooling loads obtained showed a reduction in energy demand when using PCM. The saving of heating energy in January was 35.5%, whereas the saving of cooling energy in August was 41.9%. Further, the reduction amount of annual energy load was 3013.57 kWh with a saving of 40.1%. The Initial cost of PCM was 1152.8 US$, and the annual saving was 464.51 US$. So, the payback period equals 2.5 years, as it’s seen in the following table:

Table 17 Heating and cooling loads: results and saving.

	August (Cooling) (kWh)	January (Heating) (kWh)	Annually (kWh)
Reference Case	612.46	1337.69	7517.68
PCM Case	355.64	862.77	4504.11
Reducing (kWh)	256.82	474.92	3013.57
Saving (%)	41.9	35.5	40.1
Payback Period (yrs)			2.5

Based on the previous results, there are several options available to the building owner to choose the best insulating material, according to the construction stage, construction method, number of insulation layers, internal area, insulation material thermal and physical properties, cost, and payback period. Various issues can be looked at in order to choose the suitable insulation material, including if the owner wants to use one insulation layer, it is more likely to choose PCM to use with good thermal properties and in less thickness which saves the interior space, as the heating and cooling calculations showed that when applying PCM into walls, the net conditioned building area was 140.50 m2, the volume required of material was 1.31 m3, and the cost of material was 1152.8 US$. XPS insulation is a good choice when the building is existing or is new construction as the material can be installed efficiently towards the exterior in different methods, as well as the abundance in the local market. However, it needs a higher volume according to the results. Also, XPS can be chosen in the absence of the expertise and skills necessary for the PCM installation. Paraffin (PCM) is considered a better material when it is used compared to XPS. It can be installed for newly constructed or existing buildings, with less area and volume needed. The heat transfer results and energy loads obtained showed that PCM is an efficient and applicable material in the local environment. The issue is that PCM is not common material in the local market, which makes the cost relatively higher than common materials. A criterion has been developed through which the insulating materials used in the study are compared to choose the best. When using the PCM, for thermal performance, it is noted through the thermal calculations that the PCM gave good results despite the lower thickness compared to the XPS thickness. Thus, it is possible to rely on PCM if when preferring the lower thickness, higher thermal performance, and lower material volume, in addition to a longer life span. However, when the initial cost is preferred, the XPS option is better in this case despite the larger size and lower thermal performance, in addition to the ease of installation. As for the two materials, they can be used if the building is existing, or in the case of new construction, and based on cost calculations and the price of materials. Although PCM was more expensive, the two materials were almost in the same range of payback periods. The advantages of using the insulating materials PCM and XPS are summarized in the following table:

Table 18 Advantages of using the insulating materials PCM and XPS, researcher.

Criteria	PCM (Paraffin)	XPS	Best Choice
Thermal performance	Higher	Lower	PCM
Thickness	Lower	Higher	PCM
Location	Toward Interior	Toward Exterior	Ext: XPS, Int: PCM
Installation	Not Easy	Easier	XPS
Material volume	Lower	Higher	PCM
Initial Cost	Higher	Lower	XPS
Building Stage	Exisiting, New Construction	Exisiting, New Construction	XPS, PCM
Lifeage	Longer	Lower	PCM
Payback period	2.5 yrs	1.89 - 3.81 yrs	XPS, PCM

Moreover, Using two layers of different insulations is effective and good results will be obtained than using one layer of insulation. Even when the thicknesses of the two layers were reduced by half, better results are obtained than using one layer. The sum volume of the two layers of 50% of layer thickness was less than the full thickness of the single layer of XPS with better performance of the wall.

The numerical investigation of the study will help to figure out the impact of using a new material (PCM) in the residential building wall in the local area. And determining the effectiveness of using this material compared to conventional insulation materials (XPS) based on the thermal behavior, thickness, location, cost, and the stage of construction. According to the results of Glaser-Method Model, there is no condensation in the wall, as the partial vapour pressure is at every point lower than the possible saturated vapour pressure. So, the construction build-up is physically acceptable under the given climate conditions.

5.4 Recommendations for Future Works

According to the study results, future works should consider the following:

- A future studies of new installation techniques and methods of PCM in the external walls.
- A study of the optimum thickness of Paraffin PCM in the local environment.
- A study of apartments on the last floor of the multistory building (exposed to the direct sun).
- A study of PCM effectiveness in the ceiling, and windows and linked them with external walls.
- A comparison study using more types of recent materials spread in the local market based on thermal efficiency, prices, and different installation methods.
- A practical experiment of applying Paraffin in a cross section of the external wall and studying its thermal impact.
- Studying the reference wall configurations and finding alternatives of using the common hollow block and plaster.

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