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A Novel Validated Method to Determine the Relationship Between Insulation Thickness and the Annual Cooling Cost in Desert Climates

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Abstract: Energy-efficient building envelope design is essential for minimizing cooling loads and reducing energy consumption, particularly in hot desert climates. This study presents a model that optimizes insulation thickness by taking into account climate-specific conditions and economic factors. The model employs a life-cycle cost analysis framework, incorporating energy savings, insulation costs, and payback periods across various climatic zones. A typical wall is considered with three commonly applied insulation materials. The optimization is validated by energy modeling. A key contribution of this study is the introduction of a correction factor based on average humidity for each city, which adjusts the conduction-based model to account for latent heat effects from moisture-dependent insulation degradation. Unlike existing building codes, which prescribe fixed insulation requirements regardless of regional climate conditions, our approach dynamically adapts insulation thickness based on Cooling Degree Days (CDDs) and economic feasibility. The results reveal significant variations in optimal insulation thickness across different cities, demonstrating the necessity of climate-responsive insulation strategies. The analysis indicates that locations with higher CDD, such as Jeddah and Dhahran, require thicker insulation to reduce cooling loads effectively, whereas cities with lower cooling demand, such as Khamis Mushait, necessitate thinner insulation for economic viability. The results show that polystyrene (K = 0.034 W/m.K) has the least cost, whereas polyurethane (K = 0.24 W/m.K) records the least thickness in Saudi Arabia. This study presents a model that optimizes insulation thickness by taking into account climate-specific conditions and economic factors.

Keywords: life-cycle cost; wall insulation; energy savings; optimization; energy modeling

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1. Introduction

Global energy consumption is rapidly increasing, leading to a rise in Greenhouse Gas (GHG) emissions. This trend is expected to worsen in the future unless substantial efforts are made to reduce fossil fuel consumption. Climate change, primarily caused by human activities and GHG emissions from fossil fuels, is considered one of the most significant threats to humanity [1]. To address climate change, it is crucial to transition to low-carbon

energy systems. The building sector, with its substantial energy and environmental impact, must play a key role in this transition toward a sustainable energy future [2]. Buildings consume nearly 40% of global energy, with approximately 60% of this used for heating and cooling, representing the highest percentage of energy use [3]. To limit the Earth's temperature rise to 2 °C, it is recommended to reduce overall Carbon Dioxide (CO_2) emissions by 32 Giga Tons in the global building sector by 2050 [4].

Saudi Arabia is one of the leading countries globally regarding per capita energy consumption and CO_2 emissions. The country's per capita annual electricity consumption is among the highest in the world, equivalent to 9401.5 kWh/capita, while the world average is 3131.7 kWh/capita [5]. Its building sector is experiencing fast growth in energy demand as the building stock continues to expand. Research suggests that energy consumption in buildings is influenced by multiple factors, including rapid population growth, the extreme desert climate, inefficient building designs, subsidized energy prices, and the absence of strict energy policies [6]. In Saudi Arabia, buildings face considerable energy challenges, with air conditioning (AC) systems being the primary contributors to electricity consumption. AC units account for nearly 70% of residential electricity use, largely due to the widespread lack of thermal insulation in building envelopes—approximately 70% of existing structures remain uninsulated [7–9]. The region's hot–arid climate necessitates continuous cooling to maintain indoor comfort, making it a major driver of energy demand. To mitigate economic burdens and reduce environmental pollution, enhancing building energy efficiency is essential [2]. Earlier research has highlighted that applying thermal insulation to exterior walls is one of the most efficient methods for lowering energy consumption [9–11].

Envelope insulation thickness and effectiveness are influenced by several weather-related parameters [12]. The thickness of the insulation added to the building envelope is one of the most critical factors to consider when designing such energy-efficient structures [13,14]. Economically, thermal insulation thickness considers the initial investment of the insulation systems as well as the continuing benefit of energy savings over the planned service life of the insulation. The thickness that offers the lowest overall lifetime cost is the economically optimum insulation thickness (X_{opt}). As illustrated in Figure 1, increasing the insulation thickness leads to higher installation costs, whereas heating and cooling energy expenses decline. The optimal insulation thickness is the point at which the combined cost of energy consumption and insulation is minimized. Beyond the optimal thickness, energy savings continue to increase; however, the overall cost rises due to the disproportionate growth in insulation expenses. Thus, while additional insulation beyond the optimal point may result in lower energy consumption, it does not provide economic benefits. The objective of optimizing insulation thickness is to achieve the most cost-effective balance between the energy cost savings (from sources such as electricity, natural gas, fuel oil, etc.) and the expenses of thermal insulation materials.

Generally, there are two main steps for optimizing insulation thickness in buildings. First, the annual heating and cooling transmission loads should be determined. Then, an economic analysis takes place. Each step entails a plethora of parameters that are used in either simple techniques like the degree–day's method or quite sophisticated like dynamic thermal models in order to estimate the transmission loads. After that, the cost analysis, using the Net present value analysis, determines the total cost and the optimum insulation thickness.

The optimization of thermal insulation thickness has been investigated in many studies previously. For example, Rosti et al. [15] investigated the optimal thermal insulation thickness of archetypal exterior walls in Iran. They performed the optimization analysis using the life-cycle cost analysis method together with the numerical solution to identify

the best insulation thickness. They identified that the X_{opt} in Iran is not more than 4 cm and that the X_{opt} varies depending on the climatic location. Similarly, Daouas et al. and Daouas [16,17] used the complex finite Fourier transform to determine X_{opt}, energy savings, and payback time for a wall, based on the research described above. In addition, they studied the influence of the Tunisian climate and the impact of wall orientation.

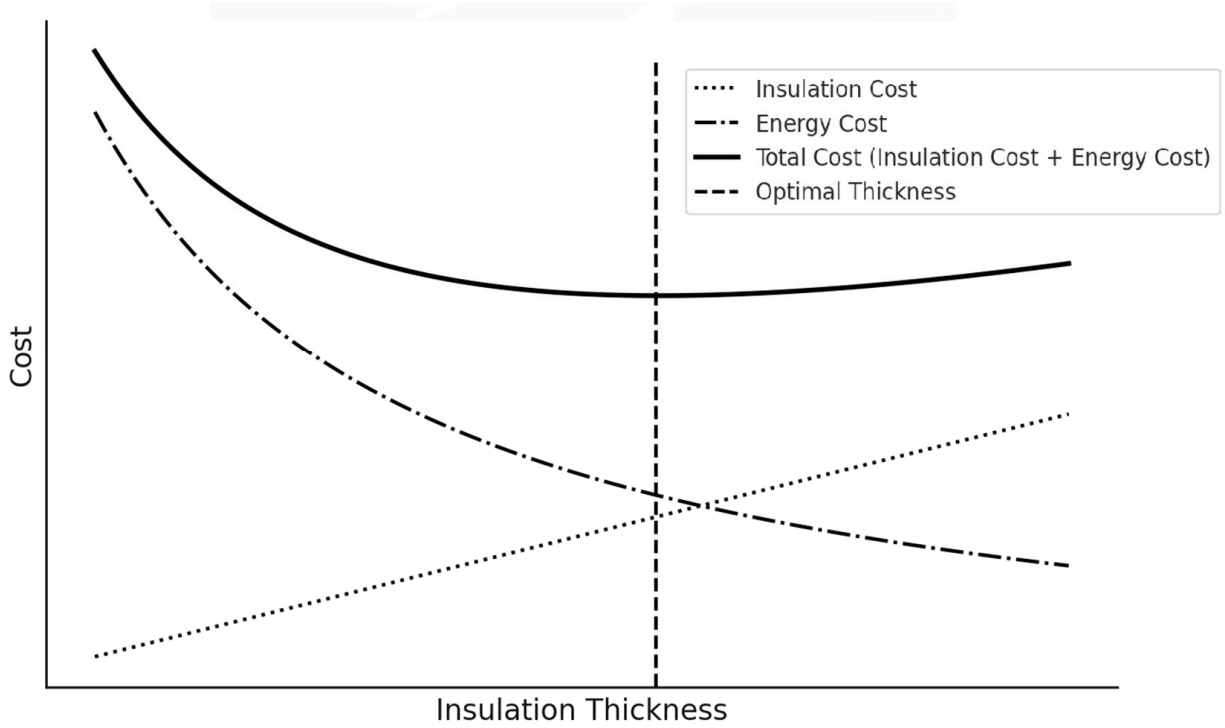


Figure 1. Optimum insulation thickness [3].

In Turkey, Ozel [18,19] employed the finite difference method to analyze optimal insulation thickness (X_{opt}), energy savings, and payback periods. His study also highlighted the influence of wall orientation on thermal performance, revealing that the north-facing wall had the lowest X_{opt}, had the smallest cooling load, and was the most cost-effective, with an X_{opt} of 3.1 cm. Similarly, Kaynakli [3] used the heating degree-hours approach to determine X_{opt} for a building in Bursa, Turkey. His findings indicated that X_{opt} ranged between 5.3 and 12.4 cm, depending on the type of fuel used, with natural gas emerging as the most economical option.

Additionally, D'Agostino et al. [20] applied the cost-optimal methodology to an office building in Italy and found that the X_{opt} based on cost considerations could be lower than the regulatory insulation requirements. A study in Palestine using life-cycle cost analysis demonstrated that polyurethane insulation required only half the X_{opt} compared to polystyrene [21]. Meanwhile, in China, Yu et al. investigated X_{opt} across various climatic zones, incorporating factors such as wall orientation and surface color [22]. Their findings revealed that polystyrene is the most economical insulation material, providing the quickest payback period and the greatest life-cycle savings.

Kaynakli [23] conducted a comprehensive analysis of economic thermal insulation systems for building exterior walls, focusing on determining the optimal insulation thickness (X_{opt}) and its impact on energy consumption. The study compared different optimization and economic analysis approaches, presenting various insulation materials and fuel types while assessing their influence on energy efficiency and emissions in buildings.

Similarly, Axaopoulos et al. [24] investigated the optimal insulation thickness for residential building exterior walls in Athens, Greece, considering factors such as construction techniques, wall orientation, and insulation placement. Their study found that X_{opt} ranged from 11.2 to 23.4 cm, depending on these variables. Additionally, the research highlighted that incorporating insulation could lower annual CO_2 emissions per unit wall area by 63.2–72.2% compared to non-insulated walls, with the extent of emission reduction influenced by both the type of insulation material and its positioning within the wall.

M. A. Kallioğlu et al. [25] assessed the thermal performance of different insulation materials and fuel types across various geographical regions in Turkey. It evaluated optimal insulation thickness, annual cost savings, payback periods, and emission impacts. Additionally, new empirical models were formulated using degree-day calculations for XPS and EPS materials. The resulting equations demonstrated a reliable capability to estimate optimal insulation thickness values with accuracy.

A. Gülten [26] analyzed the environmental impact of insulation materials while determining the optimal insulation thickness for two different wall types through a combined thermo-economic and environmental approach. This method incorporated the entransy concept, which characterizes an object's ability to transfer heat. The study assessed insulation thickness across various wall models and insulation materials in different Turkish cities using a thermo-economic method integrated with entransy analysis. The results showed that insulation thickness ranged from 6.15 cm to 0.01 cm, depending on the wall model and insulation material. The study further evaluated entransy-based cost savings, combustion parameters, and environmental impacts, revealing that insulation thickness determined through the entransy-based environmental analysis was higher compared to thermo-economic calculations. It was concluded that while the thermo-economic approach offered greater energy and cost savings, the environmental perspective prioritized sustainability by reducing fuel consumption and CO_2 emissions.

J. Jalil and S. Salih [27] employed three-dimensional numerical analysis to determine the optimal phase change material (PCM) doping content (i.e., thickness) for a double-glazed window designed for the summer climate in Baghdad, Iraq. Using a FORTRAN (F90) program, the study combined the Finite Volume method with the Enthalpy method to analyze conduction-related phase transition issues within the wax. The transient heat transfer characteristics of the insulation were meticulously examined using the developed numerical model. The findings revealed that to maintain indoor temperatures within the optimal range, the ideal doping content of paraffin wax (melting point 40 °C) varied as follows: 2 cm in May, 3 cm in June, 3.5 cm in July and August, 3 cm in September, and 1.5 cm in October.

M. Kalliolu [28] conducted a climate-geographical assessment of Jaipur, India, which features a Mid-Latitude Steppe and Desert Climate. The study employed Cooling Degree Days (CDDs) to calculate energy demand, optimal insulation thickness (X_{opt}), payback periods, and heat losses in exterior walls for two insulation materials, extruded polystyrene (XPS) and expanded polystyrene (EPS). The results indicated that X_{opt} ranged from 3.83 cm to 7.31 cm, with payback periods varying between 2.35 and 1.79 years. E. Küçüktopcu et al. [29] investigated the applicability of artificial neural networks (ANNs) for modeling *Xopt*, annual total net savings (ATS), and CO_2 emission reductions resulting from building insulation. The study utilized insulation market data, economic parameters, fuel prices, and heating degree days (HDDs) as input variables for the ANN model. Three learning algorithms and five statistical indices were employed to assess the model's accuracy, while visualization techniques were used to compare the predicted and calculated values for X_{opt}, ATS, and CO_2 reduction.

Raimundo et al. [30] assessed the energy, environmental, and economic implications of thermal insulation in different climates, highlighting that optimal insulation thickness varies significantly with climatic conditions and building usage patterns. Their findings underscore that insulation requirements should not be static but rather responsive to both climate change projections and urbanization-driven temperature variations.

In Saudi Arabia, Al-Sanea et al. [31] used seven insulation materials and seven wall configurations to investigate the impact of wall configuration on X_{opt}. Under ideal conditions, the type of insulation material used had the greatest impact on yearly transmission load and R-value, while the wall configuration had the least impact. The most economical material was polystyrene, which had a X_{opt} average for all walls of 7.8 cm.

Al-Sanea and Zedan [32] examined the impact of wall orientation on optimal insulation thickness (X_{opt}) using climatic data from Riyadh. Additionally, they conducted parametric tests to evaluate the sensitivity of X_{opt} to variations in economic parameters. Their findings indicated that an increase in electricity costs, building lifespan, and inflation rate led to higher X_{opt} values, whereas a decrease in insulation material costs, air conditioning system coefficient of performance, and discount rate resulted in lower X_{opt} values. The study also demonstrated that while wall orientation significantly influenced transmission loads and thermal lag, its effect on X_{opt} was relatively minor. Among the insulation materials analyzed, polystyrene was identified as the most cost-effective option, with X_{opt} of 9.3 cm.

In a separate study, Al-Sanea et al. [33] determined optimal R-values for building walls under the climatic conditions of Riyadh, Jeddah, and Abha. Their methodology incorporated three different insulation materials and multiple wall configurations. The study employed a combination of thermal analysis, using the control-volume finite-difference implicit method, and economic evaluation, applying the net present value method, over a 30-year life cycle. The results indicated that at X_{opt}, payback periods—accounting for inflation and financial costs—ranged between 3 and 10 years.

The literature shows an increasing interest in using life-cycle cost and thermal analyses to estimate the optimum insulation thickness of residential building walls in different climatic zones. Therefore, various insulation materials, wall configurations, and economic and environmental parameter values were considered. This study aims to present an optimization model for selecting proper insulation material for external walls and determining the optimum insulation thickness under different desert climatic conditions satisfying both financial and performance requirements. The proposed model is validated by energy modeling, and it was applied to the desert climates of Saudi Arabia as a case study. Three locally used materials were considered: polyurethane board, rock wool, and molded polystyrene. This study will significantly contribute to effective practices for applying thermal insulation to buildings in Saudi Arabia and offers an accurate validated method that can be adopted anywhere to better use walls' thermal insulation.

2. Methodology

Properly assessing buildings' cooling and heating transmission loads is crucial to optimizing insulation thickness. The study's methodology is broken down into several steps, as shown in Figure 2. All of the steps are described in detail in Sections 2.1–2.6. At first, a simplified calculation model is proposed as a base model to determine the optimum insulation thickness. In the base model, the annual heat gain is predicted based on the Cooling Degree Days (CDDs), a widely used and applied method in the literature. The Cooling Degree Days (CDDs) constitute a critical factor in determining cooling energy demand and play a significant role in insulation optimization. However, CDD values can vary across different studies due to differences in base temperature assumptions, calculation methodologies, and geographic data resolutions. For this study, CDD values were sourced

from [34], a recognized reference that aligns with the climatic and geographic characteristics of Saudi Arabia.

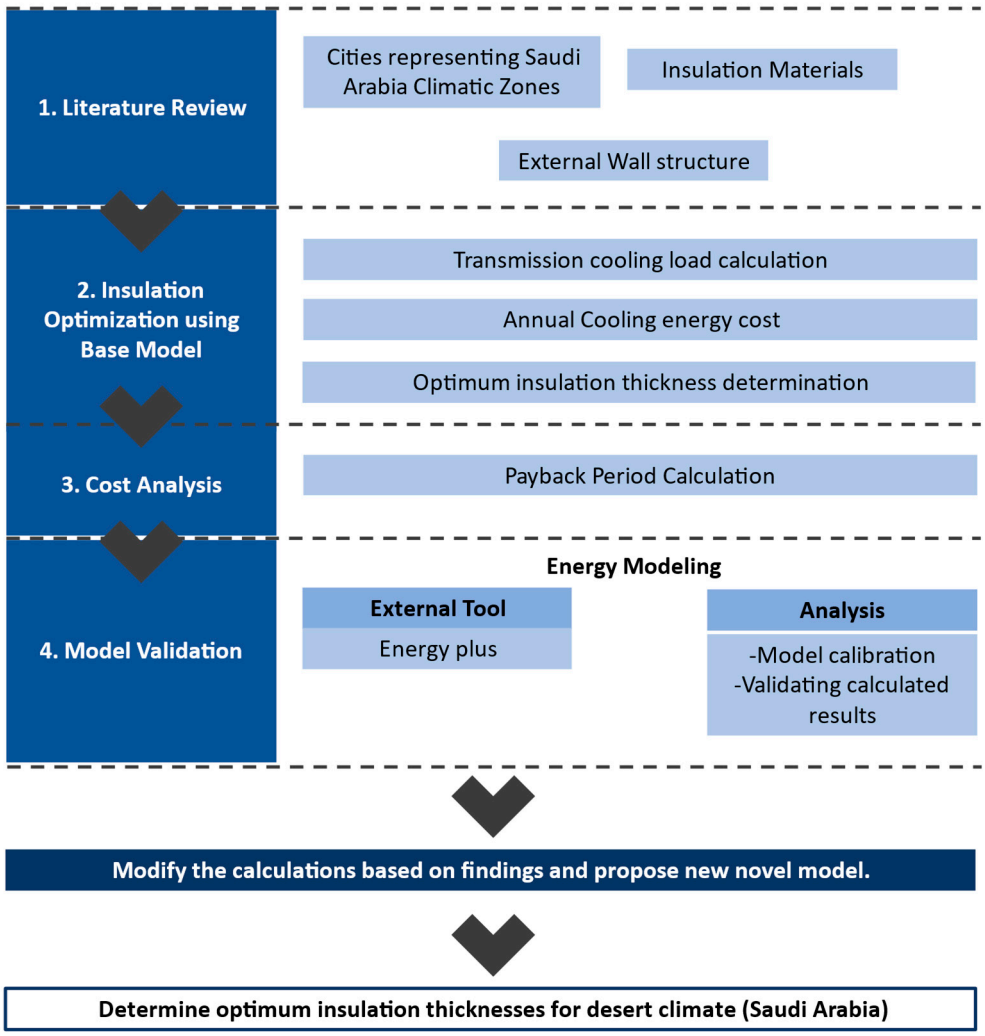


Figure 2. Summary of the methodology.

The annual cooling energy and, consequently, the annual cooling cost could be estimated based on the determined annual heat gain. Then, the optimum insulation thickness is determined by applying economic analysis. The base model is then applied to Saudi Arabia as a case study for validation. The optimum insulation thicknesses of a unit's external wall, assuming electricity as the energy source, are calculated by examining three different insulation materials integrated into a specific external wall structure in five cities representing the five climatic zones of Saudi Arabia (Sections 2.1–2.4). Optimization of the insulation thickness is conducted using the LCC analysis. The thermal analysis involved is based on the degree-days concept in which transmission cooling loads are calculated as a baseline (Section 2.1).

Then, energy modeling is used to validate and adjust the results obtained from the simplified calculation method (Section 2.6). The adjusted cooling loads are used to improve the annual cooling cost prediction and apply the economic analysis, adjusting the steps in Sections 2.1 and 2.2; therefore, determining a more accurate optimum insulation thickness. Based on the comparison between the heat gain obtained from the degree-days and energy modeling, a novel modified and verified model is developed and proposed for determining the optimum insulation thickness.

2.1. Estimation of Annual Heat Gain and Cooling Load

The degree-hours or degree-days process is one of the most common techniques for estimating the annual transmitted load for external walls, which is utilized to determine the amount of energy needed to cool or heat. For a base temperature T_b and daily mean outdoor air temperature T_o, the annual cooling degree-days (CDDs) is calculated by

$$CDD = \sum_{days} (T_o - T_b)^+ \quad (1)$$

The *CDD* values employed in this study have been calculated for a base temperature of 18.3 °C [34].

The heat loss in the exterior wall's unit surface is measured by [35]

$$q = U \times \Delta T \quad (2)$$

where U is the overall heat transfer coefficient and ΔT is the difference between the outside air temperature and the inside ambient temperature. Hence, using U and the degree-day value, the annual heat gains and losses through a unit surface can be determined by [35], as follows:

$$Q_{year,c} = 86,400 \times CDD \times U \quad (3)$$

where

$$U = \frac{1}{R_o + R_i + R_w + R_{ins.}} \quad (4)$$

R_w is the thermal transfer resistance of wall layers without insulation, and R_o and R_i are the heat transfer coefficients of the outside and inside environments, respectively. $R_{ins.}$ is the thermal resistance of the insulation materials, which is measured by [35], as follows:

$$R_{ins.} = \frac{x}{k} \quad (5)$$

x and k are the thickness and thermal conductivity of the insulation materials, respectively. The non-insulated wall layer's total resistance $R_{w,t}$ is calculated by [35], as follows:

$$R_{w,t} = R_o + R_w + R_i \quad (6)$$

therefore, the total heat transfer coefficient can be expressed by

$$U = \frac{1}{R_{w,t} + R_{ins.}} \quad (7)$$

Accordingly, the annual heat losses, $Q_{years,c}$, and gains, $Q_{years,h}$, occurring in the unit surface are determined by using U and the cooling or heating degree-day values, *CDD*, *HDD*, as follows [35]:

$$Q_{year,c} = 86,400 \times U \times CDD \quad (8)$$

$$Q_{year,h} = 86,400 \times U \times HDD \quad (9)$$

The annual energy needed for cooling ($E_{year,c}$) and heating ($E_{year,h}$) is measured by [35]

$$E_{year,c} = \frac{86,400 \times CDD}{(R_{w,t} + R_{ins.}) \times COP} \quad (10)$$

$$E_{year,h} = \frac{86,400 \times HDD}{(R_{w,t} + R_{ins.}) \times \eta} \quad (11)$$

where *COP* is the coefficient of performance of the cooling system (dimensionless) and η is the Efficiency of the combustion system.

2.2. Calculation of Optimum Insulation Thickness and Annual Energy Cost

Insulating the buildings' external walls significantly reduces the heat gain and loss through the walls' surface. However, a cost analysis should be conducted to obtain the optimum insulation thickness. The annual cost of consumed energy $C_{A,C}$ is calculated by [35], as follows:

$$\mathrm{C}_{A,C} = \frac{86,400 \times CDD \times \mathrm{C}_e}{(\mathrm{R}_{w,t} + \mathrm{R}_{ins.}) \times COP} \tag{12}$$

where C_e is the present electricity cost, which is 0.18 SAR/kWh for the case study presented in this study.

To determine the optimal insulation thickness, various financial techniques are employed. One of the most commonly used methods is the Simple Payback Period (*SPP*), which evaluates the time required for energy cost savings to offset the initial insulation investment. However, SPP does not consider the time value of money, which is a critical financial parameter [36]. To overcome this limitation, Life Cycle Cost (*LCC*) analysis is widely adopted [35]. *LCC* provides a comprehensive evaluation of the total cost of insulation over its lifespan. In this study, LCC was implemented to ensure a cost-optimal insulation strategy that balances initial investment with long-term energy efficiency benefits.

The optimum insulation method in this study is obtained using the life cycle cost analysis technique. The annual energy cost is calculated based on the Present Value Factor (*PVF*) and the lifetime (*N*). The *PVF* is determined based on the interest (*i*) and inflation (*f*) rates, as follows:

If i > f

$$\mathrm{r} = \frac{i - f}{1 + f} \tag{13}$$

If $i < f$

$$\mathrm{r} = \frac{f - i}{1 + i} \tag{14}$$

$$\mathrm{PVF} = \frac{(1 + r)^N - 1}{r\,(1 + r)^N} \tag{15}$$

If $i = f$

$$\mathrm{PVF} = \frac{N}{1 + i} \tag{16}$$

where r is the actual interest rate. Then, the cost of insulation is determined by

$$\mathrm{C}_{ins.} = \mathrm{C}_u \times x \tag{17}$$

where C_u is the cost of the insulation per unit volume. According to the life cycle cost analysis, the total cooling cost of an insulated building is obtained by

$$\mathrm{C}_{t,C} = \mathrm{C}_{A,C} \times PWF + \mathrm{C}_u \times x \tag{18}$$

The derivative of the total cost equation $C_{t,c}$ is taken and set equal to zero, which gives the optimum insulation thickness ($X_{opt,c}$), as follows:

$$\mathrm{X}_{opt,c} = 293.94 \times \left(\frac{\mathrm{C}_e \times PWF \times CDD \times K}{\mathrm{C}_u \times COP} \right)^{1/2} - k \times \mathrm{R}_{w,t} \tag{19}$$

2.3. Calculation of the Payback Period

The equation below calculates the annual total net savings for cooling buildings, $A_{year,C}$.

Where C_C represents Pre-insulation cooling energy costs.

$$\mathrm{A}_{year,C} = \mathrm{C}_c - \mathrm{C}_{t,C} \tag{20}$$

The payback period, PP_c, as follows:

$$\mathrm{pp}_C = \frac{\mathrm{C}_{ins.}}{\mathrm{A}_{year,C}} \quad (21)$$

The parameters used in the calculations are shown in Table 1.

Table 1. The parameters used in the case study calculations.

Parameter	Value
Degree-days, DD ($°C - days$)	See Table 2
External walls	See Table 3
External insulation materials	See Table 4
Electricity Cost	0.18 (SAR/kWh)
Coefficient of Performance, COP	3
Interest rate, i	3.8%
Inflation rate, f	4%
Lifetime, N	10 years

Table 2. Geographic coordinates of the selected cities in this paper and their annual cooling and heating degree-days [34].

City	Latitude ($°N$)	Longitude ($°E$)	Elevation (m)	CDD (°C-Days)	HDD (°C-Days)
Riyadh	24.9	46.7	612	5688	291
Guriat	31.4	37.3	499	3571	985
Dhahran	26.3	50.2	17	5953	142
Jeddah	21.7	39.2	12	6587	0
Khamis Mushait	18.3	42.8	2054	3390	393

Table 3. Physical properties of the materials of the external wall.

Wall Structure	X (m)	k (W/m.K)	R (m^2.K/W)
Internal plaster	0.02	0.87	0.023
Bricks	0.13	0.45	0.289
External plaster (cement-based)	0.03	1.4	0.021
R_i inside heat transfer coefficients			0.13
R_o outside heat transfer coefficients			0.04
$R_{w,t}$ (Total Resistance)			0.503

Table 4. Insulation wall parameters.

Insulation	k (W/m.K)	Cy (SAR/m^3)
Molded polystyrene	0.034	\$80 * 300
Polyurethane (board)	0.024	200\$ * 750
Rock Wool	0.042	88\$ * 330

* 1 USD = 3.75 SR.

2.4. Selected Cities

According to studies in the literature [37], Saudi Arabia is a large country that has five different climate zones, as seen in Figure 3. Riyadh, the capital city, represents the first zone, which is a hot-dry with a desert subzone, Guriat represents the second zone, which is a cold-dry with a desert subzone, Dhahran represents the third zone, with a hot-dry maritime subzone, Jeddah represents the fourth zone, which is hot-dry with a maritime desert subzone, and Khamis Mushait represents the fifth zone, which is subtropical with a Mediterranean subzone and a mountainous subtype [37].

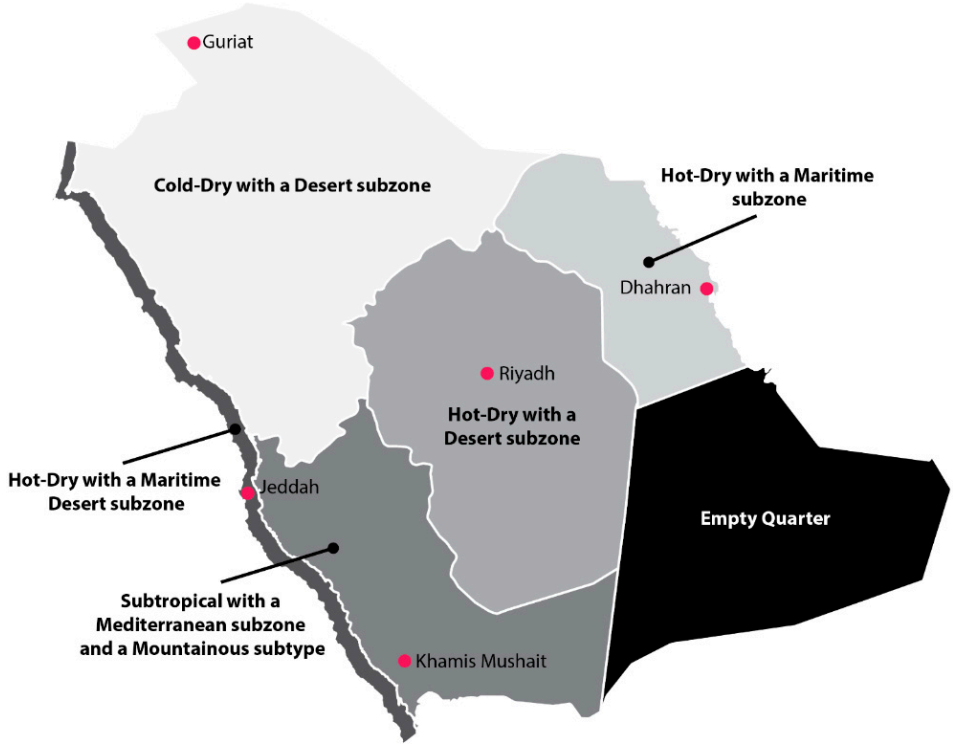


Figure 3. The climatic zones in the Kingdom of Saudi Arabia and selected cities in this study.

Table 2 shows the geographic coordinates of the selected cities in this paper; specific latitude, longitude, and altitude, and their annual cooling and heating degree-days [34]. Jeddah has an extreme case of high cooling demand in Saudi Arabia with zero heating degree days [34]. The five different climate regions are considered cooling-dominated regions, as demonstrated by Alaidroos and Krarti [38]. Their study focused on the impact of various energy efficiency measures on reducing cooling and heating loads.

2.5. Structure of the External Wall

External walls, windows, roofs, floors, and air infiltration are the most common heat loss and gain sources in buildings. One wall structure configuration represents the typical wall structure used in buildings in Saudi Arabia. As illustrated in Figure 4, the selected exterior wall is externally insulated, consisting of a 3 cm external plaster, insulant, 13 cm bricks, and 2 cm internal plaster. Table 3 lists the physical features of the wall's constituents. Only heat gains and losses through the exterior wall are employed in the equations to obtain the optimum insulation thickness. The selected insulation materials are molded polystyrene, polyurethane (board), and rock wool. The thickness of each insulation material in the wall structure is determined by optimization. Additionally, the properties and market costs of the insulation materials are listed in Table 4.

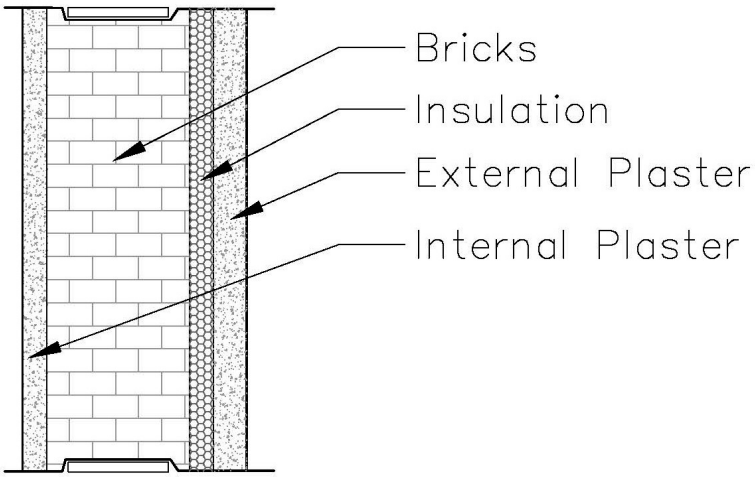


Figure 4. External wall structure [39].

Where C_y is the insulation cost per unit volume (SAR/m^3).

The data presented in Table 4 could be used as a base for comparison in selecting a proper insulation material; however, further investigation is required to find the correlation between the insulation material (Cost + performance) and the energy prices.

2.6. Energy Modeling

Energy modeling was conducted on a simple structure to verify the results in Section 2.3 and potentially substantiate the equation in the previous section. A three-meter by three-meter cube structure was modeled with a wall section typical of Figure 4. The model was intentionally simplified to enable a focused analysis of wall performance while minimizing other influences. The structure was modeled as a stand-alone structure with all surfaces exposed to the outside. Furthermore, a simple HVAC system was defined with a COP of three which was set at a base temperature of 18.3 °C to align the simulation with the CDD/HDD calculation and the base temperature was kept the same as defined for the calculation. Additional building energy parameters were incorporated as defined in previous research for the location [9], including parameters for thermal zoning, occupancy schedules, internal loads, and Domestic Hot Water (DHW) consumption.

The energy simulations were carried out using DesignBuilder (Version 5.5.2), a widely used building performance simulation tool that operates on the EnergyPlus engine. EnergyPlus is a validated and commonly accepted simulation engine known for its accuracy in dynamic thermal modeling. Simulations were conducted for five distinct climatic regions in Saudi Arabia (Figure 3), using corresponding weather files provided by EnergyPlus.

Firstly, the model was calibrated by comparing its simulated EUI with values reported in established energy studies for Dhahran City. The baseline simulation was conducted using EnergyPlus, incorporating local climate data, building characteristics, and operational parameters. The resulting EUI was then benchmarked against peer-reviewed studies to assess the model's accuracy [6,9]. The simulated EUI of 141.4 kWh/m^2/year exhibited a deviation of less than 5% from reported values, which falls within acceptable calibration tolerances. To ensure alignment with empirical data, the model was iteratively refined by adjusting key parameters, including insulation properties, envelope characteristics, occupancy schedules, and internal heat gains, until the deviation fell within the acceptable threshold. The model was most responsive to variations in insulation thickness, highlighting its significant impact on energy performance.

Next, 15 simulations are performed for each location, with five for each insulation type. Simulations were run with the wall section varying based on the insulation type and

thickness (Tables 3 and 4). The insulation thickness varied, with two points above the X_{opt} and two below. To ensure that the simulation results provide only the energy consumption due to solar heat gain through external walls for validation and comparison with the equation results, all other energy-consuming parameters were eliminated, including the occupancy, lighting system, etc. In addition, the heat gain by the roof was also eliminated by setting the insulation R-value of the roof to the maximum. Then, the total net energy was divided by the total surface area of the walls to obtain conduction gain per square meter of wall area. The chosen approach ensures that the impact of only wall insulation materials can be thoroughly analyzed without additional variables influencing the results. This simplification of the energy model is necessary to validate and modify the calculation. However, we acknowledge that in a whole-building energy assessment, accounting for all heat loss mechanisms would be necessary.

3. Results and Discussion

3.1. Simulation and Calculation Results

The annual heat gain through the external wall was calculated for the selected cities by applying the base model explained in Sections 2.1 and 2.2. The obtained results were compared with the annual heat gain determined by the validated energy model to assess the accuracy of the base model. Figures 5–9 show the comparison between the calculated heat gain and the simulated ones. The comparison is confined to the heat gain associated when the X_{opt} for each insulation material and two thicknesses below and above. In general, the calculations overestimate the model heat losses, notably, for thicknesses lower than X_{opt}. Therefore, Equations (8) and (9) need adjustment. A better prediction for the annual heat gain will improve the accuracy of the obtained optimum insulation thickness.

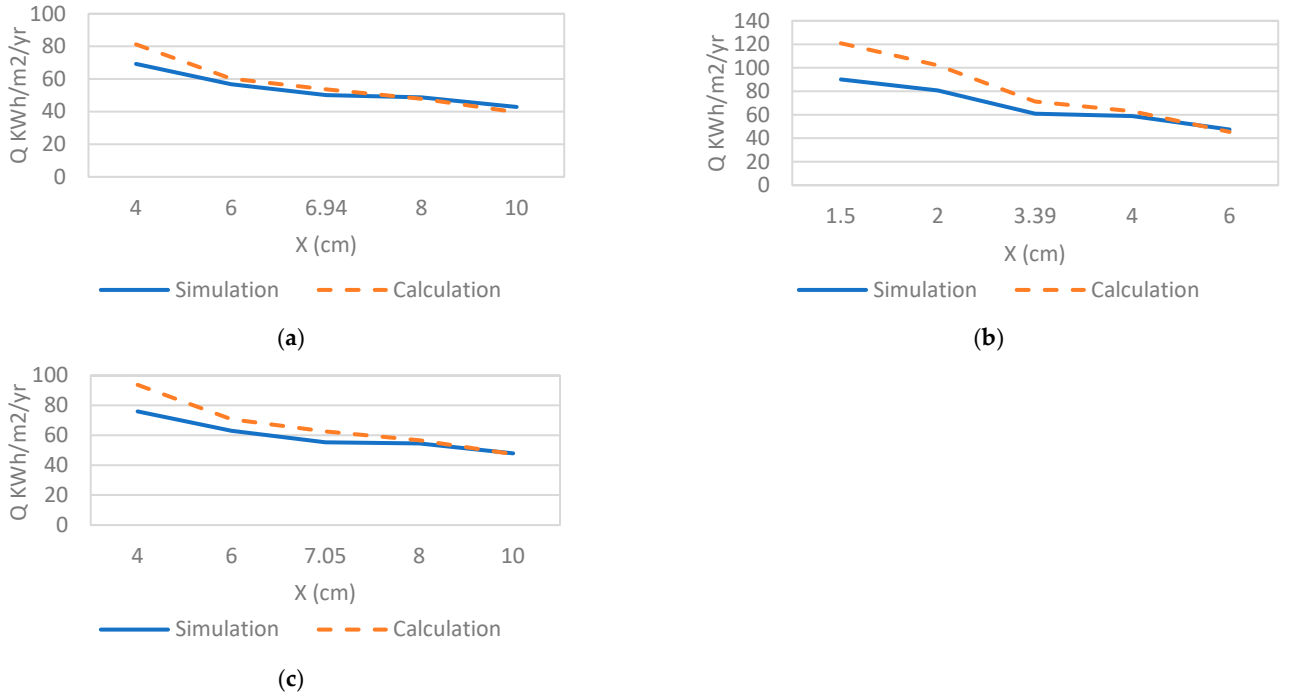
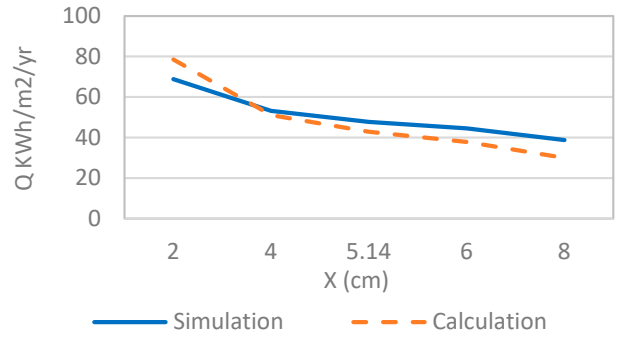
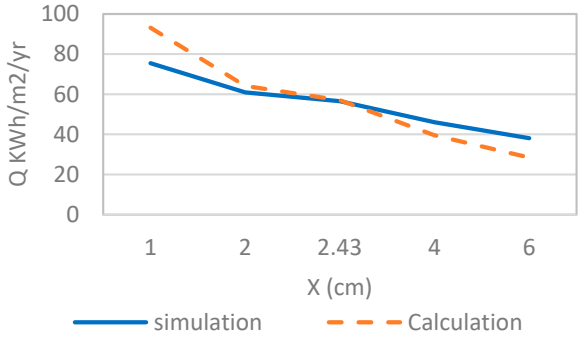


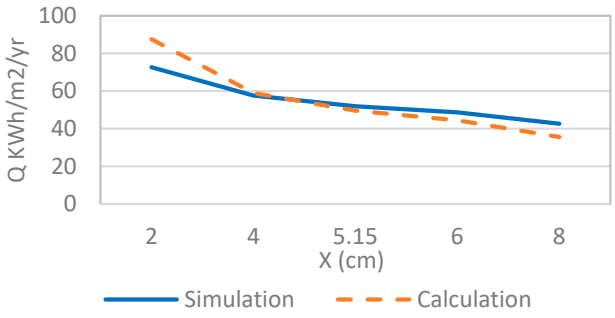
Figure 5. Comparison of calculated and simulated annual heat gain in Riyadh for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.



(**a**)

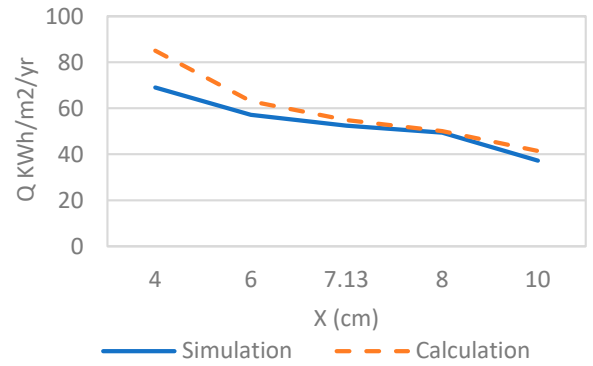


(**b**)

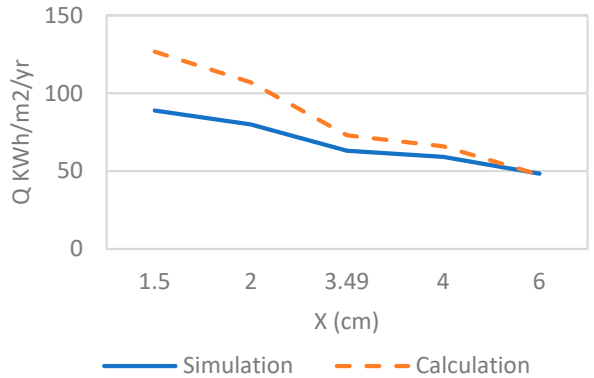


(**c**)

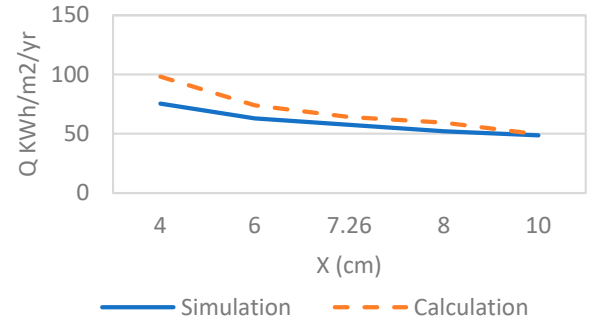
Figure 6. Comparison of calculated and simulated annual heat gain in Guraiat for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.



(**a**)

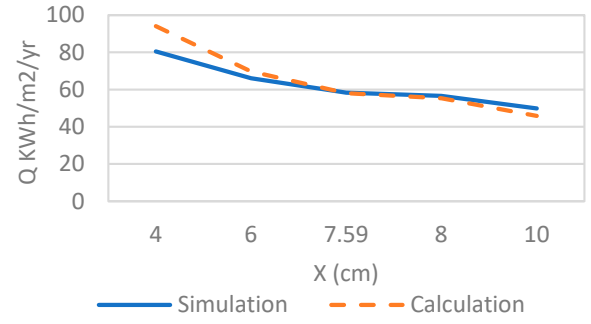


(**b**)

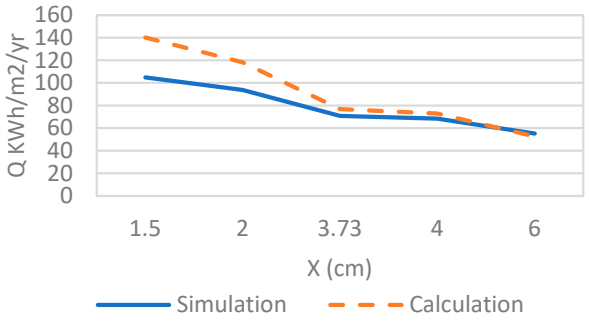


(**c**)

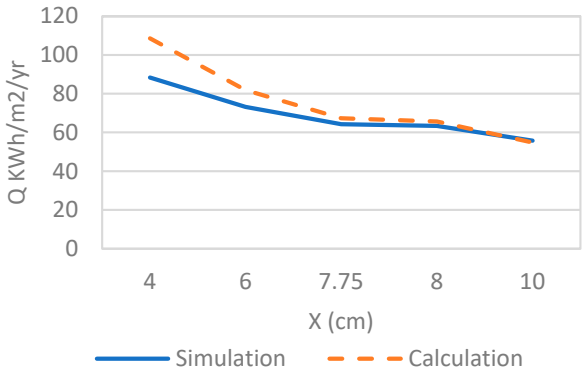
Figure 7. Comparison of calculated and simulated annual heat gain in Dhahran for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.



(**a**)

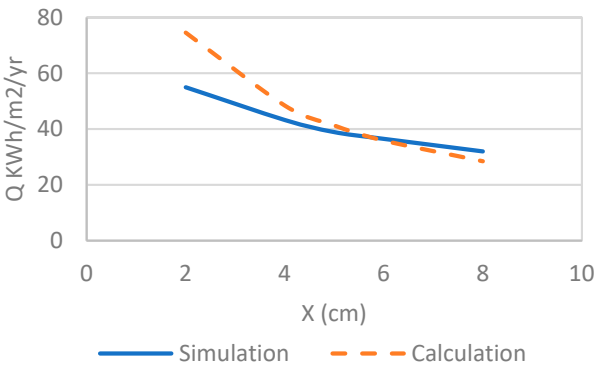


(**b**)

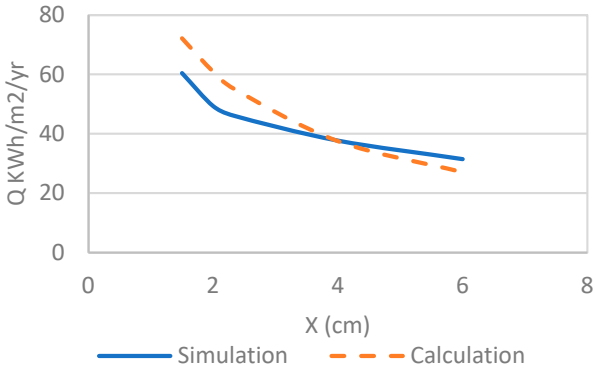


(**c**)

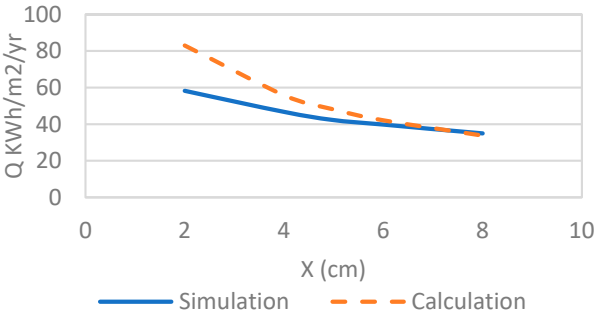
Figure 8. Comparison of calculated and simulated annual heat gain in Jeddah for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.



(**a**)



(**b**)



(**c**)

Figure 9. Comparison of calculated and simulated annual heat gain in Khamis M for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.

3.2. Adjusted Model

The humidity-adjusted annual heat gain/loss, Q_{eff}, in Equation (3) is adjusted by introducing the humidity as a relevant parameter in the following equations.

$$Q_{eff\ (year,c)} = 86,400 \times U \times CDD \times (1 - 0.6\ AH \times \frac{(X_{opt} - X_{ins})}{X_{opt}}) \quad (22)$$

$$Q_{eff(year,h)} = 86,400 \times U \times HDD \times (1 - 0.6\ AH \times \frac{(X_{opt} - X_{ins})}{X_{opt}}) \quad (23)$$

where AH is the average humidity, its values are obtained from Table 5. Although based on sensible heat transfer, the adjusted equations for cooling and heating (Equations (22) and (23)) have been adjusted to account for latent heat effects. This was achieved by integrating the humidity factor through a performance reduction term based on deviation from the optimum insulation thickness (X_{opt}). Humidity can influence the thermal conductivity of insulation materials, particularly in regions with high moisture levels, such as coastal or humid climates. This adjustment aligns with previous findings in building energy studies that emphasize the influence of moisture on insulation properties, particularly for fibrous materials such as rock wool and polystyrene-based products. Studies such as Kaynakli (2012) [3] and Wang et al. (2022) [12] highlight that thermal conductivity increases with moisture content, leading to higher heat transfer through the building envelope. The average annual humidity (AH) was introduced as a correction factor to represent moisture-dependent variations in insulation performance. The term $\frac{(X_{opt} - X_{ins})}{X_{opt}}$ reflects the relative deviation from the optimum insulation thickness, and it is multiplied by the average humidity to model its impact on the insulation's thermal efficiency. This approach assumes that insulation performance degrades proportionally with both increasing humidity and under-insulation. The correction coefficient (0.6) is an empirically derived factor representing the approximate sensitivity of thermal conductivity to average humidity levels for typical insulation materials used in the region. The adjusted heat gain/loss equations for cooling and heating, designated as $Q_{eff\ (year,c)}$ and $Q_{eff\ (year,h)}$, respectively, explicitly reflect the combined effect of temperature and humidity.

Table 5. Monthly humidity values in the five cities.

	Jeddah (%)	**Riyadh (%)**	**Dhahran (%)**	**Guraiat (%)**	**Khamis M. (%)**
January	66	45	68	65	67
February	67	34	63	56	60
March	61	26	48	43	55
April	57	24	45	37	53
May	53	17	33	31	45
June	55	21	29	30	36
July	50	15	31	29	44
August	58	16	43	36	46
September	70	19	48	39	35
October	68	20	58	42	38
November	70	39	62	53	59
December	70	47	68	62	66
AH	62.1	26.9	49.7	43.6	50.3

Using Equations (22) and (23) in calculating the annual heat gain/loss (Model results) gives better results than the simulated results, as shown in Figures 10–14. The suggested equation adjustment considers that the deviation shown in Figures 5–9 obtained mainly with thicknesses lower than X_{opt}.

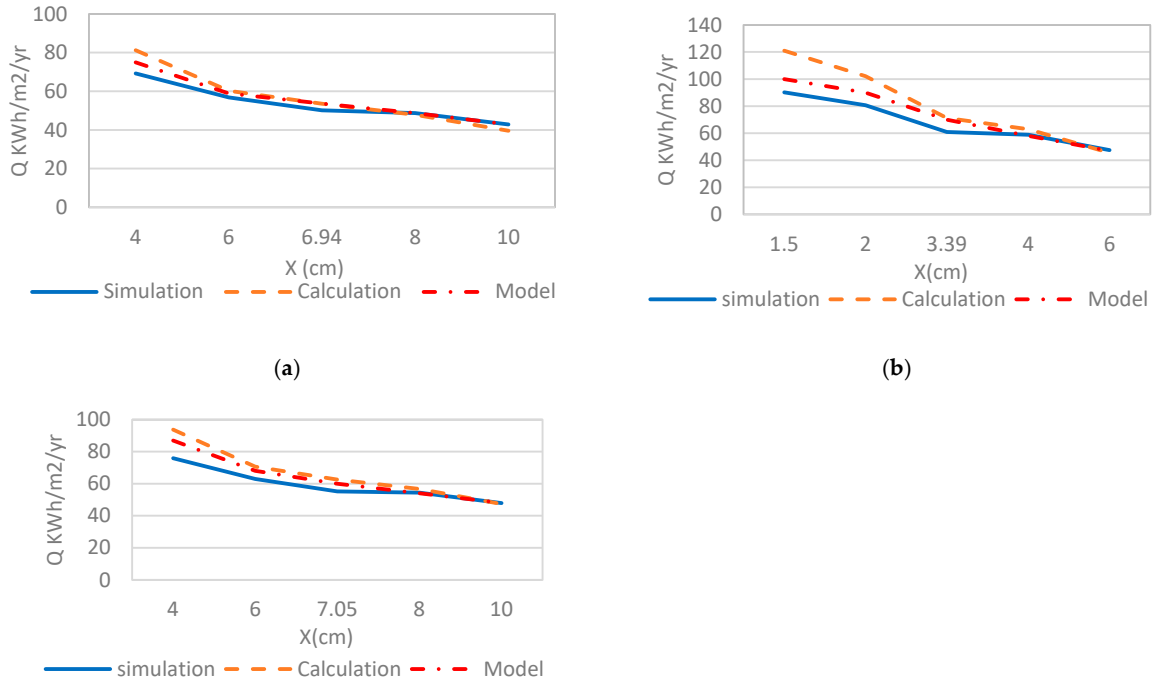


Figure 10. Comparison of calculated, simulated, and modeled annual heat gain in Riyadh for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.

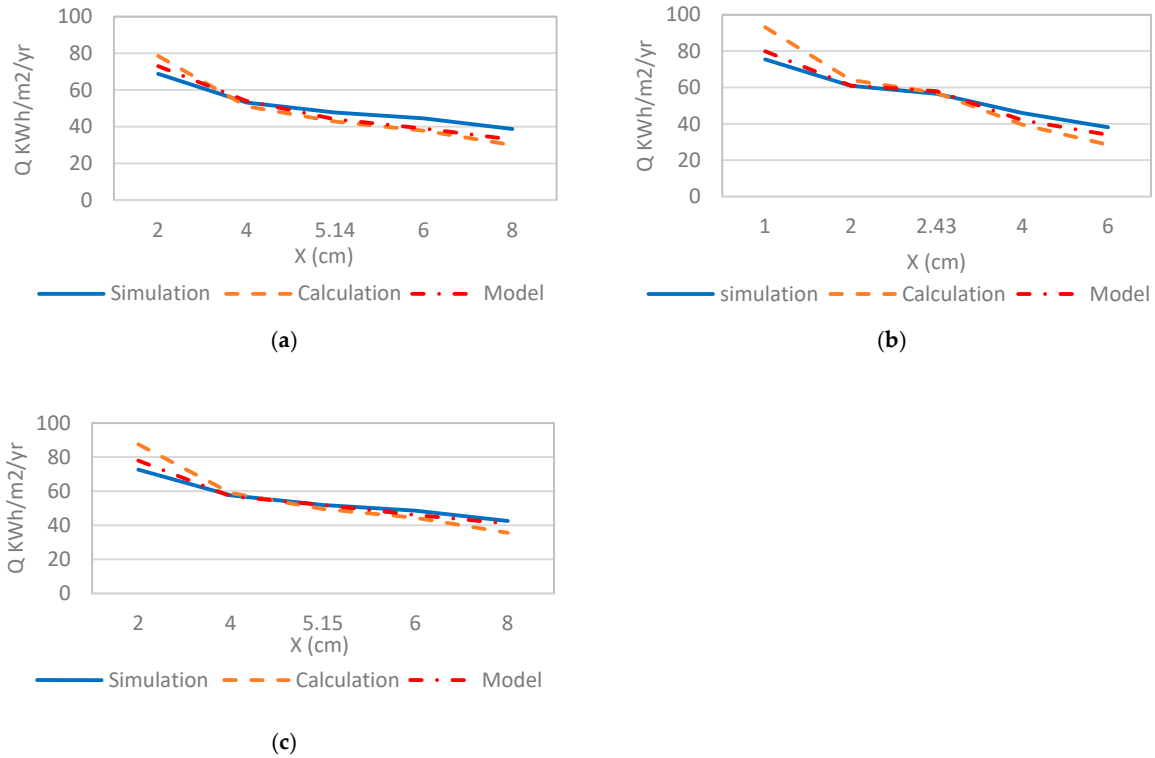
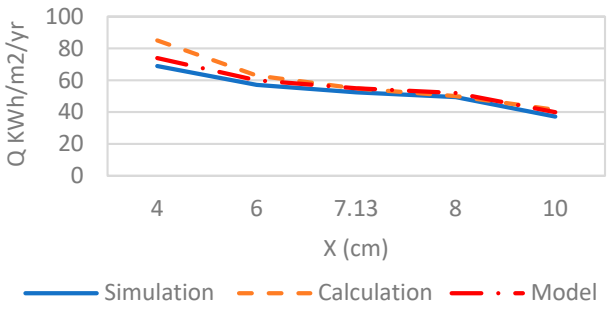
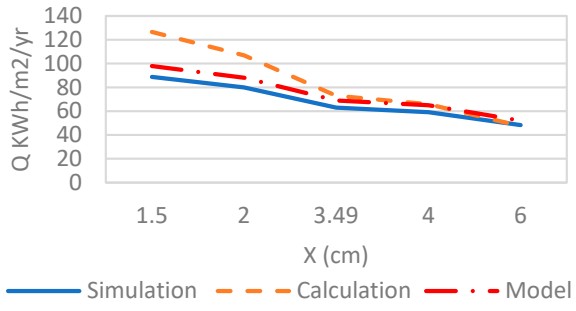


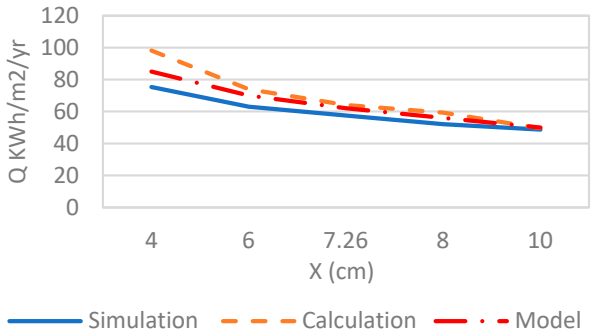
Figure 11. Comparison of calculated, simulated, and modeled annual heat gain in Guraiat for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.



(**a**)

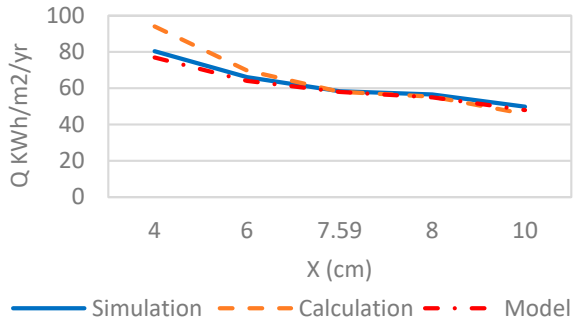


(**b**)

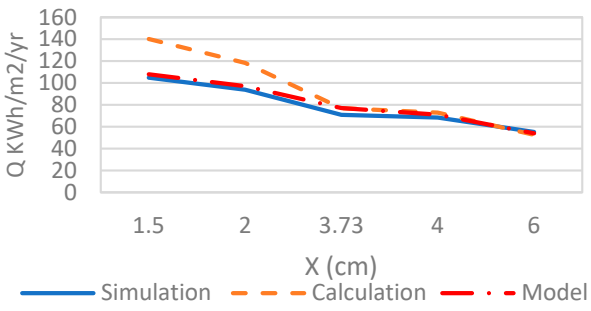


(**c**)

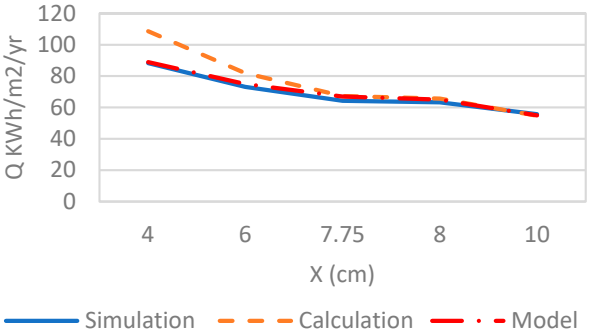
Figure 12. Comparison of calculated, simulated, and modeled annual heat gain in Dhahran for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.



(**a**)



(**b**)



(**c**)

Figure 13. Comparison of calculated, simulated, and modeled annual heat gain in Jeddah for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.

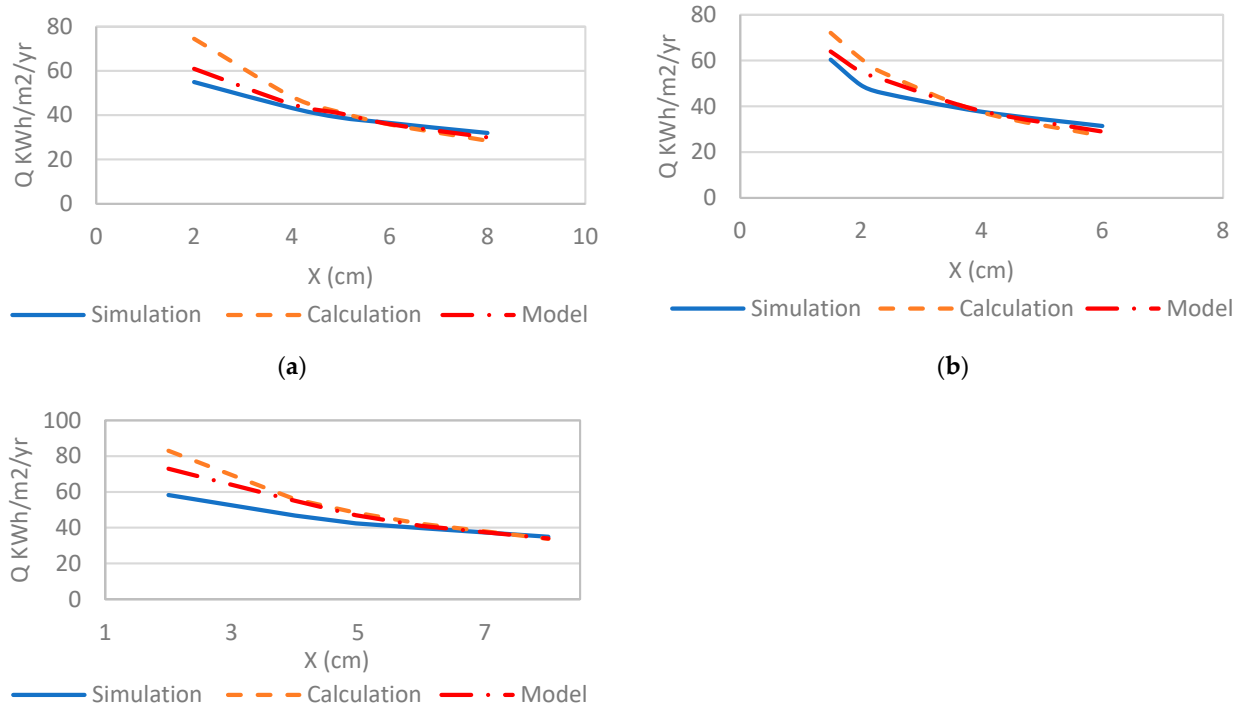


Figure 14. Comparison of calculated, simulated, and modeled annual heat gain in Khamis M. for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.

3.3. Optimal Insulation Thickness Results

Equations (10)–(19) are adjusted based on the suggested correction factor introduced in Equations (22) and (23) to better improved total costs for cooling energy and insulation material. As the insulation thickness (X_{ins}) increases, the annual cost of cooling energy (C_{ac}) decreases. The total cost (C_{tc}) includes both the cost of the electricity and the cost of the insulation material. Furthermore, the insulation cost rises linearly with the thickness of the insulation. The optimum insulation thickness is estimated by determining the thickness corresponding to the lowest overall cost. Figures 15–19 show the change in the insulation cost (C_{ins}), annual cooling energy (C_{ac}), and the total cost (C_{tc}) in the selected five cities for the three insulation materials.

The results show that C_{tc} decreases as X_{ins} increases, but the decrease is abrupt initially and then becomes gradual as X_{ins} increases. As a result, at low X_{ins}, a significant percentage fall in (C_{tc}) can be achieved, and this percentage drop diminishes as X_{ins} increases.

Since the cost of insulation material increases linearly with the thickness while the cost of energy consumption is proportional to annual heat transmission, it is expected that the overall cost initially decreases as X_{ins} increases, then rises as X_{ins} increases more. This behavior indicates the existence of a minimum overall cost that corresponds to an optimal insulation thickness. Based on the insulations' thermal conductivity values, polyurethane has the smallest Q_{year} for a given X_{ins}, followed by polystyrene and finally rock wool. The same trends can be seen in [33] for Riyadh and Jeddah.

As shown, all curves yield minimum values reflecting minimum total costs ($C_{t,min}$) for each insulation material, which correspond to optimum insulation thicknesses (X_{opt}). The optimum thicknesses, corresponding payback periods, and minimum total cost values for all types of insulations and climate conditions are summarized in Table 6. Polystyrene has the lowest $C_{t,min}$, rock wool, polyurethane with the highest $C_{t,min,}$ and least X_{opt}. Polystyrene

is the most economical insulation, according to $C_{t,min}$. These results are consistent with other work [33].

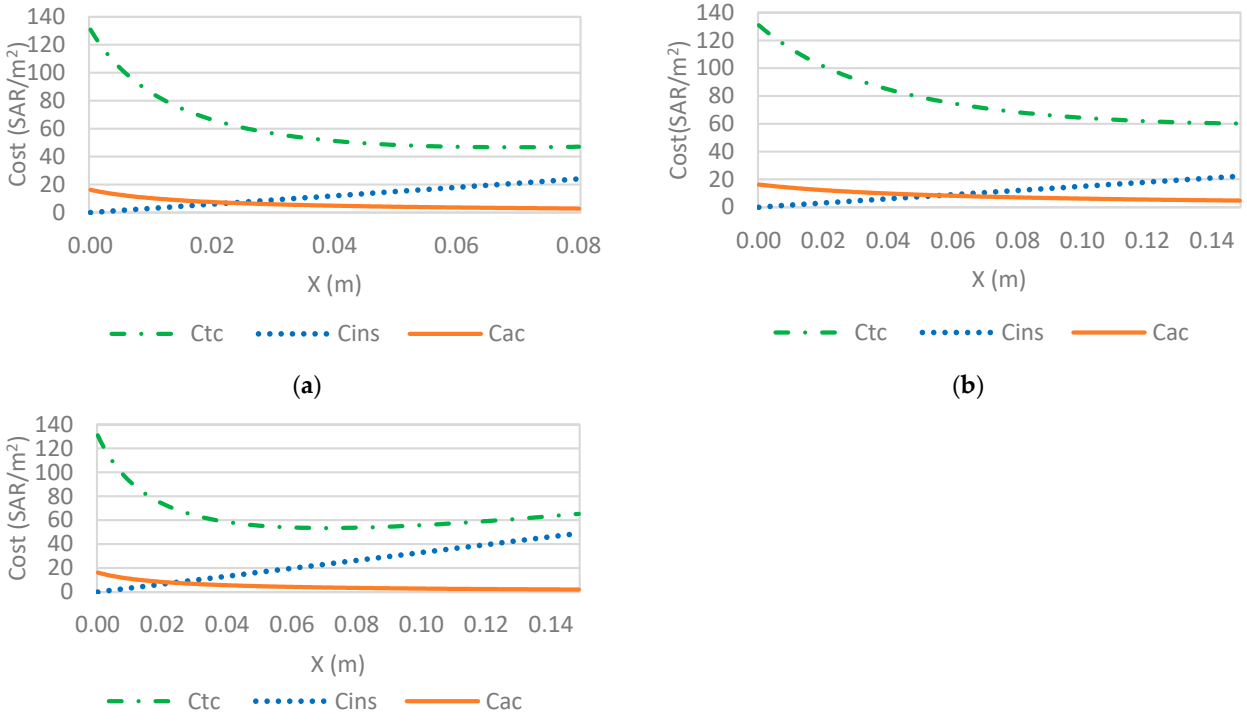


Figure 15. Relationship between insulation cost, annual cooling energy, and total cost in Riyadh for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.

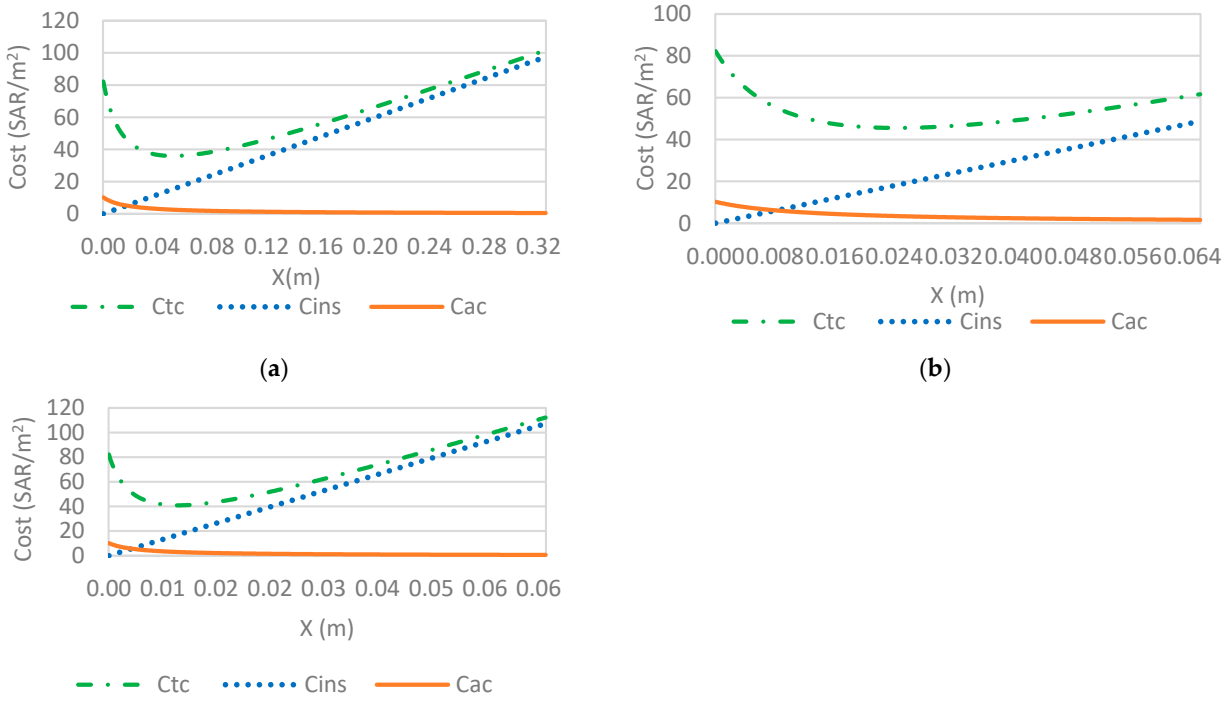


Figure 16. Relationship between insulation cost, annual cooling energy, and total cost in Guraiat for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.

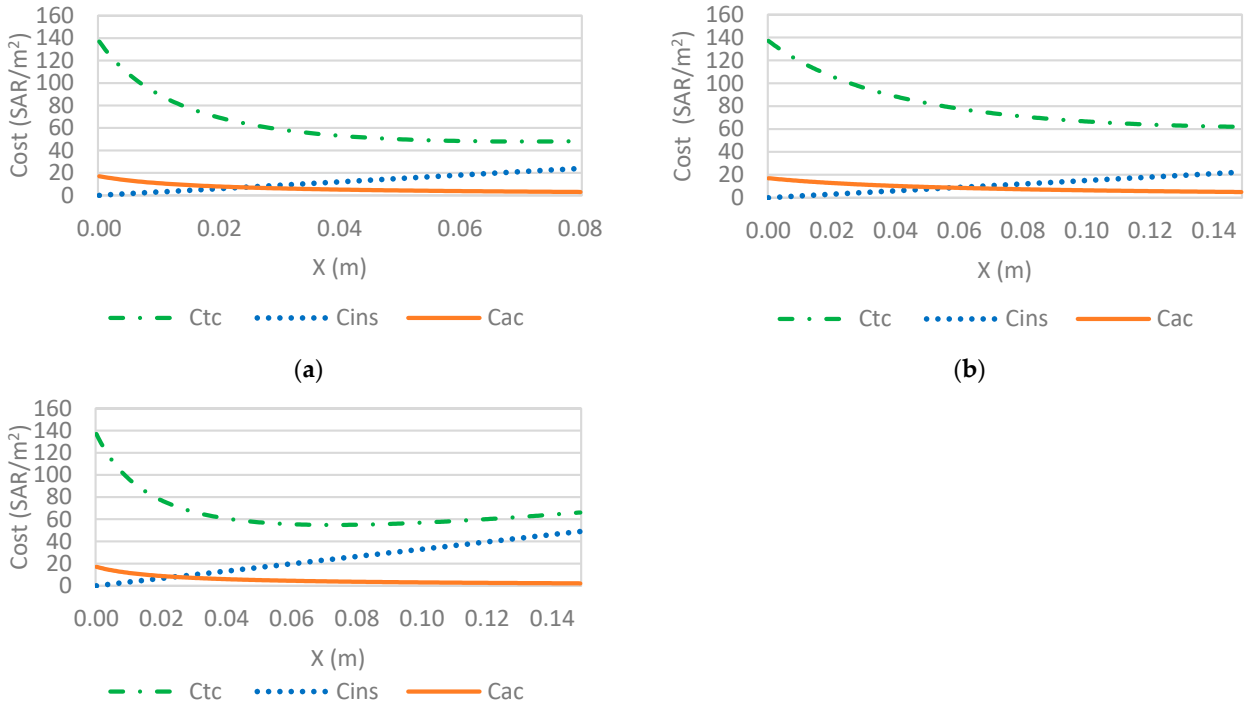


Figure 17. Relationship between insulation cost, annual cooling energy, and total cost in Dhahran for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.

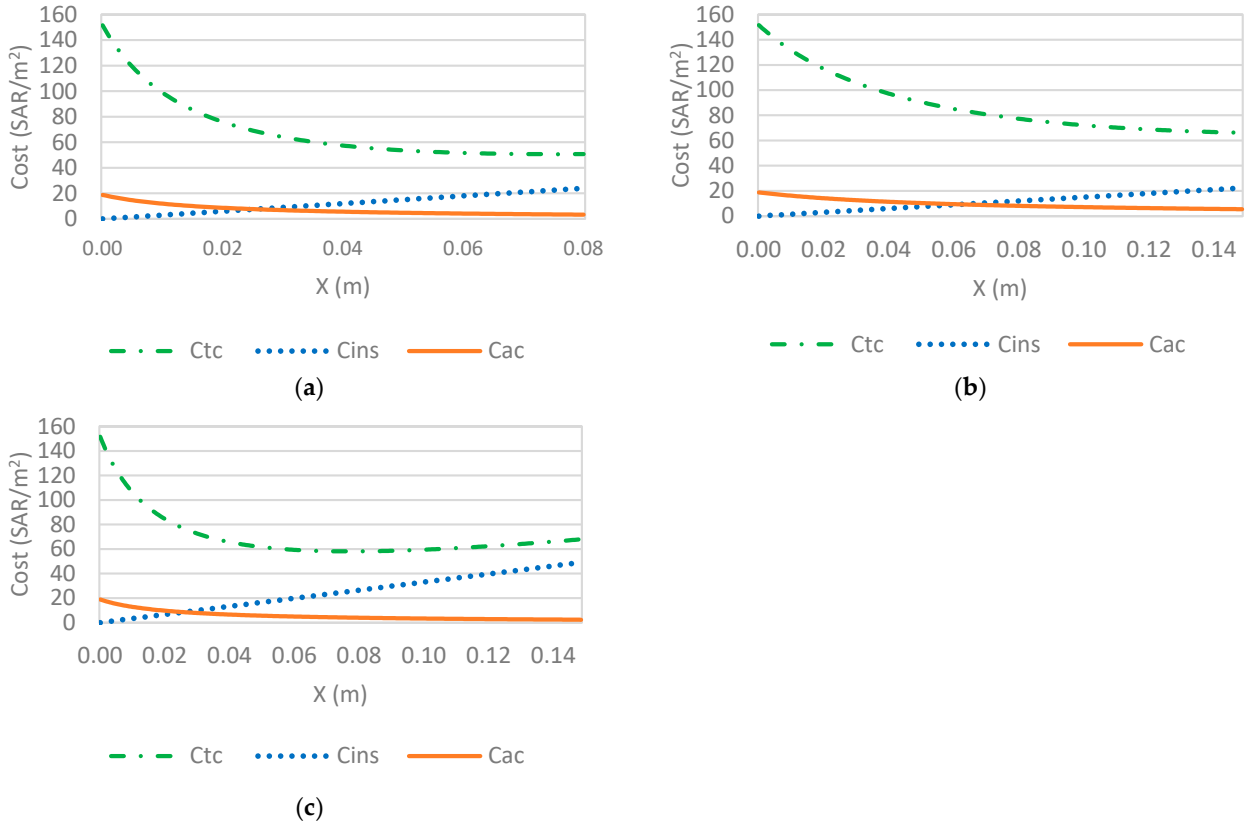


Figure 18. Relationship between insulation cost, annual cooling energy, and total cost in Jeddah for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.

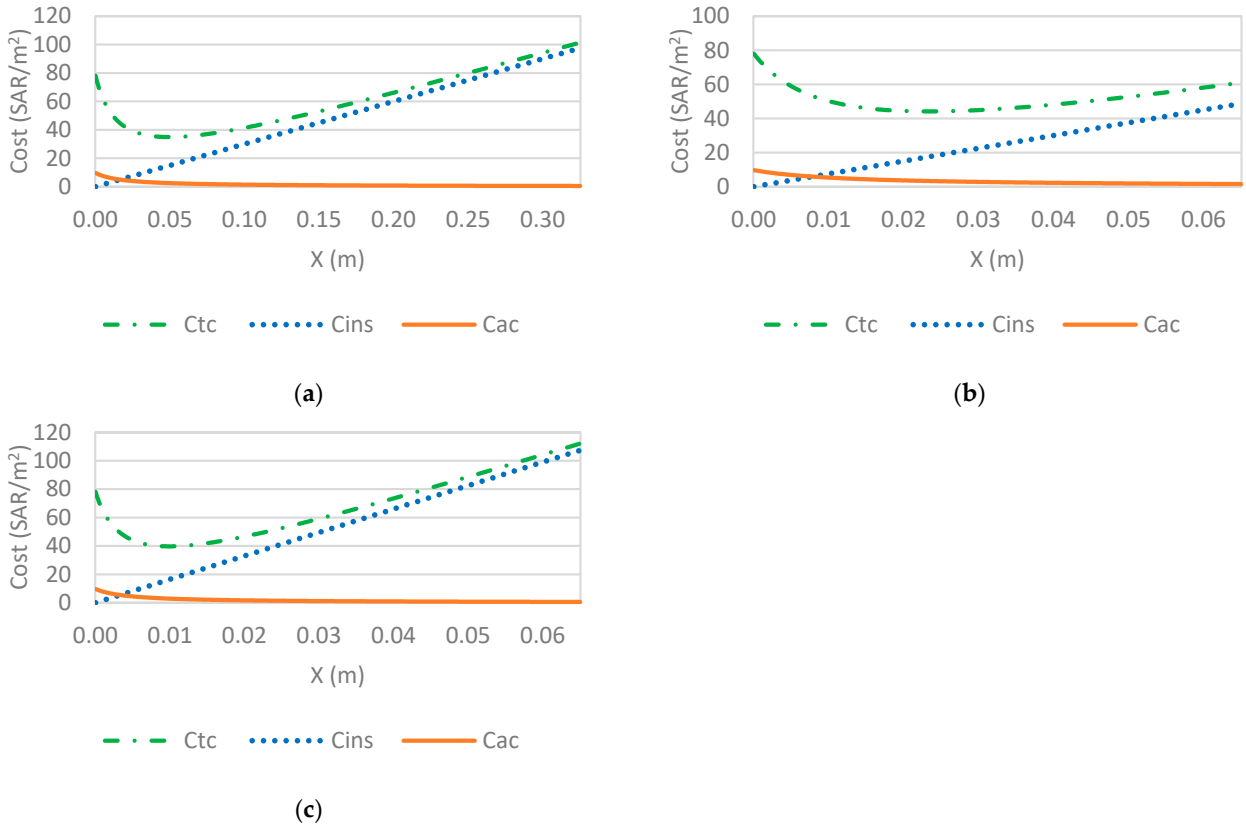


Figure 19. Relationship between insulation cost, annual cooling energy, and total cost in Khamis M. for different insulation materials: (**a**) molded polystyrene; (**b**) polyurethane; (**c**) rock wool.

Table 6. Overview of findings for molded polystyrene (MP), polyurethane board (PB), and rock wool (RW) across five different climate conditions.

City	Insulation	$C_{t,min}$ (SAR/m^2)	*PP* (Year)	X_{opt} (cm)	R_{opt} (m^2.K/W)	U_{opt} (W/m^2.K)
Khamis M. (CDD = 3390 °C-day)	MP	34.89	2.06	4.96	1.46	0.69
	PB	44.12	2.74	2.34	0.98	1.03
	RW	39.69	2.4	4.96	1.18	0.85
Guriat (CDD = 3571 °C-day)	MP	35.95	2.01	5.14	1.51	0.66
	PB	45.52	2.65	2.43	1.01	0.99
	RW	40.92	2.34	5.15	1.23	0.82
Riyadh (CDD = 5688 °C-day)	MP	46.72	1.6	6.94	2.04	0.49
	PB	59.82	2.12	3.39	1.41	0.71
	RW	53.47	2.86	7.05	1.68	0.60
Dhahran (CDD = 5953 °C-day)	MP	47.91	1.63	7.13	2.10	0.48
	PB	61.41	2.07	3.5	1.46	0.69
	RW	54.86	1.8	7.2	1.71	0.58
Jeddah. (CDD = 6587 °C-day)	MP	50.66	1.48	7.59	2.23	0.45
	PB	65.07	1.97	3.74	1.56	0.64
	RW	58.07	1.73	7.75	1.85	0.54

It is worth noting that the total cost includes the cost of insulation material as well as the cost of energy used due to cooling and heating loads. Associated costs, such as

installation expenses, are not considered. These charges can be applied to the net cost without affecting X_{opt}. Furthermore, the results presented in Table 6 illustrate the impact of climatic conditions on the optimal R-value and U-value for various insulation materials. As expected, cities with higher Cooling Degree Days (CDDs), such as Jeddah and Dhahran, exhibit higher optimal R-values and lower U-values, indicating the necessity for thicker insulation to mitigate cooling loads effectively. For instance, in Jeddah, the highest cooling demand location molded polystyrene (MP) achieves an R-value of 2.23 m^2K/W with a corresponding U-value of 0.45 W/m^2K, which is below the SBC 601 and SBC 602 maximum U-value requirements [40]. Conversely, locations with lower cooling demands, such as Khamis Mushait and Guriat, require thinner insulation, resulting in relatively higher U-values. The results emphasize that a uniform insulation requirement, as prescribed by SBC, does not account for climatic variations and may lead to suboptimal energy savings. Our findings demonstrate the necessity of climate-responsive insulation strategies to enhance energy efficiency while considering economic feasibility

It should be stated that the payback period values are not mere values since inflation and the cost of money are considered. The payback period was determined using the same analysis, representing the number of years it takes for the initial insulation cost to be offset by energy savings. The payback period increases with X_{ins} almost linearly. For Dhahran, Polystyrene and rock wool yield similar results, but polyurethane has a much more extended payback period due to its higher price. The molded polystyrene yields the shortest payback period in all cities due to its low cost and relatively low conductivity, as shown in Table 6. The noticed short payback period in all cities and insulation materials significantly promotes insulation use. Riyadh, Dhahran, and Jeddah have close results because the climate in the three cities is cooling-dominated with relatively similar CDD.

On the other hand, Guriat and Khamis M. yield almost the same payback period for each insulation material. Payback period values are similar to other studies [41]. Although polyurethane has the best conductivity performance, its high cost resulted in the highest $C_{t,c}$ in the five cities, which emphasizes the importance of considering both performance and economic factors.

A comparative analysis with a previous study [33] reveals shorter payback periods and adjusted optimal insulation thickness values in the present work. These improvements are attributed to updated economic parameters, enhanced optimization methodology, and refined consideration of climatic influences. The differences underscore the necessity of periodic updates to insulation strategies to account for evolving climatic and economic conditions, particularly in rapidly urbanizing regions like Riyadh and Jeddah.

4. Conclusions

Energy conservation is increasingly important in countries where energy consumption is increasing astronomically, such as Saudi Arabia. This paper presents a novel method for optimizing external wall insulation, considering performance and economic factors. As a case study, the suggested method was implemented with different insulation materials for the five climatic zones of Saudi Arabia represented by five cities: Riyadh, Jeddah, Dhahran, Guriat, and Khamis Mushait. The cost of insulation materials and electricity in KSA and economic conditions representing the country's economy are used. A single-layer wall made of bricks is considered. In addition, the three commonly used insulation materials considered for this study are molded polystyrene, polyurethane board, and rock wool. Thermal and economic analyses are carried out for the base model to determine the annual heat gain and X_{opt} for each insulation material. The thermal heat gain was determined based on the cooling degree day's concept, and it was validated and adjusted based on an energy simulation, while the economic analysis is based on the net present value method.

Based on the comparison with the energy simulation results, the model was adjusted by introducing a correction factor based on the average humidity in each city. The modified model resulted in a better estimation of the annual heat gain, X_{opt}, and payback periods. The results show that the insulation of residential buildings in Saudi Arabia is economically feasible and should be implemented as it will provide higher rates of comfort accompanied by lower air conditioning energy costs.

The main results are summarized as follows:

1. In all the climatic zones, yearly cooling loads dominate over yearly heating loads. However, heating is absent for Jeddah, while yearly cooling loads are the highest;
2. The annual cooling loads proposed in the method are benchmarked against energy simulation;
3. Polystyrene gives the lowest total cost ($C_{t,min}$) followed by rock wool and polyurethane for all climates. Therefore, polystyrene is the most economical insulation with the shortest payback period. In addition, polyurethane has the lowest thickness among the insulation materials in the five zones;
4. The optimal insulation values using molded polystyrene (MP), polyurethane board (PB), and rock wool (RW) as insulation materials were obtained for the five climatic zones of Saudi Arabia. The values of Riyadh, Jeddah, and Dhahran range between 3 and 8 cm, while Guriat and Khamis Mushait, with a moderate climate (i.e., low CDD), range between 2 and 5.5 cm;
5. $C_{t,min}$, and X_{opt} values for Dhahran and Riyadh are very close; those for Guriat and Khamis Mushait are almost equal and much smaller. Therefore, the moderate climate of Guriat and Khamis Mushait is much more cost-effective regarding energy consumption;
6. Payback periods calculated at X_{opt}, considering inflation and cost of money, range from about 1 to 3 years, reflecting the high feasibility of applying thermal insulation;
7. The study's findings highlight the significant impact of climatic conditions on the optimal insulation thickness and the corresponding thermal performance metrics, R-value, and U-value. Unlike the Saudi Building Code (SBC 601 and SBC 602), which sets a single standard for maximum U-values and minimum R-values across all regions, our results demonstrate the need for climate-adaptive insulation strategies. The optimal insulation thickness varies considerably between cities, with locations experiencing higher cooling demand requiring thicker insulation to achieve lower U-values. These findings reinforce the necessity of incorporating both economic and climatic considerations when establishing insulation guidelines, ensuring energy-efficient and cost-effective building envelope designs tailored to specific regional conditions. This study provides a more precise methodology for determining the most effective insulation thickness, leading to enhanced energy savings and improved thermal performance in desert climates;
8. The effects of thermal bridging, external air film, shading effects, oversimplified thermal boundary conditions, thermal mass, and thermal lag were not explicitly considered in the optimization process. Additionally, the integration of other passive cooling strategies, such as shading devices, natural night ventilation, and roof overhangs, was beyond the scope of this study but holds significant potential for enhancing cooling efficiency. Future research should incorporate these parameters alongside insulation optimization for a more comprehensive evaluation of building energy performance, particularly under dynamic thermal conditions where these factors significantly impact heat transfer and overall energy savings.

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Nomenclature

C	Cost (SAR)
C_y	Cost of insulation (SAR/m^3)
C_e	Cost of electricity (SAR/kWh)
$C_{A,C}$	Annual cost of consumed energy (SAR/m^2)
C_C	Pre-insulation cooling energy cost (SAR/m^2)
C_t	Total cost of consumed energy and insulation costs (SAR/m^2)
COP	Coefficient of performance of HVAC system (Dimensionless)
η	Efficiency of the combustion system (Dimensionless)
Q_{year}	Annual heat loss and gain (kWh/m^2)
$Q_{eff\ (year)}$	Humidity-adjusted annual heat loss and gain
E_{year}	Annual cooling energy (kWh/m^2)
k	Thermal conductivity (W/m.K)
R	Thermal resistance (K.m^2/W)
R_{opt}	Thermal resistance for the optimum insulation thickness (m^2.K/W)
U	Over all heat transfer coefficient (W/m^2.K)
U_{opt}	Overall heat transfer coefficient for the optimum insulation thickness (W/m^2.K)
X	Layer thickness (m)
X_{ins}	Insulation thickness (m)
N	Building lifetime (years)
PP	Payback period (years)
X_{opt}	Optimum insulation thickness (m)
R_W	Wall layers heat transfer resistance (K.m^2/W)
R_o, R_i	Heat transfer coefficients of the outside and inside environments (K.m^2/W)
PVF	Present Value Factor (dimensionless)
q_{year}	Yearly transmission load (kWh/m^2.yr)
q	Heat transfer rate (W/m^2)
i, f	Interest and inflation rates (%)
r	Actual interest rate
SAR	Saudi Riyal (1 US dollar = 3.75 SAR)
T	Temperature (°C)

CDD	Cooling Degree Days (°C-day)
HDD	Heating Degree Days (°C-day)
$A_{year,C}$	Annual total net savings for cooling buildings (SAR/m^2)
T_o	Daily mean outdoor air temperature (°C)
T_b	Base temperature (°C)
AH	Average annual humidity (%)

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