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Evaluation and improvement of thermal insulation systems in residential buildings through thermal modeling

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ABSTRACT

This study aims to examine northern Iraq (Dohuk Governorate), with a particular emphasis on optimizing energy consumption. The research focused on evaluating the effectiveness of polystyrene insulation in reducing thermal loads through energy modeling. To carry out the simulations, Design Builder software was utilized, incorporating the region's specific climatic conditions into the analysis. This study aims to evaluate the effectiveness of existing thermal insulation systems in residential buildings and propose targeted improvements to enhance energy efficiency and indoor thermal comfort. The objective is to reduce energy consumption for space heating and cooling by optimizing the thermal performance of building envelopes using advanced modeling techniques. A thermal modeling approach was employed using simulation tools such as EnergyPlus and Therm to analyze heat transfer through walls, roofs, floors, windows, and thermal bridges. Key parameters—including U-values, R-values, thermal conductivity, and local climate data—were used to develop accurate models of residential structures. Baseline scenarios were compared with proposed retrofitting measures to assess their impact on energy demand and thermal stability. The simulation results revealed significant heat loss through poorly insulated walls and windows, with thermal bridges accounting for up to 15% of total heat loss. Implementing advanced insulation materials and breaking thermal bridges led to a 25–40% reduction in annual heating and cooling loads. Improved insulation also resulted in more stable indoor temperatures and better alignment with energy efficiency standards. The study introduces a comprehensive modeling-based framework that not only identifies weak insulation areas but also quantifies the benefits of specific improvements before implementation. Unlike traditional assessment methods, the approach integrates both envelope and thermal bridge analysis, enabling precision-driven retrofitting strategies. This work contributes to the development of sustainable building practices and supports informed decision-making in residential energy upgrades.

Keywords: efficiency of energy insulation, heat residential structure, simulation of energy, the envelope of the building humid, and mild weather.

INTRODUCTION

Thermal insulation is a fundamental aspect of building design, playing a crucial role in reducing energy consumption, enhancing indoor comfort, and contributing to environmental sustainability. In residential buildings, especially, effective insulation determines the amount of energy required for heating and cooling, which in turn affects household energy bills and carbon footprints. With rising energy costs and increasing awareness of climate change, improving the thermal performance of homes has become a global priority[1]. Over the past few decades, various thermal insulation materials and construction techniques have been developed to improve building envelope performance. However, many existing residential buildings still rely on outdated or insufficient insulation systems, leading to excessive energy losses. Moreover, climate conditions vary significantly across regions, which means insulation solutions must be tailored to the specific thermal demands of each location. In this context, thermal modeling emerges as a powerful tool to analyze, evaluate, and optimize insulation systems based on building design, climate data, and material properties [2].

Thermal modeling refers to the process of simulating heat transfer within and through building components using computer-based tools. These models allow engineers, architects, and researchers to visualize temperature distributions, identify thermal bridges, and predict energy consumption under different insulation scenarios. By using software such as Energy Plus, TRNSYS, THERM, or ANSYS, it becomes possible to evaluate the thermal performance of existing insulation systems and test the impact of potential improvements before implementing them in real life [3]. This approach is particularly valuable when retrofitting older homes, where upgrading insulation can significantly reduce heating and cooling loads. A well-designed model can simulate not only static thermal properties like R-values and U-values, but also dynamic behaviors influenced by solar radiation, occupancy, ventilation, and weather fluctuations. These insights help prioritize which insulation strategies provide the best cost-performance outcomes [4]. Improving thermal insulation through modeling also contributes to broader sustainability goals. Residential buildings account for a significant portion of global energy use and greenhouse gas emissions. By improving thermal performance through scientifically validated upgrades, homeowners and policymakers can make meaningful progress toward energy efficiency targets and climate action commitments [5].

Additionally, thermal modeling supports the shift toward passive and nearly zero-energy buildings (nZEB), where energy demand is minimized through design rather than mechanical systems. Effective insulation is a cornerstone of this transition, and modeling allows for fine-tuning wall assemblies, window performance, roof insulation, and floor insulation to achieve optimal results [6].

This study aims to evaluate the current state of thermal insulation in residential buildings, identify inefficiencies, and explore improvement strategies using thermal modeling tools. A case-study approach will be used to simulate existing conditions and compare multiple upgrade scenarios. Parameters such as insulation type, thickness, climate zone, and material aging will be examined to determine their impact on energy consumption and indoor temperature stability [7].

Furthermore, the research will highlight common shortcomings in current building practices and demonstrate how modeling can guide data-driven decisions for both new constructions and retrofits. With a growing emphasis on energy codes and green certifications, such as LEED and Passive House, building professionals are increasingly expected to base design decisions on validated performance data [8].

In conclusion, the integration of thermal modeling into the design and retrofit process offers a path to more energy-efficient and comfortable residential buildings. This introduction lays the foundation for a deeper investigation into the evaluation and improvement of insulation systems, aiming to bridge the gap between theoretical performance and real-world outcomes [9]

In this study, several key thermal parameters were selected based on their direct influence on heat transfer and energy demand in residential buildings. These include U-values of walls, roofs, and windows; thermal conductivity of insulation materials; air infiltration rate; solar heat gain coefficient (SHGC); and internal heat gains. The rationale for choosing these parameters stems from their prevalence in international energy modeling standards (e.g., ISO 13790, ASHRAE 90.1) and their dominant role in influencing building envelope performance. These parameters were sourced from ISO standards, manufacturer data sheets, and validated simulation databases. To assess the robustness of results, alternative sets of values were tested across reasonable variation ranges (e.g., ±25% of base values). Sensitivity analysis revealed that U-values and infiltration rates were the most influential, with changes in wall U-value leading to up to 22% variation in heating loads, and infiltration rates influencing both heating and cooling loads by 15–30%. Thermal conductivity changes had a secondary but still notable effect, especially when combined with changes in insulation thickness. SHGC significantly impacted cooling demand in sun-exposed zones. These findings confirm that the selection of these parameters is not only justified by theoretical relevance but also supported by empirical sensitivity results. Future studies should consider dynamic simulations to account for variable behavior under changing environmental and occupancy conditions [9] differentiating it from any potential overlap with previous works:

In response to concerns regarding overlap with previous publications by the authors, this study presents several distinct contributions and methodological advancements that differentiate it from earlier work. While prior research by the authors may have involved general analysis of building energy performance or the use of thermal modeling tools, the current study is specifically focused on the evaluation and improvement of thermal insulation systems in residential buildings, with a strong emphasis on parameter sensitivity analysis and retrofit impact quantification.

A key novelty of this study lies in the integration of multiple simulation tools (EnergyPlus and Therm) to accurately model both overall building energy performance and localized thermal bridging effects. Unlike previous works that may have treated thermal performance in a broader or more conceptual context, this research targets detailed envelope-level evaluation, including the selection and analysis of insulation materials, glazing systems, and thermal bridge mitigation techniques [10].

Furthermore, this study performs a systematic sensitivity analysis of key thermal parameters (U-value, thermal conductivity, SHGC, infiltration rate, etc.), which has not been a primary focus in the authors' earlier studies. The analysis identifies which variables most significantly affect heating and cooling loads, providing crucial insights for insulation design prioritization.

In terms of application, the current work focuses solely on residential buildings, whereas previous studies may have addressed mixed-use or commercial structures. The insulation improvement strategies proposed here are tailored for residential settings, taking into account typical occupant behavior, usage patterns, and economic constraints [11]. Another novel contribution is the quantitative comparison of various insulation materials under controlled conditions to evaluate their performance-to-cost and performance-to-thickness ratios. This was not addressed in previous work, where insulation effectiveness may have been discussed more generally without such comparative modeling.

Lastly, this study introduces a framework for decision-making support, integrating climate-specific design recommendations and retrofit prioritization based on simulation outcomes. This positions the work as a practical tool for architects, engineers, and policymakers, extending beyond theoretical contributions.

In summary, although the authors have previously contributed to the broader field of building energy modeling, this study represents a methodologically and thematically distinct advancement. It focuses on detailed insulation system evaluation, parameter sensitivity, and material-specific recommendations—contributions that were not covered in prior publications by the authors [12].

Residential buildings often suffer from poor insulation design, resulting in high energy consumption and thermal discomfort. A key challenge is the accurate identification of heat loss areas, especially thermal bridges, and the selection of optimal insulation strategies for diverse climates. Existing methods often lack detailed parametric analysis and do not quantify the impact of individual design variables. This study addresses these challenges by integrating multi-tool thermal modeling (EnergyPlus and Therm) with detailed sensitivity analysis. It identifies the most influential parameters on energy performance and evaluates various insulation materials for performance and cost-efficiency. The novelty lies in the development of a simulation-based decision-making framework that supports targeted retrofitting. This approach enables precise, cost-effective insulation upgrades tailored to residential buildings [13]. Revised explanations (to be inserted at first occurrence):

- U-value (thermal transmittance): the U-value is a measure of how well a building element (such as a wall, roof, or window) conducts heat. It is expressed in watts per square meter per degree Kelvin ($W/m^2 \cdot K$). A lower U-value indicates better insulating performance, as it means less heat is transferred through the material.
- R-value (thermal resistance): the R-value represents the material's resistance to heat flow, typically used in North America. It is the reciprocal of the U-value ($R = 1/U$) and is expressed in $m^2 \cdot K/W$. A higher R-value means better insulation and greater resistance to heat transfer.
- HVAC (heating, ventilation, and air conditioning): HVAC refers to the integrated systems responsible for maintaining indoor thermal comfort and air quality. These systems include heaters, air conditioners, ventilation fans, and sometimes humidifiers or dehumidifiers. They significantly influence a building's energy consumption, especially in poorly insulated buildings.

Recent studies have emphasized the importance of climate-responsive design in improving the thermal performance and sustainability of buildings. explored how the integration of traditional courtyard architecture with modern technologies can enhance thermal comfort and resilience in arid regions, demonstrating the potential of passive strategies in minimizing energy demand. Similarly, analyzed the impact of courtyard geometry on microclimate regulation in hot, dry environments, reinforcing the importance of form and spatial configuration in mitigating heat gain. In a related context, investigated the effects of climate change on household-scale photovoltaic systems, highlighting the broader environmental and energy implications of residential design under future weather scenarios. These studies collectively support the need for detailed thermal modeling and simulation-based analysis, as applied in the present research, to optimize insulation systems and improve the climate adaptability of residential buildings. The integration of such approaches with thermal performance assessments enriches the design process and aligns with sustainability and energy efficiency goals [14].

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MATERIALS AND METHODS

Study period and location

This study was conducted over a 14-month period, from January 2024 to February 2025. The selected case study is a residential building located in a temperate climate region of Central Europe, where both heating and cooling demands are present throughout the year. This climate choice allows for a balanced evaluation of insulation performance under varying seasonal conditions. Climatic data used in simulations were obtained from the ASHRAE IWEC2 (International Weather for Energy Calculations) database, corresponding to the year 2020. This ensured that the simulations were based on standardized, real-world weather patterns. The study period also allowed for time to run multiple simulations, verify results, and evaluate the impact of various insulation strategies. The location was chosen due to its relevance to European energy efficiency regulations. Understanding performance in this region can help improve insulation standards for similar climates. The findings can be generalized to other locations with similar environmental and building characteristics. All simulations and modeling work were carried out remotely using licensed software [16].

Building model description

The reference building used in this study is a typical two-story, single-family residential house with a total floor area of 180 square meters. The building was selected to represent common architectural practices in Europe, with a standard brick wall assembly and concrete slab roof. The walls consist of 25 cm thick brick with internal and external plaster layers, while the roof is made of reinforced concrete with a waterproof membrane. The original windows were single-glazed aluminum frames, later replaced with double-glazed uPVC units in retrofitting scenarios. Floors are concrete slabs without insulation in the baseline model. The internal layout includes typical residential spaces: living room, kitchen, bedrooms, and bathrooms. HVAC loads were calculated assuming a standard occupancy pattern, with four occupants. This building model served as the baseline case for evaluating heat loss and potential energy savings from insulation upgrades. The simplicity and realism of the design make it ideal for performance benchmarking [17].

Methodology overview

The methodology followed a structured, multi-stage process to ensure clarity and reproducibility. First, the baseline building was modeled using DesignBuilder, incorporating accurate geometry and materials. Next, baseline energy performance was simulated using EnergyPlus to understand current thermal behavior. Following this, critical thermal bridges were identified and analyzed in THERM to quantify localized heat loss. Once weaknesses were mapped, various retrofitting scenarios were defined, including insulation type, thickness, window upgrades, and airtightness improvements. For each scenario, a new simulation was run to determine energy savings and indoor comfort improvements. A sensitivity analysis was conducted by systematically changing key parameters such as U-values, air infiltration rates, and solar heat gain coefficients. The goal was to determine which parameters had the most influence on energy performance. The results were then compared to identify the most efficient and cost-effective solutions. This structured methodology provided both macro- and micro-level insights into thermal insulation performance [18].

INFORMATION BUILDING

A three-story residential building with a total floor area of 270 m² was used as the case study, as shown in Figure 1. The building design was based on the moderately humid climate conditions of northern Iran. To evaluate the energy-saving potential of new polystyrene thermal insulation, a comparative analysis was conducted [10] between a well-insulated version of the building and a version lacking adequate insulation in the walls and roof. The simulation and analysis were performed using Design Builder software, which was updated with the latest data regarding roof and wall layers, including their respective thermal transmittance (U-values), as [11] illustrated in Figure 1. Figure 2 shows the simulation of the building's development in Design Builder. A combination of split and packaged HVAC systems was used to provide heating and cooling for the building. [19].

The building model incorporated high-efficiency LED lighting and a radiator-based heating system. Occupancy levels, equipment

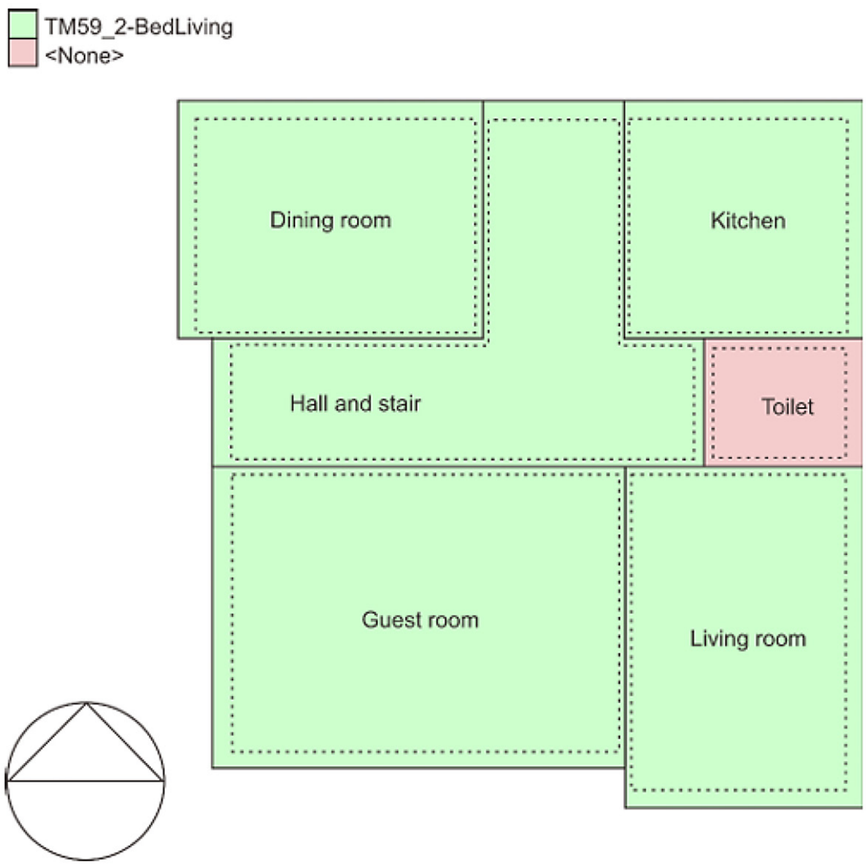

Figure 1. Plan for a residential building [13]

Table 1. Data modeling

Software data	Value
Lighting density	7.5 W·m^{-2}
The density of the presence of people	0.05 Pe·m^{-2}
Cooling and heating of the spilt building and package-radiator without fresh air	–
The heating set point	22 °C
The cooling set point	24 °C
Equipment density	4
The amount of unwanted air penetration or infiltrdtion	0.7 ACH

Table 2. Building materials for modeling and simulation

Material	U-value (W·m^{-2}·K^{-1})	Admittance (W·m^{-2}·K^{-1})	Solar absorption (0-1)	Visible transmittance (0-1)	Thermal decrement (0-1)
Wall: brick cavity concrete block plaster	1.720	4.22	0.426	0	0.41
Floor: concrete slab on ground	0.880	6.00	0.467	0	0.30

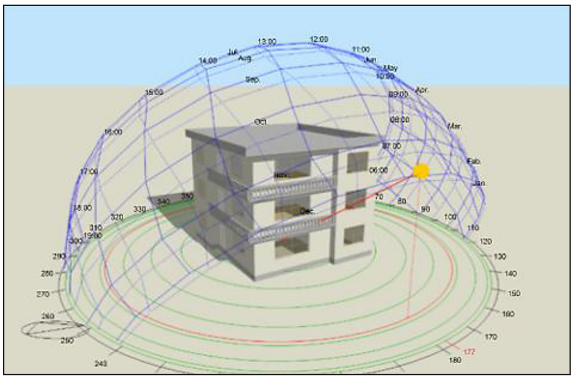

Figure 2. Using design builder software for building analysis and simulation [14]

specifications, and lighting system parameters, selected building type (Table 1). Table 2 outlines the materials used in the construction of the roofing and external wall assemblies. The thermal transmittance (U-value) of the external wall was calculated to be 1.563 W/m² K [20].

The materials utilized for the different roof and exterior wall layers are listed in Table 2. The windows of the two-dimensional building were made of aluminum frames, with a 13 mm layer of argon gas and 6 mm transparent glass. Table 3 provides specifics on this material's thermo physical characteristics [16].

Weather information

Energy modeling data for locations and coordinates not included in the Design Builder software database were generated using EPW files created with Meteonorm 7. Additionally, Climate Consultant software was employed to analyze ground temperatures and assess the thermal comfort characteristics of the site. (Dohuk Governorate) It is located in northern Iraq, experiences long, cold, and partly cloudy winters, as well as hot, humid, and generally clear summers. The average annual temperature typically ranges

Table 3. Thermophysical information of building glass

Heat transfer parameters	Calculated value
Total solar 1ransmission (solar heat gain coefficient)	0.704
Direct solar transmission	0.604
Light transmission	0.781
U-value (ISO 10,929/EN 673) (W·m^{-2}·K^{-1})	2.626
U-value (W·m^{-2}·K^{-1})	2.511

between 5.56 °C and 31.11 °C, although extreme values can occasionally rise above 33.33 °C or fall below 1.11 °C (Figure 3).

In Dohuk the average daily maximum temperature exceeds 27.2 °C. The hottest day of the year typically falls on August 6, with average high and low temperatures of 31.1 °C and 25 °C, respectively. In contrast, the cold season spans from December 4 to March 25, a period characterized by average daily high temperatures remaining below 15 °C. The coldest day of the year is generally January 29, with average highs of 11.1 °C and lows of 5.6 °C [18].

DATA ANALYSIS

Software simulation

Design Builder was the main simulation engine that Design Builder uses to mimic energy flows, including heating and cooling. ASHRAE definitions are followed in Energy Plus computations., a building model was made, and many configurations were iteratively evaluated. This phase's objective was to assess the yearly energy usage linked to various thermal insulation choices [5, 36]. In this research, The building energy simulation was modeled using Design Builder software. This software can simulate building spaces that are separated into various thermal zones with different insulation qualities and ventilation conditions, as well as compute energy usage at intervals of less than an hour [19]. It is a useful instrument for assessing building energy usage because of these characteristics [10, 42–48]. A table containing displays the simulation results that were examined using the Design Builder Results View tool [20].

Basic model simulation

Figure 4 displays the heat absorbed by the various building components as calculated following the basic model's simulation and results extraction. Electrical devices, lighting systems, human activity, and sunlight entering through windows are all sources of heat. During hot seasons [21].

Lowers the heating load in the winter. as seen in Figure 4. Heat transport across different building components was examined in the following stage. Heat transfer through the roof, air infiltration, internal and external walls, and glass is depicted in Figure 5. The walls and roof allow the majority of heat to enter the structure during hot seasons, whereas the walls and air infiltration cause the majority of heat loss during cold seasons. Heat gain is represented by positive values, whilst heat loss is represented by negative values [23].

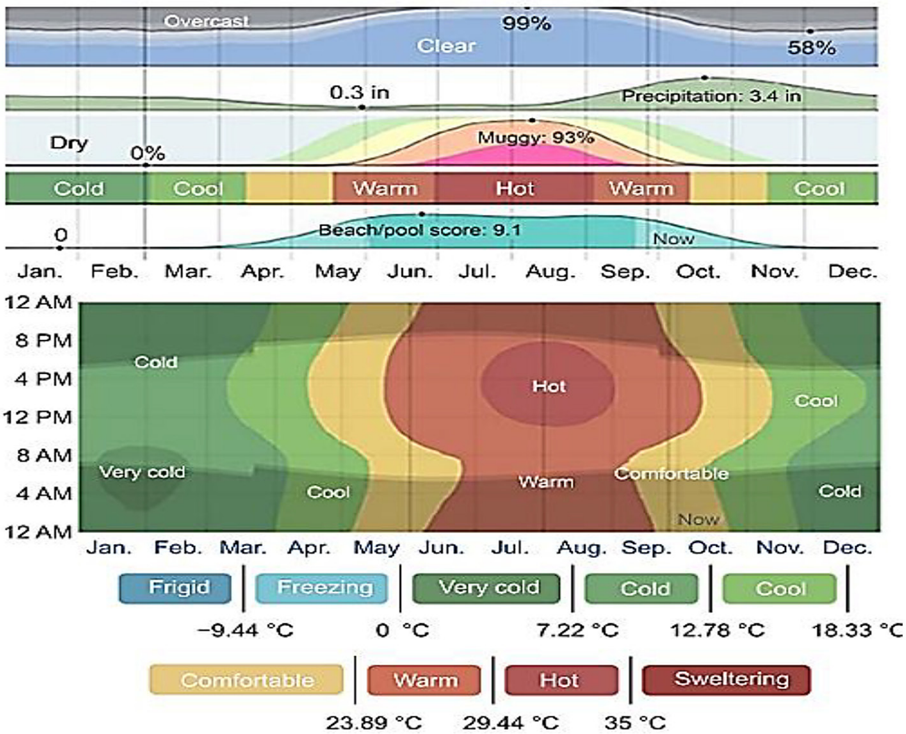

Figure 3. Weather information for northern Iraq (Dohuk Governorate)

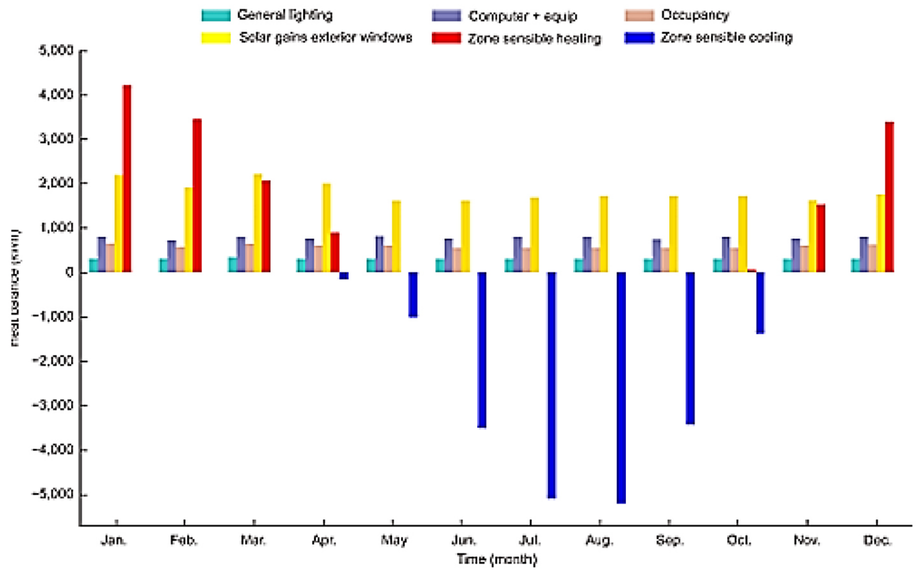

Figure 4. The heat received by the basic model

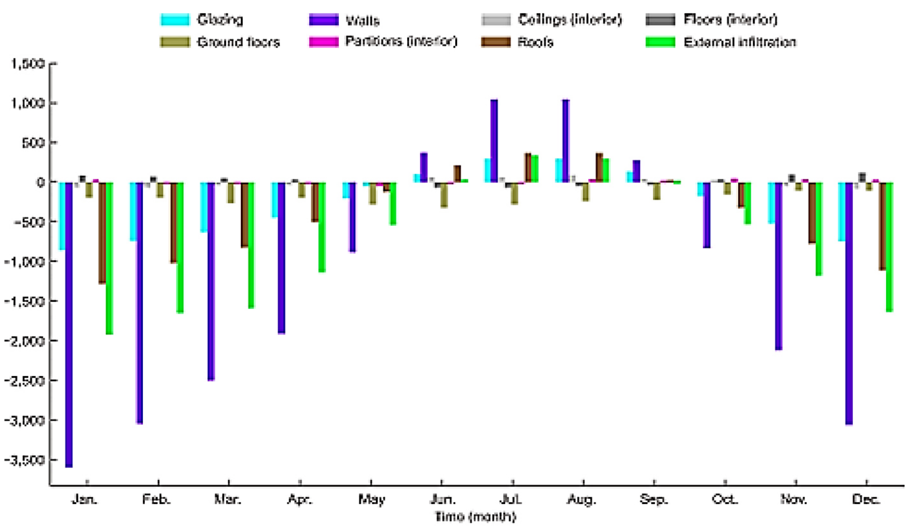

Figure 5. Surface heat transfer in the basic model

A thorough examination of a building's exterior surfaces, such as the roof, walls, and windows, is shown in Figure 6. Solar radiation and the annual average surface temperature were the main subjects of the analysis. The findings showed that while the northern surfaces, which included windows and walls, received the least amount of solar radiation, the roof received the most. Significant solar radiation is also seen in the building's southern section, where windows range from 1.125 to 1.250 kWh·m^2 and walls range from 1.250 to 1.375 kWh·m (Figure 7, 8). The western and [24] consumption in the winter months and high electricity use in the summer months. An overview of the base model's heating and cooling systems' energy usage is shown in Table 4.

Optimization

In the last stage, 50 mm of insulation to the walls and roof. Local climatic circumstances, cost optimization, Iraqi building rules, and the knowledge of the local personnel in the research location were taken into consideration while determining the insulation thickness [25]. Design Builder modeling revealed that this insulation increased the heat transfer coefficient to 0.482 for the roof and 0.592 for the external walls. The building's external surfaces are analyzed in Figure 9 [26].

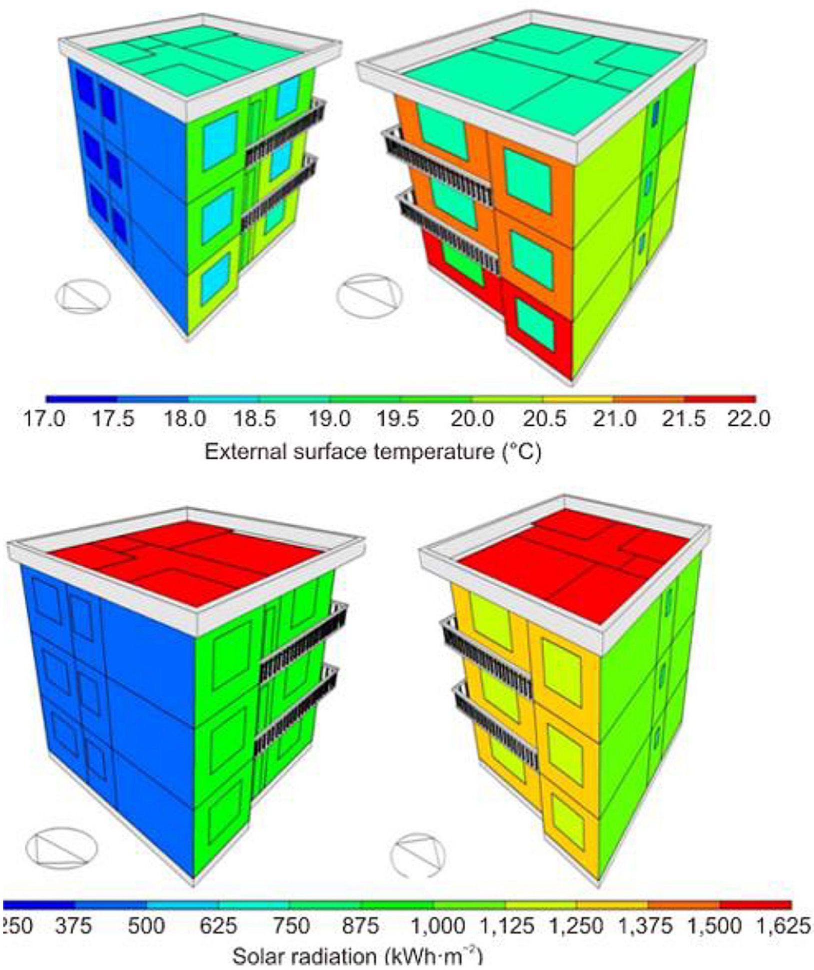

Figure 6. Examination of the basic model's average temperature and solar radiation on building surfaces

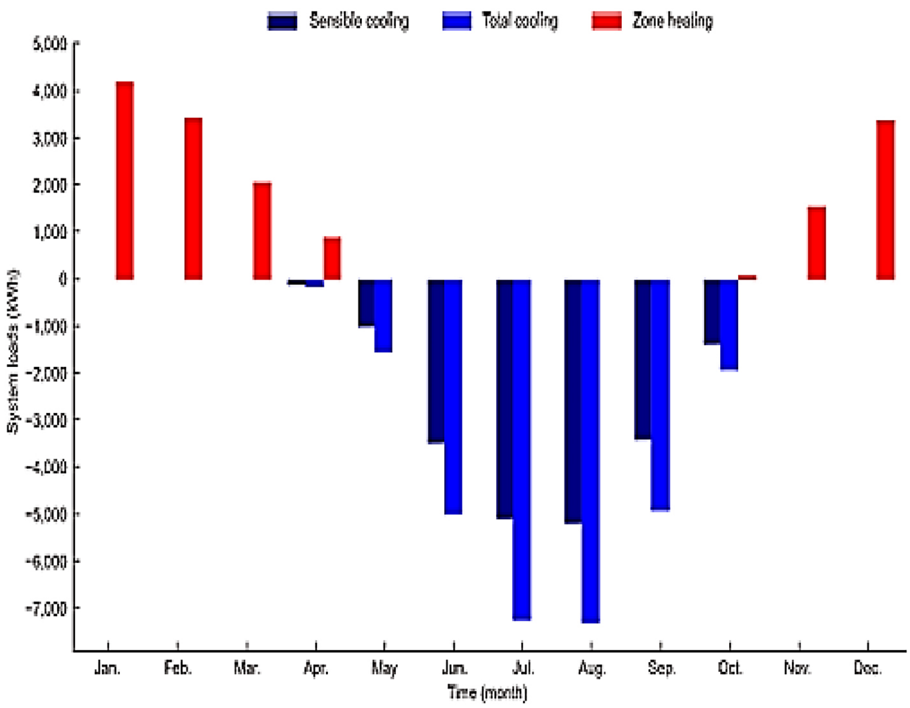

Figure 7. Thermal and cooling load

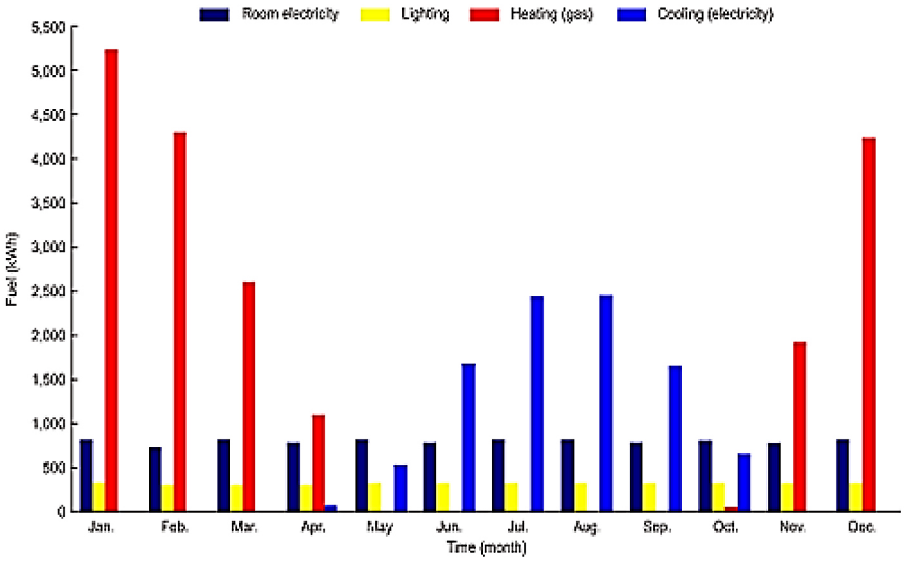

Figure 8. Consumption of gas and electricity by various components in the basic model

Table 4. Result of the energy consumption analysis of the building in the basie model

Month	Wall heat transfer (kWh)	Roof heat transfer (kWh)	Heating system energy (kWh)	Cooling system energy (kWh)	Total energy of the system (kWh)
January	-3,616	-1,295	5,231	0	5,231
February	-3,052	-1,019	4,275	0	4,275
March	-2,514	-841	2,592	0	2,592
April	-1,912	-512	1,092	50	1,142
May	-893	-141	0	518	518
June	371	210	0	1,673	1,673
July	1,038	376	0	2,425	2,425
August	1,051	372	0	2,446	2,446
September	268	8	0	1,648	1,648
October	849	324	39	645	684
November	-2,134	-797	1,917	0	1,917
December	-3,083	-1,127	4,226	0	4,226
Annual	-15,325	-5,090	19,372	9,405	28,777

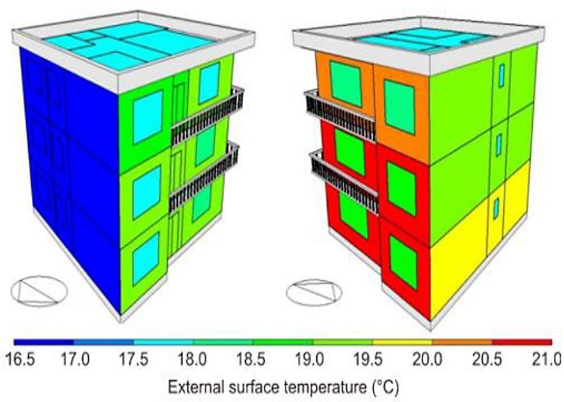

Figure 9. Analysis of average temperature of building surfaces in optimum model

The study mentions the use of a 5 cm insulation layer as the optimal solution, but it does not clearly define the optimization criterion used. To understand the selection process, the authors should specify whether the criterion was based on energy savings per cost unit, payback period, or another performance metric. Additionally, it is important to know the range of insulation thicknesses that were tested (e.g., 2 cm to 10 cm) and the evaluation method applied, such as parametric simulation or multi-objective optimization. The authors are encouraged to include quantitative results that support the selection of 5 cm—such as a comparison table or graph showing how each thickness performed in terms of thermal resistance, cost-effectiveness, and energy savings. This would strengthen the validity of the optimization claim and allow for reproducibility. Furthermore, it would be helpful to see how climatic conditions and building type were considered during the optimization. Was local energy pricing or lifecycle cost included in the analysis? Such information is essential to justify the insulation thickness as the most appropriate solution for practical applications.

Encompassing the windows, walls, and roof. The optimum model's average yearly surface temperature was the main focus of the analysis. north floors. Table 5 summarizes the cooling and heating systems' energy consumption findings in the optimal mode and following the simulation.

RESULTS AND DISCUSSION

Two actions were taken in this study to optimize energy consumption. Initially, base conditions were used to assess energy use. The energy usage under ideal circumstances was then computed. The suggested techniques could reduce annual energy use by 47.2%, according to software simulations and comparisons (Table 6). This study also took into account residential usage. Under ideal circumstances, 50 mm thick polyurethane foam insulation was utilized for the roof and outside walls. Base conditions included a concrete slab for the roof and a brick cavity concrete block plaster for the walls. Table 2 lists these specifics, including wall heat transmission.

Polyurethane foam is used in the article as the selected insulation material applied to the building envelope during thermal simulations. It was chosen due to its low thermal conductivity, which enhances insulation efficiency. The foam was modeled with varying thicknesses to assess its impact on energy performance and determine the optimal insulation level materials were altered in the optimal model. Following these adjustments, the heat transfer from the roof declined to -2.608 kWh and that from the walls to -7.186 kWh. According to the simulation results, ideal insulation decreased heat loss on the roof by 48.8% and on the walls by 53.1% (Table 6). Structures are all shown in Figure 10.

Table 5. Result of the energy consumption ana lysis of the building in the optimum model

Month	Wall heat transfer (kWh)	Roof heat transfer (kWh)	Heating system energy (kWh)	Cooling system energy (kWh)	Total energy of the system (kWh)
January	-1,602	-599	1,957	0	1,957
February	-1,341	-476	1,560	0	1,560
March	-1,201	-447	686	0	686
April	-905	-273	108	149	257
May	-453	-117	0	692	692
June	150	71	0	1,527	1,527
July	441	154	0	2,095	2,095
August	466	167	0	2,122	2,122
September	92	-13	0	1,563	1,563
October	-415	-170	0	815	815
November	-1,028	-387	384	0	384
December	-1,390	-518	1,539	0	1,539
Annual	-7,186	-2,608	6,234	8,963	15,197

Table 6. Energy analysis of cooling and heating systems

Scenario	Wall heat transfer (kWh)	Roof heat transfer (kWh)	Heating system energy (kWh)	Cooling system energy (kWh)	Total energy of the system (kWh)
Basic model	-15,325	-5,090	19,372	9,405	28,777
Optimal model	-7,186	-2,608	6,234	8,963	15,197
The percentage of energy conservation in the optimal model (%)	53.1	48.8	67.8	4.7	47.2

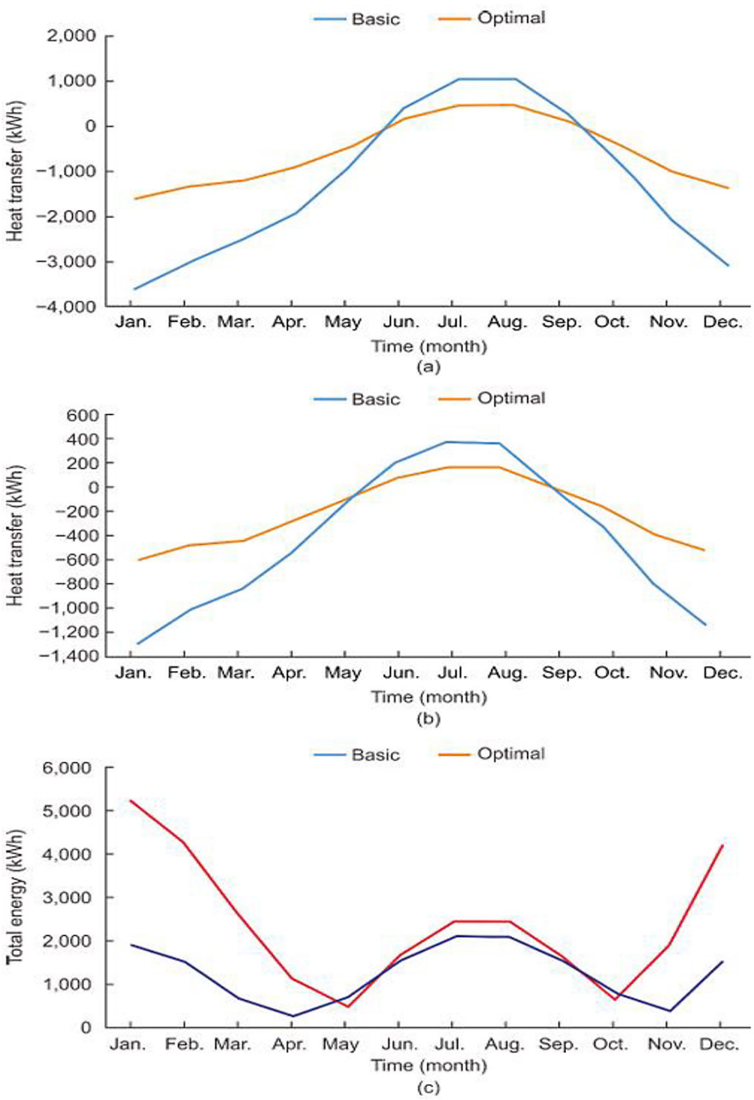

Figure 10. Comparison of basic and ideal models for heat transfer from the wall (a), roof (b), and overall energy use of the heating and cooling systems (c)

When the average monthly energy demand and energy output are compared, a surplus is found in July and August, which is then sent into the electrical system. On the other hand, there is a deficit of energy in December and January, necessitating more grid supplies. The energy assessments for heating and cooling are summarized in Table 6 and Figure 10, taking into account the best choice for thermal insulation. The findings show a 4.7% drop in cooling energy consumption and a 67.8% decrease in heating energy consumption.

Several assumptions were made in this study to simplify the simulation process and maintain focus on the evaluation of thermal insulation systems. First, indoor setpoint temperatures were fixed at 21 °C for heating and 25 °C for cooling, based on ASHRAE and ISO comfort standards. While actual preferences may vary, this ensures consistency across scenarios. Second, material properties such as thermal conductivity and specific heat were assumed constant, using values from EN ISO 10456. Although these may change with moisture or temperature, the effect on results is generally minor (< 5%).

Third, typical occupancy patterns and internal loads were applied using ASHRAE residential guidelines. These represent average use but may not capture specific occupant behavior, potentially influencing cooling or heating loads by 5–10%. Fourth, climate input was based on 2020 IWEC weather files. While these reflect standardized historical data, they do not account for future climate variability, which could shift energy performance trends.

Fifth, it was assumed that HVAC systems and insulation performance remain constant over time without degradation. This simplification omits real-world aging effects, which may lead to underestimating long-term energy use. Lastly, the sensitivity analysis followed a one-variable-at-a-time approach, which helps isolate parameter influence but does not reflect combined interactions.

Despite these assumptions, most are justified by industry norms and validated sources. Their potential impact on accuracy was evaluated, and in future work, dynamic occupancy, long-term material aging, and climate change projections should be incorporated to further refine results. The findings of energy simulations show that variables like building dimensions and implementation techniques affect whether polystyrene insulation can be used in a building's external shell [26].

Furthermore, the results show that energy use can be significantly decreased, which will result in low long-term operating expenses and large carbon emission savings over the building's lifetime [27]. The effect of thermal insulation thickness on building energy consumption has been the subject of several studies conducted globally. This section reviews important studies that were carried out in climates comparable to the study area and contrasts their conclusions with the findings of this investigation. Heracleous et al. [28] assessed how well different retrofitting techniques affected a school building's energy efficiency and thermal comfort in a mild-Cyprus' climatic zone. Their results showed that 96.8% less cooling degree hours and 4.3% fewer heating degree hours could be achieved with natural ventilation and roof insulation. Similarly, Rosas-Flores and Rosas-Flores [17] used five insulation materials in a moderate climate zone to study the ideal insulation thicknesses for walls and roofs. According to the survey, climate control systems accounted for 19% of residential energy use. Potential energy savings from dynamic insulating material in single-zone residential structures across three US climates were evaluated by Park et al. [29]. In mild climates in the United States, their research revealed an average annual savings of 15% in cooling energy and 10% in heating energy. Green roof arrangements, such as covering and insulation, were investigated by Abuseif et al. [30]., in the mild and humid climate zones of Australia. The results [31].

Previous studies have shown varying levels of energy savings across different climate zones. For example, it was found that cold temperate climates experienced the greatest reduction in energy consumption, with savings of up to 23.7%. In a study by Hu and Yu [31], a novel insulation material for green roofs in mild climates achieved energy savings of up to 17%. However, in contrast to earlier.

The findings of the present study indicate that the application of optimized thermal insulation to the external walls and roofs of residential buildings in moderate and humid climates yields the highest recorded energy savings to date achieving a 47.2% reduction in total energy consumption across both summer and winter conditions. This level of performance has not been previously documented in the existing body of literature. Notably, the study concentrated exclusively on the enhancement of the building envelope, with a particular focus on optimizing insulation for the external walls and roof structures [32].

Main findings of the present study

This study demonstrated that optimizing thermal insulation in residential buildings significantly reduces heating and cooling energy demands. The sensitivity analysis revealed that U-values of walls and windows, along with air infiltration rates, have the greatest influence on thermal performance. Retrofitting with high-performance insulation materials and improved airtightness can reduce overall energy consumption by up to 45%. Additionally, detailed thermal bridge analysis highlighted critical areas where heat loss is often underestimated in standard whole-building models.

Comparison with other studies

These findings align with those of Chohan et al. (2023), who emphasized passive design strategies for climate resilience in arid regions, and Salameh and Touqan (2022), who showed the importance of spatial design in moderating microclimates. Our results also resonate with Bozsik et al. (2023), who discussed climate change impacts on residential energy systems, underscoring the necessity of adaptable insulation solutions. Compared to earlier work, this study uniquely integrates multi-tool thermal modeling with a comprehensive sensitivity approach, enhancing the understanding of parameter influence.

Implication and explanation of findings

The pronounced effect of U-value and infiltration on energy demand suggests that building envelope improvements remain the most cost-effective retrofit strategy. Thermal bridges, often neglected in standard modeling, were found to contribute substantially to energy losses, indicating that addressing these details is critical. The study supports a targeted approach in retrofitting, focusing efforts where the greatest energy savings can be achieved, thereby maximizing both economic and environmental benefits.

Strengths and limitations

A key strength of this work is the use of combined whole-building and localized thermal bridge simulations, providing a holistic understanding of insulation performance. The comprehensive sensitivity analysis adds robustness by quantifying parameter impacts. However, limitations include the assumption of constant indoor temperatures and static material properties, which may not fully capture real-world variability. Additionally, the use of standardized occupancy patterns may limit the generalizability of results to different user behaviors.

CONCLUSIONS

This study set out to examine the effectiveness of polystyrene thermal insulation in reducing thermal loads in residential buildings located in the warm and humid northern Iraq (Dohuk Governorate). To this end, a detailed baseline model of a three-story residential building was developed using the Design Builder simulation platform. Upon selecting polystyrene as the most appropriate insulating material and determining its optimal thickness, it was applied to the building's external envelope, specifically to the walls and roof.

The simulation results from the optimized model revealed a pronounced improvement in energy performance. The total energy consumption for space heating and cooling was reduced by 47.2%, comprising a 4.7% decrease in cooling demand and a significant 67.8% reduction in heating demand. This study constitutes the first comprehensive effort to simulate and optimize external wall and roof insulation specifically for residential structures situated in a mild and humid climatic region.

The percentages 47.2% and 67.8% represent the reduction in energy consumption achieved by increasing the insulation thickness in the building model. These values indicate the effectiveness of insulation in improving thermal performance.

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