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Development of a Quantitative Exergy Cost Model for Assessing Thermal Bridge Effects in Ultra-Low Energy Building Enclosures

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ABSTRACT

With the escalating global energy crisis and increasing environmental concerns, ultra-low energy buildings have garnered significant attention as a sustainable architectural paradigm. The enclosure structure plays a crucial role in the energy consumption of buildings, with thermal bridge effects exerting a significant impact on energy efficiency and carbon emissions. Although considerable progress has been made in the study of thermal bridge effects in buildings, a comprehensive quantitative analysis specific to ultra-low energy building enclosures remains insufficient. In particular, a systematic evaluation framework and standardized assessment methodology for life-cycle energy and exergy consumption have not yet been established. Consequently, accurately quantifying the influence of thermal bridge effects and conducting cost analyses based on this quantification have become critical issues in building energy efficiency research. Existing studies have primarily focused on localized analyses of thermal bridge effects, lacking a systematic investigation of the entire building enclosure and its life-cycle energy and exergy consumption. Most models fail to account for the cumulative impact of thermal bridge effects on long-term energy performance and do not adequately quantify the integrated costs associated with building materials, construction, and operational phases. These limitations hinder the practical application and promotion of research findings in engineering practice. This study addresses the thermal bridge effects in ultra-low energy building enclosures, focusing on two key aspects: (a) a systematic analysis of life-cycle energy and exergy consumption in ultra-low energy building enclosures, and (b) the development of a quantitative exergy cost model for thermal bridge effects. By introducing novel analytical and modeling approaches, this study aims to provide a more precise assessment tool for evaluating thermal bridge effects, thereby advancing the application of ultra-low energy buildings in energy conservation and carbon reduction. The findings of this research offer theoretical foundations and practical guidance for the green development of the building industry.

1. INTRODUCTION

Amidst the growing global energy crisis and escalating environmental pollution, the issue of building energy consumption has become a critical challenge that must be addressed by nations worldwide [1, 2]. Ultra-low energy buildings have emerged as a focal point in building energy efficiency research due to their significant advantages in reducing energy consumption and carbon emissions [3-6]. As one of the primary contributors to building energy demand, the enclosure structure plays a crucial role, with thermal bridge effects exerting a particularly significant impact on overall energy performance. However, existing research on the thermal bridge effects of enclosure structures in ultra-low energy buildings remains inadequate, necessitating the development of a systematic and comprehensive quantitative model to assess their impact and associated costs.

The significance of investigating the thermal bridge effects in ultra-low energy building enclosures lies in providing scientific guidance for architectural design through in-depth analysis and quantification of their impact on energy and exergy consumption, thereby optimizing design schemes and reducing energy and exergy consumption throughout the building's life cycle [7-9]. Additionally, this research holds practical importance for promoting the green development of the building sector, mitigating carbon emissions, and achieving sustainability goals [10-12].

Existing research methodologies exhibit several limitations in the quantification of thermal bridge effects in ultra-low energy building enclosures. First, most studies focus solely on the localized heat loss caused by thermal bridge effects, while their comprehensive impact on the entire building system is often overlooked [13-18]. Second, a systematic analysis of life-cycle energy and exergy consumption is generally absent from existing models, making it difficult to accurately reflect the cumulative energy costs over long-term operation [19-21]. Furthermore, certain studies involve simplifications in data acquisition and model development, which compromise the precision and reliability of the results.

This study primarily addresses two key aspects: (a) a systematic analysis of life-cycle energy and exergy consumption in ultra-low energy building enclosures, evaluating the impact of thermal bridge effects over the entire life cycle, and (b) the development of a quantitative exergy cost model for thermal bridge effects, providing a scientifically rigorous and comprehensive assessment tool. The significance of this research lies in the proposal and validation of a novel quantitative model, which not only strengthens the theoretical foundation of thermal bridge effect studies in ultra-low energy buildings but also serves as a critical reference for practical engineering applications. These contributions facilitate the achievement of energy efficiency and green development objectives in the building sector.

2. LIFE-CYCLE ENERGY AND EXERGY CONSUMPTION ANALYSIS OF ULTRA-LOW ENERGY BUILDING ENCLOSURES

The thermal bridge effect refers to the phenomenon in which localized areas of an enclosure structure exhibit accelerated heat transfer due to differences in thermal conductivity among materials or discontinuities in structural composition, leading to energy loss. This effect not only intensifies the heating and cooling loads of a building but also increases overall energy consumption and thermal regulation demands. Throughout the life cycle of an ultra-low energy building, the thermal bridge effect of enclosure structures must be carefully considered not only during the initial design phase but also during operation and maintenance, where its influence persists. By increasing the building's total energy demand, the thermal bridge effect affects the total energy consumption of the building, contributing to higher operational costs and elevated carbon emissions. Within this context, the thermal bridge effect is not merely a measure of localized heat loss but also serves as a critical indicator of energy consumption and environmental burden across the entire building life cycle. Therefore, the definition of thermal bridge effects in ultra-low energy building enclosures should comprehensively account for their impact on energy efficiency, costs, and carbon emissions at each stage of the building's life cycle. In particular, the increase in energy consumption, additional exergy consumption, and heightened carbon dioxide (CO_2) emissions resulting from thermal bridge effects in enclosure design must be systematically evaluated and controlled through the development of precise quantitative models.

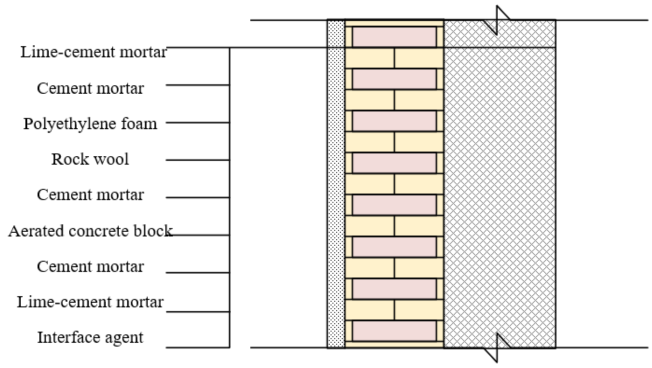

Figure 1. Detailed structure of the enclosure in an ultra-low energy building

The structural composition of ultra-low energy building enclosures is illustrated in Figure 1. The primary objective in the design of ultra-low energy buildings is to minimize energy demand by optimizing the thermal performance of the enclosure to reduce heat loss. However, thermal bridge effects frequently emerge at joints, openings, and material interfaces within the enclosure, forming localized pathways for heat conduction. The energy loss at these locations is significantly higher than in other areas. The presence of thermal bridges increases the thermal load during building operation, necessitating higher energy consumption for heating, cooling, and air conditioning. Figure 2 presents an example of a thermal bridge node in an ultra-low energy building enclosure with an insulation layer. Conducting a life-cycle energy consumption analysis of ultra-low energy building enclosures allows for the accurate assessment of the long-term impact of thermal bridge effects on building energy efficiency and highlights the challenges posed by thermal bridge effects to energy-efficient design objectives, thereby providing a scientific basis for design optimization.

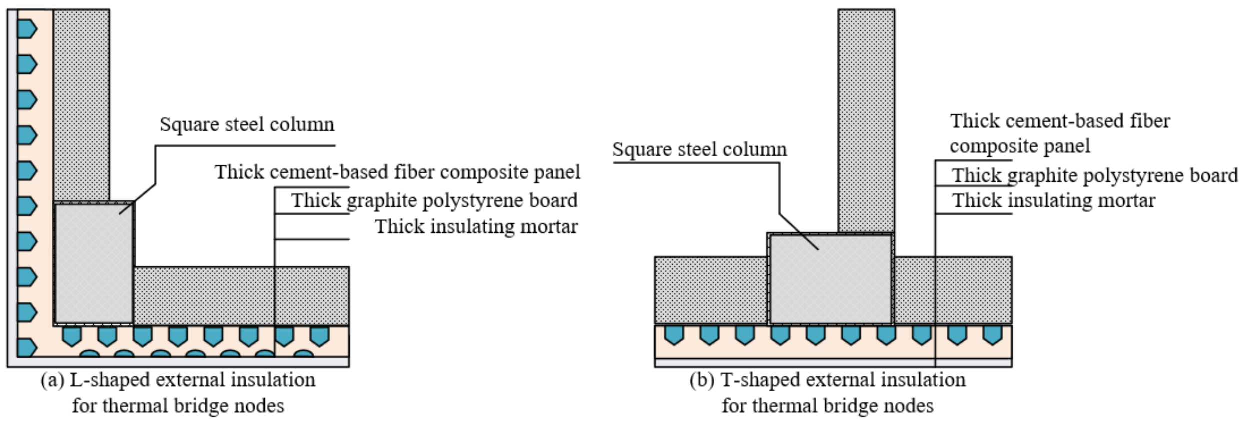

Figure 2. Example of a thermal bridge node in an ultra-low energy building enclosure with an insulation layer

The calculation of energy consumption during the production phase of enclosure materials is a critical aspect of evaluating the life-cycle energy efficiency and exergy emissions of buildings. For ultra-low energy buildings, the design of the enclosure structure necessitates the use of high-performance, low-energy-consumption materials to mitigate thermal bridge effects, minimize energy loss, and reduce long-term energy burdens. However, the energy consumption associated with material production must not be overlooked, as the manufacturing processes of building materials often involve substantial energy demand. This is particularly true for high-performance insulation materials and structural components, whose production may require high-temperature processing and heavy industrial manufacturing, leading to significant energy expenditures. Therefore, when calculating the energy consumption of the enclosure structure, all stages of material processing must be considered, from raw material extraction to production and transportation. Let R_v represent the energy consumption of building materials, l denote the material mass, and R_{vl} indicate the energy intensity per unit mass. The energy consumption R_v is computed using the following equation:

$$R_v = l \times R_{vl} \tag{1}$$

During the operational phase of ultra-low energy buildings, energy consumption primarily arises from heating, cooling, lighting, and hot water supply systems, all of which are influenced by the thermal performance of the enclosure structure. Optimization of the thermal properties of the enclosure, including thermal conductivity, heat capacity, and density, is essential for reducing energy loss and minimizing the impact of external environmental fluctuations on indoor temperature stability, thereby enhancing the building's overall energy efficiency. However, thermal bridge effects within the enclosure structure lead to localized increases in energy consumption. In particular, thermal bridge effects at joints, window and door frames, and material interfaces facilitate rapid heat transfer through these "weak points," resulting in unnecessary thermal losses. Figure 3 presents a schematic representation of structural thermal bridges at material interfaces within an ultra-low energy building enclosure. Such localized heat losses necessitate additional energy input to maintain indoor thermal stability, leading to increased demand for heating, cooling, and other energy-consuming systems. When calculating the energy consumption during the operation phase of ultra-low energy building envelope structures, it is necessary to comprehensively consider the impact of thermal bridge effects on the building's cooling and heating loads. In this study, the dynamic simulation software Dest-C was employed to precisely simulate the variations in heating and cooling loads under different enclosure configurations, thereby determining the actual energy consumption of the building.

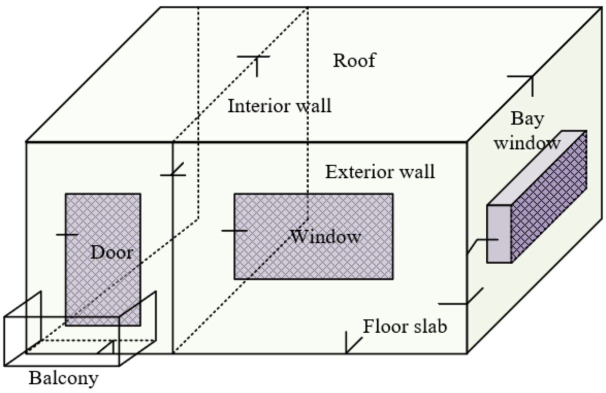

Figure 3. Schematic representation of structural thermal bridges at material interfaces in ultra-low energy building enclosures

In terms of exergy consumption analysis, ultra-low energy buildings aim to minimize overall exergy emissions while reducing energy consumption. The thermal bridge effect contributes to increased building energy demand, indirectly leading to greater energy consumption. In buildings that rely on conventional energy sources, these additional energy demands result in elevated carbon emissions. For ultra-low energy buildings, even minor energy losses or additional energy requirements may impose a significant environmental burden over extended periods of operation. Therefore, a life-cycle exergy consumption analysis of ultra-low energy building enclosures must account not only for the immediate energy losses caused by thermal bridge effects but also for their long-term impact on carbon emissions.

To accurately quantify the exergy consumption associated with the production phase of enclosure materials, a series of systematic computational steps must be undertaken. First, the exergy content per unit mass of building materials must be determined. This parameter, known as mass exergy content, represents the amount of energy contained in a unit mass of a given material. The value is typically obtained from energy databases or experimental measurements. The mass exergy content of a building material encompasses not only the energy required for raw material extraction and processing but also the energy consumed during manufacturing, including electricity and fuel inputs. Let R_{al} represent the mass exergy content of the building material, R_{vl} denote the energy content per unit mass, and η_l be the equivalent energy-mass coefficient of the material. The mass exergy content per unit building material can be computed using the following equation:

$$R_{al} = R_{vl} \times \eta_l \tag{2}$$

The equivalent exergy-mass coefficient of building materials must be determined based on the proportion of various energy sources used in material production relative to the total energy consumption. Different energy sources, such as electricity, natural gas, coal, and petroleum, possess distinct energy densities and environmental impacts. Therefore, these energy characteristics must be considered when calculating the total exergy consumption of building materials. The exergy-mass coefficient serves as a comprehensive index that quantifies the relative importance and contribution of each energy source during the production process. By analyzing the proportion of different energy sources consumed in the production process and incorporating their respective exergy-mass coefficients, the contribution of each energy type to the total exergy consumption of building materials can be calculated. This process typically involves the application of energy conversion factors to ensure comparability across different energy forms. For instance, if the production of a particular building material requires a substantial amount of electricity but a smaller quantity of natural gas, the contributions of both electricity and natural gas to the total exergy consumption must be computed separately and then aggregated. Specifically, let $\eta_1,\eta_2,\ldots,\eta_v$ represent the exergy-mass coefficient of the v-th energy source, and let $a_1,a_2,\ldots,a_v$ denote the percentage share of the v-th energy source in the total energy consumption for material production. The equivalent exergy-mass coefficient of building materials is calculated using the following equation:

$$\eta_l = \eta_1 \times a_1 + \eta_2 \times a_2 + \ldots + \eta_v \times a_v \tag{3}$$

By summing the contributions of all energy sources, the total exergy consumption of the material production phase can be determined. This total exergy consumption value is a critical parameter for evaluating the life-cycle exergy cost of ultra-low energy building enclosures. In particular, when considering thermal bridge effects, the selection and application of building materials directly influence localized heat loss and overall building energy efficiency. Therefore, accurately calculating the exergy consumption of the material production phase not only facilitates the quantification of thermal bridge effects on building energy consumption but also provides a scientific basis for optimizing material selection and design. Let R_a represent the total exergy consumption of the material production phase, l_u denote the mass of the u-th building material, and R_{alu} represent the unit mass exergy content of the u-th material. The total exergy consumption of the material production phase is computed as follows:

$$R_a = \sum_{u=1}^{v} l_u \times R_{al_u} \tag{4}$$

The primary design objective of ultra-low energy buildings is to minimize overall energy consumption, with the thermal performance of the enclosure structure directly affecting the heating and cooling loads of the buildings. By simulating the cooling energy consumption during the air-conditioning season and the heating energy consumption during the heating season over an entire year, detailed data on heat demand R_{ag} and cooling demand R_{az} can be obtained. These calculations not only reveal seasonal variations in building energy demand but also quantify the specific impact of thermal bridge effects on energy consumption. Due to the increase in localized heat loss caused by thermal bridge effects, additional energy is required to maintain indoor thermal comfort, thereby increasing the load on heating and cooling systems. Let W_g represent the heating energy demand, W_z denote the cooling energy demand, S_0 indicate the outdoor environmental temperature, and S represent the indoor environmental temperature. The exergy calculation for heating energy is given by the following equation:

$$R_{ag} = W_g \times \left(1 - \frac{S_0}{S}\right) \tag{5}$$

Similarly, the exergy calculation for cooling energy is expressed as:

$$R_{az} = W_z \times \left(\frac{S_0}{S} - 1\right) \tag{6}$$

During the material production phase, the CO_2 emissions associated with primary energy sources such as coal, natural gas, and electricity must be quantified based on the emission factors of each energy type. The CO_2 emissions of different energy sources vary significantly; for example, coal typically produces higher emissions than natural gas, while electricity emissions depend on the method of power generation. In the selection of building materials for ultra-low energy buildings, the emphasis is placed on enhancing the thermal performance of the enclosure and mitigating thermal bridge effects. Therefore, choosing low-carbon and low-energy building materials is the key to reducing CO_2 emissions throughout the entire life cycle. The presence of thermal bridge effects increases localized heat loss in the building enclosure, leading to higher heating and cooling loads during operation. Consequently, greater electricity consumption and increased CO_2 emissions occur. Therefore, when calculating the CO_2 emissions from the material production phase, it is essential to not only account for the energy consumption of each material but also evaluate its role in reducing thermal bridge effects and improving overall building energy efficiency.

3. DEVELOPMENT OF A QUANTITATIVE EXERGY COST MODEL FOR THERMAL BRIDGE EFFECTS IN ULTRA-LOW ENERGY BUILDING ENCLOSURES

To simplify the complexity of building thermal behavior and systematically evaluate the energy efficiency and greenhouse gas emissions of enclosure structures, thermoeconomics was employed in this study to conceptualize the building enclosure as a black-box system. This approach effectively focuses on the energy input and output of the enclosure structure without necessitating an in-depth examination of the microscopic heat transfer processes within each material. By analyzing the boundary conditions of the enclosure structure, the impact on overall building energy efficiency and thermal load can be rapidly assessed.

When developing a quantitative exergy cost model for thermal bridge effects in ultra-low energy building enclosures, three fundamental steps must first be defined. The initial step involves identifying and quantifying the energy consumption cost of the enclosure structure at various stages. Specifically, the energy consumption of the enclosure structure during building operation must be modeled, with an emphasis on the precise computation of the additional annual energy demand induced by thermal bridge effects, particularly in the operation of air-conditioning and heating systems. Thermal bridge effects exacerbate localized heat loss in the enclosure, necessitating additional energy input from air-conditioning and heating equipment to maintain stable indoor temperatures, thereby increasing overall building energy consumption. By utilizing efficiency data from air-cooled heat pump units and other relevant systems, the energy cost incurred during the operational phase of the enclosure structure can be further calculated. This energy cost is incorporated as the first component of the exergy cost model, i.e., energy consumption cost.

Further analysis of the total investment cost of the building enclosure structure is required, followed by the calculation of the annualized discounted cost. The design of ultra-low energy building enclosures typically demands a higher initial investment due to the incorporation of high-performance insulation materials and optimized design strategies aimed at mitigating thermal bridge effects. By discounting these investment costs, long-term expenditures can be converted into annualized costs, further reflecting the economic viability of energy-efficient design solutions. This component of the model is quantified by considering construction, material selection, and installation costs of the enclosure structure while integrating the impact of thermal bridge effects to evaluate the balance between the initial investment of the design solutions and future energy savings. A lower discounted cost indicates a shorter payback period for the energy-efficient design and greater economic benefits achieved through reduced operational energy consumption costs.

The third step involves assessing the maintenance and demolition costs of the enclosure structure. This mainly considers the maintenance costs of the enclosure structure during use, including expenses associated with repairs, replacements, or the renewal of degraded materials. In ultra-low energy buildings, the presence of thermal bridge effects may cause localized damage or accelerated aging, especially when the thermal conductivity of the enclosure structure is poor. Therefore, within the exergy cost model, maintenance costs must account for the additional impact of thermal bridge effects, particularly in cases where the energy efficiency of the enclosure structure declines over time. These costs are closely linked to the maintenance cycle and influence the overall life-cycle cost of ultra-low energy buildings. Finally, demolition costs represent the expenses associated with dismantling and waste disposal at the end of the enclosure structure's service life. These costs usually need to be adjusted appropriately based on the impact of thermal bridging effects after long-term use.

Specifically, let R_{ar} represent the thermal and cooling sources, R_{aq} denote the exergy value of the annual water consumption for heating and cooling sources, and R_{ad} denote the exergy value of the fuel consumption for heating and cooling sources, and R_{au} indicate the exergy value of the annual heating or cooling supply. Additionally, let z_r represent the unit cost of electricity, z_q denote the unit cost of water supply, and z_d indicate the unit cost of fuel. The annualized engineering cost of the energy-efficient enclosure design is represented by Z_c, while the operational and management costs of the building are denoted by Z_h, and the demolition costs of the enclosure structure are represented by Z_z. The unit exergy cost is given by z, and the unit exergy cost calculation equation of the enclosure structure based on economic equilibrium is as follows:

$$z_r R_{ar} + z_q R_{aq} + z_d R_{ad} + Z_c + Z_h + Z_z = zR_{au} \tag{7}$$

If the water consumption and fuel consumption of the heating and cooling sources are neglected, the above equation can be simplified as follows:

$$z_r R_{ar} + Z_c + Z_h + Z_z = zR_{au} \tag{8}$$

Let Z_c represent the annualized engineering cost, Z_h denote the annual operational and management costs, and Z_z indicate the annualized renovation and demolition costs of the enclosure structure. The unit exergy cost can then be computed using the following equation:

$$z = \frac{z_r R_{ar}}{R_{au}} + \frac{Z_c}{R_{au}} + \frac{Z_h}{R_{au}} + \frac{Z_z}{R_{au}} \tag{9}$$

Assuming that the engineering cost of the energy-saving renovation is represented by J, the discount rate of investment by u, and the building lifespan after renovation by v, then Z_z can be calculated as follows:

$$Z_c = J \times \frac{u}{1-(1+u)^{-v}} \tag{10}$$

By following these three fundamental steps, the quantitative exergy cost model for ultra-low energy building enclosures systematically integrates energy consumption, investment, maintenance, and demolition costs across different stages, which provides a scientific basis for energy-efficient building design and maximizes economic benefits and environmental impact while reducing thermal bridge effects.

4. EXPERIMENTAL RESULTS AND ANALYSIS

From the data of exterior wall materials of ultra-low energy building enclosures in Table 1, significant differences in thickness, thermal conductivity, and thermal resistance values among different materials can be observed. For instance, polystyrene foam exhibits a low thermal conductivity of 0.046 and a thickness of 0.4 mm, resulting in a thermal resistance of 0.007, which indicates low thermal conductivity and high thermal insulation performance. In contrast, aerated concrete blocks, despite having a substantially greater thickness of 214.6 mm, possess a higher thermal conductivity of 0.21, leading to a relatively lower thermal resistance of 0.715. Additionally, as for the combinations of materials such as rock wool and cement mortar, although their variations in thickness are present, they have lower thermal conductivities, exhibiting superior performance in enhancing the thermal resistance of the enclosure structure. For example, rock wool has a thermal conductivity of only 0.041 and a thermal resistance of 5.125, while cement mortar, despite its widespread application for structural stability, has a significantly higher thermal conductivity of 0.92, resulting in lower thermal resistance values. Overall, a direct correlation is observed between thermal resistance and thermal conductivity. The selection of appropriate material combinations can effectively enhance the thermal insulation performance of exterior walls.

Based on the data presented in Table 2, significant variations in thermal conductivity and thermal resistance values are observed among different roofing materials used in ultra-low energy building enclosures, indicating their respective insulation performance. Among the materials analyzed, extruded polystyrene board exhibits the most outstanding thermal insulation properties, with an extremely low thermal conductivity of 0.03 and a remarkably high thermal resistance of 7.526. This suggests that extruded polystyrene board effectively reduces heat loss when incorporated into the roof structure as the thermal insulation layer. In contrast, fine aggregate concrete and cement mortar, with thermal conductivities of 1.68 and 0.92, respectively, exhibit thermal resistance values of 0.016 and 0.026. Although these materials possess relatively greater thicknesses, their higher thermal conductivity results in inferior insulation performance compared to extruded polystyrene board. Additionally, waterproof membranes lack explicit thermal conductivity and thermal resistance values, likely due to their primary function being waterproofing rather than thermal insulation. When comparing thermal resistance across different materials, it is evident that thin layers such as waterproof membranes and roof surface tiles provide inadequate thermal isolation, whereas materials such as lightweight aggregate concrete cushion offer moderate insulation performance.

Table 1. Heat transfer coefficient calculation of the ultra-low energy building enclosure wall

Exterior Wall Material	Thickness (mm)	Thermal Conductivity (W/m·K)	Thermal Resistance (m^2·K/W)
Lime-cement mortar	9.1	0.88	0.011
Cement mortar	6.1	0.92	0.006
Polystyrene foam	0.4	0.046	0.007
Rock wool	235.6	0.041	5.125
Cement mortar	5.1	0.92	0.005
Aerated concrete block	214.6	0.21	0.715
Cement mortar	6.1	0.92	0.006
Lime-cement mortar	7.2	0.88	0.008

Table 2. Heat transfer coefficient calculation of the ultra-low energy building enclosure roof

Roof Material	Thickness (mm)	Thermal Conductivity (W/m·K)	Thermal Resistance (m^2·K/W)
Roof surface and floor tiles	1.7	2.25	0.001
Cement mortar	23.6	0.92	0.026
Waterproof membrane	4.1	/	/
Fine aggregate concrete	31.6	1.68	0.016
Extruded polystyrene board	312.8	0.03	7.526
Lightweight aggregate concrete cushion	31.7	0.62	0.047
Waterproof membrane	4.2	/	/
Cement mortar leveling layer	21.3	0.92	0.021
Reinforced concrete	114.8	1.68	0.062

Table 3. Unit exergy cost of ultra-low energy building enclosures

Type	Operational Cost (CNY/m^2)	Investment Cost (CNY/m^2)	Management Cost (CNY/m^2)	Unit exergy Cost (CNY/m^2)
Before exergy cost optimization	1,256.3	1,269.2	378.5	2,569.4
After exergy cost optimization	1,248.5	1,145.8	345.2	2,458.7

Table 4. Energy consumption, CO_2 emissions, and exergy consumption during the operational phase of ultra-low energy buildings

Category	Annual Cooling Energy Consumption (kWh)	Annual Heating Energy Consumption (kWh)	CO_2 Emissions (kg)	Cooling Exergy Consumption (CNY/m^2)	Heating Exergy Consumption (CNY/m^2)
After exergy cost optimization	112,458.25	15,263.56	62,585.23	5,148.69	726.35
Before exergy cost optimization	112,458.36	17,852.36	67,894.25	5,126.39	958.61

A comparative analysis of the data in Table 3 reveals significant variations in cost components before and after exergy cost optimization for ultra-low energy building enclosures. Prior to optimization, the operational cost was 1,256.3 CNY/m^2, while the investment cost reached 1,269.2 CNY/m^2. After optimization, these values decreased to 1,248.5 CNY/m^2 and 1,145.8 CNY/m^2, respectively, indicating a notable reduction in both categories. Similarly, management costs were reduced from 378.5 CNY/m^2 before optimization to 345.2 CNY/m^2 after optimization. As a result, the unit exergy cost decreased from 2,569.4 CNY/m^2 to 2,458.7 CNY/m^2, demonstrating a significant overall cost reduction. These findings indicate that the exergy cost optimization measures are highly effective. Among the cost reductions, investment and management costs exhibited the most pronounced decreases, particularly investment costs. This decline underscores the impact of refined material selection and construction management strategies, facilitated by optimization of façade insulation design, window-frame-to-wall junctions, and the application of high-efficiency thermal bridge insulation technologies, in achieving improved cost control.

A comparative analysis of the data presented in Table 4 demonstrates a significant improvement in energy consumption, CO_2 emissions, and exergy consumption following exergy cost optimization. First, annual cooling energy consumption remained nearly unchanged, with values of 112,458.25 kWh after optimization and 112,458.36 kWh before optimization, indicating minimal variation. However, annual heating energy consumption decreased from 17,852.36 kWh to 15,263.56 kWh, representing a reduction of approximately 14.5%, highlighting the effectiveness of optimization measures in improving heating efficiency. Furthermore, CO_2 emissions during operation decreased by approximately 7.8%, from 67,894.25 kg before optimization to 62,585.23 kg after optimization, reflecting the energy-saving benefits of the optimized design. Regarding exergy consumption during operation, cooling exergy consumption exhibited negligible change, with values of 5,148.69 CNY/m^2 after optimization and 5,126.39 CNY/m^2 before optimization. However, heating exergy consumption was significantly reduced by approximately 24.3%, decreasing from 958.61 CNY/m^2 before optimization to 726.35 CNY/m^2 after optimization. This reduction indicates that improvements in thermal bridge mitigation and insulation design effectively controlled heat loss, leading to lower overall heating exergy consumption.

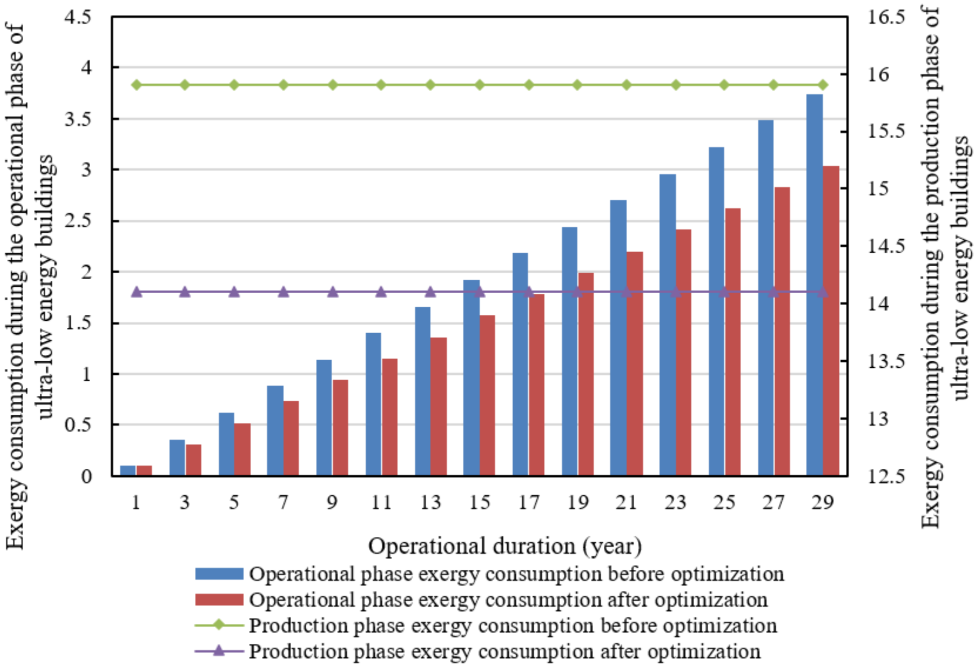

Figure 4. Life-cycle exergy savings of ultra-low energy buildings at different operational durations before and after exergy cost optimization

A comparative analysis of the data presented in Figure 4 reveals substantial differences in exergy consumption during both the operational and production phases before and after exergy cost optimization. During the operational phase, the exergy consumption before optimization increased from 0.1 in the first year to 3.74 in the 29th year, whereas the optimized design resulted in a lower increase, from 0.1 to 3.04, demonstrating a clear downward trend. At each time interval, the exergy consumption in the operational phase after optimization remained consistently lower than before optimization. This trend was particularly evident over the long term, where the exergy consumption was 2.62, significantly lower than the 3.22 recorded before optimization. In the production phase, exergy consumption remained constant at 15.9 before optimization, while a reduction to 14.1 was observed after optimization, further highlighting the benefits of an optimized design in reducing exergy consumption. Overall, the optimized design exhibited energy-saving effects in both the operational and production phases. The most pronounced benefits were observed in the cumulative exergy savings over long-term operation, where the total life-cycle exergy consumption of the building was significantly reduced through optimization strategies.

Analysis of the data in Figure 5 indicates that the linear heat transfer coefficient of the thermal bridge varies as a function of unit exergy cost, following a discernible trend. At lower unit exergy costs, the linear heat transfer coefficient tends to be higher. For instance, when the wall height is 0.5 m, the linear heat transfer coefficient is 0.1435. As the unit exergy cost increases, the linear heat transfer coefficient gradually decreases. Notably, at a unit exergy cost of 250, the linear heat transfer coefficient of a 0.5 m-high wall drops to 0.137. Beyond this point, further increases in unit exergy cost do not result in a significant reduction in the linear heat transfer coefficient. Instead, slight fluctuations are observed, suggesting that within certain cost ranges, the linear heat transfer coefficient stabilizes and ceases to decrease significantly.

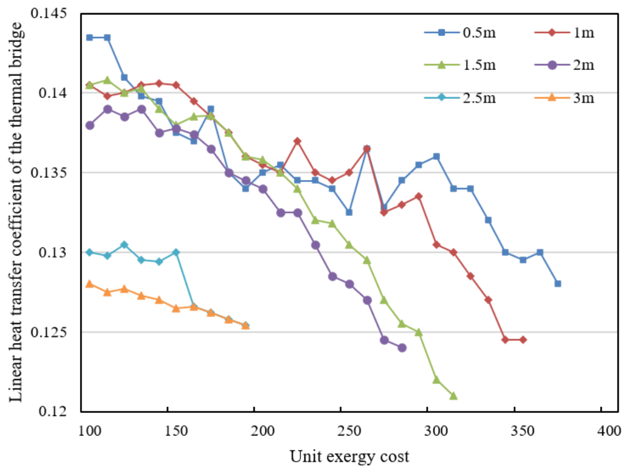

Figure 5. Linear heat transfer coefficient of the thermal bridge under different exergy costs

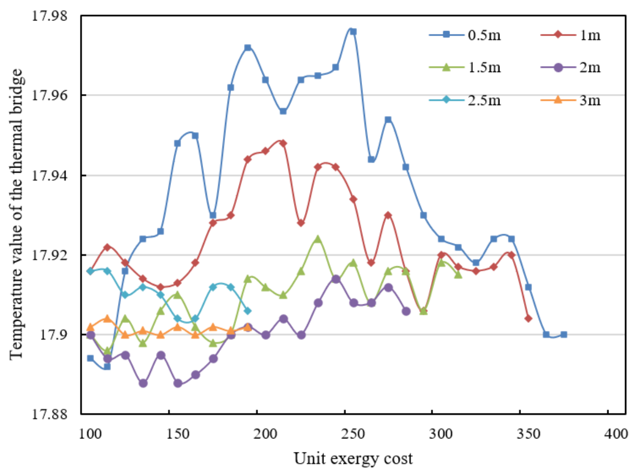

Figure 6. Temperature value of the thermal bridge under different exergy cost optimization schemes

Analysis of the data in Figure 6 indicates that temperature variations of the thermal bridge exhibit a distinct trend under different unit exergy costs. For a wall height of 0.5 m, when the unit exergy cost is 100, the temperature of the thermal bridge is 17.894°C. As unit exergy cost increases, a slight rise in thermal bridge temperature is observed. For instance, at a unit exergy cost of 350, the temperature of the thermal bridge increases to 17.950°C, demonstrating a minimal change. A similar trend is observed across other wall heights. Overall, as unit exergy cost increases, thermal bridge temperatures fluctuate within a narrow range across different wall heights, with variations generally maintained at approximately ±0.05°C. This suggests that within different cost intervals, the impact of optimization design on thermal bridge temperatures remains relatively insignificant, and the trend remains consistent across different wall heights.

The exergy cost optimization strategy proposed in this study focuses on enhanced façade insulation design, optimized window-frame-to-wall junctions, and high-efficiency thermal bridge insulation techniques to effectively mitigate thermal bridge effects and improve building energy efficiency. Based on the experimental data, temperature fluctuations of the thermal bridge remain minimal under different unit exergy cost scenarios, exhibiting a stable trend. This finding indicates that the optimization design effectively maintains low thermal bridge temperatures while ensuring minimal temperature fluctuations, thereby reducing heat loss. Notably, in the unit exergy cost range of 200 to 250, temperature stability is most pronounced, with the smallest fluctuation range, which can be attributed to the application of multilayer insulation materials and finely engineered thermal break layers in the optimization scheme. Overall, the optimization design successfully lowers thermal bridge temperatures while maintaining minimal temperature fluctuations across different wall heights and unit exergy cost intervals, ensuring long-term energy efficiency in buildings.

5. CONCLUSION

This study primarily focused on two key aspects. First, a systematic analysis of the life-cycle energy and exergy consumption of ultra-low energy building enclosures was conducted, evaluating the impact of thermal bridge effects throughout the building's life cycle. Second, a quantitative exergy cost model for ultra-low energy building enclosures was developed, providing a scientifically comprehensive assessment tool. During the research process, an exergy cost optimization strategy was implemented, incorporating façade insulation design, window-frame-to-wall junction optimization, and high-efficiency thermal bridge insulation techniques to ensure the lowest possible thermal bridge temperature while maintaining reasonable unit exergy costs. Data analysis demonstrated that under varying unit exergy costs, changes in the linear heat transfer coefficient and temperature of the thermal bridge confirmed the effectiveness of the optimization design, particularly in achieving optimal energy efficiency and balance within medium-to-high cost ranges. This study holds significant implications for the design and optimization of ultra-low energy buildings. By constructing and validating the quantitative exergy cost model, a scientific and comprehensive evaluation tool was provided for building design, facilitating the accurate assessment and optimization of the impact of thermal bridge effects on life-cycle energy consumption. The results indicate that reasonable control of unit exergy costs, combined with refined thermal break layer design—particularly within medium-to-high cost ranges—can achieve the best thermal bridge control and energy efficiency balance, thereby enhancing both energy savings and economic benefits in buildings.

Despite the valuable conclusions drawn, certain limitations remain in this study. First, the study data focused primarily on specific cost and wall height combinations, lacking a more comprehensive examination of additional variables. Second, the analysis was predominantly based on simulation data, and real-world applications may be influenced by construction quality, material performance variations, and other factors. Additionally, the long-term effects of material aging and insulation degradation were not extensively explored, which may impact actual energy performance. Future research should prioritize the following areas: a) Expanding the data sample to include a broader range of cost intervals, wall height combinations, and climatic conditions to enhance the applicability and generalizability of the model. b) Conducting long-term monitoring of real-world building projects to validate the effectiveness of the optimization design in practice and accumulate empirical data. c) Exploring advanced high-efficiency insulation materials and innovative thermal break technologies to further enhance thermal bridge control and provide more effective technological support and theoretical foundations for the development of ultra-low energy buildings. By addressing these areas, the quantitative exergy cost model can be further refined and optimized, contributing to the sustainable development of ultra-low energy buildings.

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