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A Revit-Energy Plus Methodology for Carbon-Negative Retrofit of Existing Residential Buildings

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Abstract. The proportion of carbon emissions from the global building sector in energy-related carbon emissions has remained high for a long time, and existing buildings, due to their large scale and low energy efficiency, have become a key area for low-carbon transformation. Faced with the reality of high heating energy consumption and urgent need for renovation in frigid climate zones, promoting building energy efficiency upgrades and life-cycle carbon reduction has become an important path for green development. This study focuses on a public building built in the 1990s in Tieling County, Liaoning Province, addressing its problems of insufficient thermal insulation performance of the building envelope, poor indoor comfort, and high energy intensity, and conducting a systematic energy-saving renovation and life-cycle carbon reduction study. Through a dual-path strategy of low-carbon material substitution and energy efficiency improvement, the project achieved significant results: a 40.9% reduction in total carbon footprint, a 46.6% reduction in occult carbon, and a 20.9% reduction in operational carbon. The results indicate that the synergistic effect of low-carbon material application and passive energy-saving design is key to achieving deep decarbonization in the renovation of existing buildings in frigid regions, providing a replicable technical path for similar projects.

Keywords: Existing building renovation, Carbon emission reduction, Life cycle assessment, Building energy consumption.

1. Introduction

China's building sector accounts for nearly 40% of the total carbon emissions of the whole society. Among them, existing buildings have become the key and difficult points for energy conservation and carbon reduction due to low construction standards and poor building envelope performance. In the frigid Northeast region, the heating season lasts for 5 months, and the extreme winter temperature can reach -30°C. Heating accounts for more than 60% of building energy consumption, making carbon emission reduction even more urgent. In addition, although residential buildings are the main objects of life cycle assessment (LCA) research, there is still insufficient research on in-depth renovation of old residential buildings in frigid regions under the material-energy efficiency synergistic carbon reduction path. This study selects a typical old public building in Tieling County,

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Liaoning Province, with an annual energy consumption intensity of up to 351.5 kWh/m² and a winter room temperature of only 12-15 ℃, facing the dual challenges of comfort and carbon emissions [1].

This study first employs a life-cycle assessment approach to systematically quantify the changes in carbon emissions before and after the retrofit. Secondly, it explores two main emission reduction pathways. The first focuses on material substitution strategies, directly reducing occult carbon by using lightweight concrete, Low-E glass, and wood fiber insulation. The second emphasizes energy efficiency improvement strategies, reducing operational energy consumption by optimizing the performance of the building envelope. Ultimately, the study reveals the trade-off between material carbon footprint and operational carbon emissions under frigid climate conditions and verifies the synergistic effects of the systematic retrofit scheme, thus providing valuable data support and practical reference for the low-carbon retrofitting of existing buildings.

2. Carbon emission assessment and emission reduction strategies

2.1. Project background and technical challenges

This project is located in Tieling County, Liaoning Province. The original building was constructed in the 1990s. The local climate is characterized by a long, cold season, with a heating season lasting five months (November to March of the following year). Extreme winter temperatures reach -30°C, while extreme summer temperatures reach 35°C, resulting in a significant temperature difference between winter and summer. The building before renovation had the following core problems:

The building envelope exhibited significant deficiencies before the renovation. The exterior walls lacked insulation during use, and the windows retained a single-pane glazing system, resulting in a noticeable cold feeling at the window openings. Simultaneously, the building's indoor thermal environment failed to meet basic comfort requirements in winter, with indoor air temperatures only maintained at approximately 12–15°C. During operation, the building also exhibited the dual characteristics of high energy consumption and high carbon emissions, with an annual energy intensity of 351.5 kWh/m² and a life-cycle carbon footprint of 500.5 tons of CO_2 equivalent. To address these issues, the project constructed a dual-track strategy framework of "direct carbon reduction" and "energy efficiency-driven" approaches.

2.1.1. A review of direct carbon reduction and energy efficiency improvement strategies in building renovation

In direct carbon reduction strategies, the substitution of high-carbon materials constitutes a key pathway for building carbon emission reduction. Taking silicate cement concrete, with a carbon emission coefficient as high as 441 $kgCO_2e/m^3$, as an example, replacing it with lightweight concrete, with a carbon emission coefficient of only 339 $kgCO_2e/m^3$, not only significantly reduces the structural weight but also reduces carbon emissions per unit volume of material by 23.1%, thus forming the most significant single measure in terms of emission reduction contribution. Simultaneously, replacing ordinary laminated flat glass with Low-E glass, whose carbon emission coefficient drops from 146 to 120 $kgCO_2e/m^2$, can reduce occult carbon by 17.8% during the manufacturing stage and, thanks to its low emissivity, reduce heating and cooling energy consumption during building operation by 15–20%, achieving a simultaneous reduction in occult carbon and operational carbon. In energy efficiency-driven strategies, strengthening the insulation system achieves long-term energy-saving benefits through low-carbon materials. The newly added

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wood fiber and glass fiber insulation materials have carbon emission coefficients of only 8.9 and 8.47 $kgCO_2e/m^3$, respectively. They can form a highly efficient insulation layer in roofs, exterior walls, and interior partitions, achieving significant energy savings during operation at extremely low carbon costs, thus creating a "leveraged carbon reduction" effect. Furthermore, the in-situ foamed insulation material achieves seamless filling of building gaps with a low emission level of 11.4 $kgCO_2e/m^3$, improving building airtightness by more than 40%, thereby effectively reducing heat loss through infiltration and further promoting the reduction of operational carbon emissions.

2.2. Overall emission reduction results

This renovation project achieved a significant reduction in the building's carbon footprint throughout its entire lifecycle through systematic measures:

Table 1. Comparison of key carbon indicators before and after renovation

Indicators	Before Renovation	After Renovation	Improvement Effect
Total carbon footprint	500.5 t	296.0 t	↓ 40.9%
Operational carbon	111.9 t	88.5 t	↓ 20.9%
Embodied carbon	388.6 t	207.5 t	↓ 46.6%
Energy use intensity	351.5 kWh/m^2	288.4 kWh/m^2	↓ 18.0%

As shown in Table 1, this project achieved significant life-cycle carbon reduction after the renovation. The total carbon footprint decreased from 500.5 tons to 296.0 tons, a reduction of 40.9%, indicating a clear synergistic effect between systematic energy conservation and carbon reduction measures. The data in the table also shows that embodied carbon contributed the most to the reduction, with a decrease of 46.6% (from 388.6 tons to 207.5 tons), mainly due to the application of lightweight materials and localized procurement strategies. In contrast, operational carbon decreased from 111.9 tons to 88.5 tons, a reduction of 20.9%, reflecting the effectiveness of improved building envelope insulation performance and optimized heating system in reducing heating energy consumption. Simultaneously, energy intensity decreased by 18.0%, verifying the positive impact of passive energy-saving design on building performance in cold regions. Overall, Table 1 clearly demonstrates the dominant role of embodied carbon reduction in this renovation, while operational carbon optimization further consolidated the life-cycle carbon reduction achievements.

2.3. Embodied carbon emission reduction analysis

The occult carbon emissions after the renovation decreased by 46.6% (from 388.6 tons to 207.5 tons), contributing 88.6% of the total emission reduction, showing a very significant emission reduction effect. This result is mainly due to three factors: lightweight concrete reduced the amount of structural materials by about 22%, the carbon intensity of glass and insulation materials decreased by more than 50%, and the transportation radius of the main materials was controlled within 200 kilometers, thereby reducing carbon emissions during the transportation stage by 35%. The above strategy strictly follows the design principle of Life Cycle Thinking (LCT). Chiara Passoni pointed out that the LCT method must be adopted in the early stage of renovation design, which is the only way to minimize the environmental impact of the building throughout its entire life cycle [2]. It should be noted that the occult carbon emissions after the renovation still account for 70% of the

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total carbon footprint, which is highly consistent with the study of Rodrigues et al. [3]. Their analysis of the renovation of existing buildings in Portugal showed that under the optimistic scenario of 90% decarbonization of the power grid, 72% of the renovation schemes showed the characteristic of occult carbon dominating [3].

2.4. Operational carbon emission reduction analysis

Annual operational carbon emissions decreased from 111.9 tons to 88.5 tons, a reduction of 20.9%, driven primarily by three factors. Passive energy-saving measures reduced heating demand by 29.4% by decreasing the heat transfer coefficient of the building envelope by 40%, laying the foundation for emissions reduction during operation. Optimization of the energy structure further improved the efficiency of the heating system and reduced the carbon emission factor per unit of heat by 12%, reducing operational emissions at the source. Meanwhile, demand-side response strategies, through thermal storage floor systems, enabled time-of-use heating, effectively reducing peak loads and further reducing carbon emissions generated during operation.

2.5. Retrofit materials and technical measures

Table 2. Details of building material improvements

Material Type	Material Description Before Renovation	Material Description After Renovation	Function and Improvement
Exterior Wall Insulation	Basically no insulation material	External Insulation Layer (EIFS) and wood fiber insulation	Improves insulation performance, reduces energy consumption, and lowers operational carbon emissions
Wall Materials	Ordinary concrete and gypsum board	Lightweight concrete blocks and gypsum board	Reduces material usage and lowers implicit carbon emissions
Roof Materials	Ordinary concrete and ordinary insulation	Cast-in-place concrete and reinforced dense concrete	Improves roof insulation performance and reduces energy consumption
Windows	Ordinary glass	Triple-pane Low-e glass	Improves window insulation performance and reduces energy consumption
Internal Partitions	Ordinary gypsum board	Gypsum board with mineral wool	Improves internal partition insulation performance and facilitates zoned temperature control

As shown in Table 2, the key aspects of the material and technical modifications in this project focused on improving the performance of the building envelope and reducing material-related occult carbon. First, the exterior walls were upgraded from almost no insulation to an EIFS system and wood fiber insulation layer, significantly improving the insulation capacity of the building envelope and reducing heating energy consumption at the source. Second, the wall material was replaced with lightweight concrete blocks, reducing material usage and effectively lowering carbon dioxide emissions. The roof section improved thermal performance by using reinforced dense concrete and optimized insulation layers, further reducing heat loss in winter. Simultaneously, the windows were upgraded from ordinary glass to triple-glazed Low-E glass, significantly improving heat transfer performance and enhancing passive energy-saving effects. Finally, the interior partitions used gypsum board with mineral wool filling, improving insulation performance and facilitating zoned temperature control. Overall, the material substitutions and structural optimizations shown in Table

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2 constitute the core technical path of this renovation, laying the foundation for subsequent energy consumption reduction and carbon emission reduction.

2.6. Discussion

This part achieved a significant reduction in carbon emissions from existing buildings through systematic energy-saving renovations under the harsh climate conditions of Tieling. Related practices further demonstrate that the overall strategy is far superior to individual measures. The core experience is first reflected in the strong synergistic effect: single material substitution usually only produces a linear carbon reduction effect, while systematic renovation can form a super-additive effect, making the total carbon emission reduction rate reach 40.9%, which is significantly greater than the sum of the independent contributions of each measure. In their review, Obead et al. pointed out that sustainable material renovation can reduce energy consumption by 54% and carbon emissions by 64%, but this study did not quantify the synergistic amplification effect between materials and energy efficiency [4]. Secondly, the renovation process shows that the emission reduction potential of implicit carbon (46.6%) is significantly higher than that of operational carbon (20.9%). Therefore, implicit carbon control should be the priority design principle for the renovation of existing buildings, and key breakthroughs should be achieved through the selection of lightweight and localized materials. Equally important, climate-adaptive technologies play a decisive role in frigid regions. Research has validated that external wall insulation, high-performance doors and windows, and airtightness treatment constitute the most effective "three-in-one" approach, with passive insulation strategies taking precedence over active system upgrades. Finally, the fact that occult carbon still accounts for 70% of the total carbon footprint after renovation underscores the need for future building carbon reduction to adhere to a life-cycle perspective, controlling the carbon footprint of materials from the design stage and accelerating the promotion of revolutionary technologies such as low-carbon cement and bio-based materials [5].

3. Basic case of old-style residential building simulation in cold region

According to the zoning standards and methods of the Code for Thermal Design of Civil Buildings (GB50176-2016), Tieling City is located in northeastern Liaoning Province and belongs to the "severe cold region." The most frigid regions are mainly the three northern regions of my country: Northeast, North China, and Northwest. These regions experience low temperatures for nearly half the year, resulting in significant energy consumption for building heating. Therefore, the heat consumption indicators of buildings must be controlled during the design phase [6]. Therefore, the renovation of buildings mainly focuses on the long, cold winters, and must fully meet the winter insulation requirements; summer heat protection is generally not considered.

Taking into account the climate and environmental conditions, this study uses Revit to establish a basic model and as the analysis tool. The old residential building has a total floor area of 1546.77㎡, a land area of 1546.77㎡, seven floors, a total building height of 24m, and a symmetrical layout.

3.1. Overview of analytical methods

This analysis systematically evaluates the individual and synergistic effects of various energy-saving measures on building energy use by simulating building energy consumption performance under different combinations of insulation strategies. Based on the baseline energy consumption before the

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renovation (946.11), the energy-saving effects of single and hybrid strategies were simulated, respectively.

As is shown in Table 3, Figure 1 and Figure 2, this is a multi-story, old-style residential building located in a cold climate zone, featuring a symmetrical and regular floor plan. The building is of moderate size, with a multi-story structure and a relatively square proportion. The room dimensions are uniform, and the space is clearly and regularly divided, reflecting the emphasis on practicality and standardized construction characteristic of residences during that period. Both the building's exterior and interior layout reflect the basic considerations of insulation and structural stability for residences in cold regions.

Table 3. Basic information of the basic model

Gross floor area	1546.77㎡
Building footprint	220.97㎡
Usable area of room	1546.77㎡
Number of floors	7 floors
Building height	24m
Length and width dimensions (in terms of longest side)	21.6m*14.1 m
Layout characteristics	Symmetrical layout
Average size of rooms	3.6m*5.4m rooms

Figure 1. Basic model rendering (picture credit: original)

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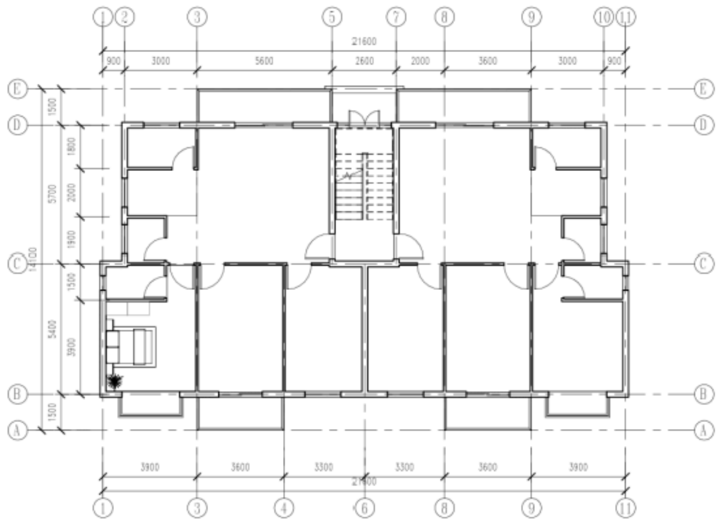

Figure 2. Floor plan (picture credit: original)

Table 4. Basic building attributes of the basic model

Building type	equipment
Building operating schedule	Year-round university
Hvac system	Central VAV, HW heating, chiller 5.96COP, boiler efficiency 84.5
Fresh air information	Fresh air per person(P):8.00L/s
External mass wall	Lightweight construction - typical mild climate insulation
Volume interior wall	Lightweight construction - no insulation
Volume roof	Typical insulation - light roofing
Bulk glass	Double clear - no coating

As shown in Table 4, the parameters for the building simulation analysis were set in Revit. Since this paper does not involve updating or optimizing building equipment, the default settings were used for all equipment selections. For the construction level, to simulate the lack of insulation design in older buildings, the following settings were adopted: Lightweight construction - typical mild climate insulation, Lightweight construction - no insulation, Typical insulation - light roofing, and Double clear - no coating. This facilitates and demonstrates the optimization of energy parameters before and after the renovation.

4. Comparative analysis and optimization strategy of building schemes

4.1. Renovation of old buildings

According to the research of Jiawen Hou et al., for areas requiring thermal insulation, the U-value and E-value of window glass correspond to different annual energy demand (ED) and economic benefits (EB), respectively. For buildings facing due south, a U-value of 1.0 corresponds to the lowest ED (31.34), and an E-value of 0.95 corresponds to the lowest ED (33.84 kWh/m²). Therefore, this study selects high-transparency Low-E insulated glass with E=0.95 and U=1.0.

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Similarly, according to the research by Jiawen Hou et al., the maximum acceptable cost prices of window systems correspond to different Window-to-Wall Ratio (WWR) and Air Changes per Hour (ACH) when the target Dynamic Power Path (DPP) equals 25 years and the insulation thickness equals 50 mm [7].

As shown in Table 5, it adopted differentiated renovation strategies for different components of the building envelope. Each renovation improved the overall energy efficiency of the building from the perspectives of reducing heat loss, improving thermal performance, and optimizing indoor heat distribution.

Table 5. Basic building attributes of the basic model

Building componen ts	Material description before renovation	Description of materials after modification	Functions and Enhancements
Exterior wall	Ordinary concrete and gypsum board	Internal insulation uses XPS insulation layer plus gypsum board, and external insulation uses EIFS system.	Reduce cooling and heating load caused by room temperature fluctuations
roof	Cast-in-place concrete and ordinary insulation layer	Add a mineral wool inner insulation layer inside the existing roof.	Reduce direct radiant heat gain and roof heat loss.
Window glass	Ordinary glass	Triple-layer high-transparency low-e glass	Increase radiative heat gain and reduce window thermal bridge effect
floor	Laminate flooring	Thermal Wood Flooring	Reduce the required heating temperature and distribute heat evenly.
Interior walls	Brick walls and ordinary gypsum board	Adding mineral wool to gypsum board	Control the cooling and heating temperatures in different areas of the room

4.2. Energy intensity comparison analysis

This study categorizes various thermal insulation construction methods into vertical and horizontal insulation structures, and conducts simulation analyses for each. Table 6 presents the energy analysis results for three renovation strategies: roof and floor renovation only, window and wall renovation only, and a hybrid application of all strategies. To facilitate comparison and analysis with other similar studies, this paper selects energy intensity per unit area as the unit of energy analysis.

Table 6. Energy consumption analysis of different transformation strategy in the basic model

Stats	Total Site Energy / Total Source Energy [MJ/m2]	District Heating Water Intensity[MJ/m2]	District Cooling Intensity[MJ/m2]	Electricity Intensity [MJ/m2]
Basic model	946.11/3074.13	685.29	108.02	152.80
Roof and floor renovation only	913.20/2961.47	655.67	105.75	151.78
window and wall renovations only	800.16/2498.92	522.53	127.12	150.50
Full-strategy hybrid application	759.30/2357.45	483.82	24.65	150.83

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Table 6 shows that wall and window renovations contributed the most to the overall energy consumption reduction, decreasing total energy consumption by 15.4%, with a significant decrease in heating energy consumption, demonstrating the fundamental role of the building envelope in insulation. Walls constitute the largest proportion of the building envelope and have a significant insulation effect; improvements in glass reduce thermal bridging and enhance the building's insulation capacity. Meanwhile, cooling energy consumption increased, possibly due to reduced heat dissipation at night in summer and the absorption of solar energy by high-transparency low-e glass in summer.

Roof and floor renovations alone had a limited impact on improving cooling energy consumption, decreasing total energy consumption by 3.5%, mainly due to reduced heating energy consumption, indicating that the original roof and floor had some insulation effect. Consider using lower-cost insulation materials for supplementary insulation.

The combined effect of the entire strategy far exceeded the sum of the individual strategies, resulting in a 19.8% decrease in total energy consumption and a 29.4% decrease in heating energy consumption, validating the synergistic value of systematic energy-saving design.

Considering economic factors, this study uses a total of 50 mm of insulation layer, consisting of 20 mm external wall insulation and 30 mm internal wall insulation, in the building [7].

Beyond building structure, there are many other methods to improve building performance. The concept of green roofs, also known as living roofs, is a good example of a passive strategy that can improve building energy efficiency and ambient air quality. Given the same solar reflectance coefficient on the outer surface, the double-skin roof demonstrates a higher comprehensive evaluation index compared to the single-skin roof. This indicates that the double-skin design provides superior integrated benefits, both economically and environmentally [8]. In subsequent studies, it will take into account the impact of double-layered roofs and the ventilation involved on building energy consumption. However, current research on the modification of building envelopes is still limited to analyzing the impact of changes in single materials. The Taguchi method was used in the study by Aidin Nobahar Sadeghifam et al. To analyze the signal-to-noise ratio and mean of thermal modifications, which can be used as a reference in future studies [9]. The research by Jiawen Hou et al. compiled a table showing the economic benefits corresponding to different window-to-wall ratios and glass e-values and u-values. This study can also refer to this method to quantitatively analyze carbon emission reduction and energy consumption reduction, and to study the usage methods of various building materials and building structures [7]. Future research will consider systematically optimizing building functional areas and spatial characteristics to create energy-efficient interior layouts and enhance building thermal performance at the design level. For example, green roofs, also known as living roofs, are a good example of passive strategies that can improve building energy efficiency and ambient air quality [10].

5. Conclusion

Current research focuses on the optimization of building envelope components, but does not include the impact analysis of indoor functional layout on energy consumption. Subsequent research will further quantify the economic cost and feasibility of renovation strategies, and construct a multi-objective optimization model of carbon reduction, economic benefits and technical feasibility. studied multiple climate zones in Australia and found that global warming will cause the risk of building overheating to surge from the current average of 4.91% to 23.98% in 2050, and renovation schemes optimized for the current climate may not be able to maintain performance in the future. This warns that renovations in cold regions need to proactively assess the "dual impact" of climate

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warming on the decline in winter heating demand and the increase in summer overheating risk, and embed dynamic climate adaptation mechanisms in the material-energy efficiency synergy strategy.

This project, taking residential buildings in Tieling as an example, studied energy-saving and emission-reduction strategies for traditional uninsulated residential buildings under severe cold thermal zoning. It simulated the impact of changes in different types of building envelopes on building carbon emissions and energy consumption, successfully achieving a significant reduction in building carbon emissions and a comprehensive improvement in energy performance. The comprehensive technical strategies adopted during the renovation included improving the thermal insulation performance of the building envelope, applying high-efficiency window systems, and selecting low-carbon materials. Simulation analysis and research indicate that in residential renovation projects under cold thermal zoning, priority should be given to economically adapting thermal modifications to the walls and windows for the building envelope. For roof and interior floor modifications, lower-cost methods should be used to supplement insulation. This study focuses on optimizing building components for energy conservation and emission reduction. Since the project focuses on the renovation strategy of old buildings, the economic factors and feasibility of the renovation are also very important. Currently, considerations in these two aspects are limited to qualitative analysis. It is necessary to conduct further in-depth research and quantitatively analyze the four factors: carbon emission reduction, energy consumption reduction, economic benefits, and feasibility

Authors contribution

All the authors contributed equally and their names were listed in alphabetical order.

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