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Economic Evaluation and Budgeting Methods for Green Material Replacement in Existing Building Renovation

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Abstract: Against the backdrop of global "dual carbon" goals, the renovation of existing buildings has become a critical pathway for achieving energy conservation and emissions reduction in the construction sector. As a core element of renovation projects, the application of green materials can significantly enhance building environmental performance, yet it is often accompanied by increased initial costs, leading to challenges in project decision-making. This paper focuses on the economic aspects of green material replacement in existing building renovations, systematically reviewing the definition and classification of green materials and their typical application scenarios in retrofits. It provides an in-depth analysis of the applicability and limitations of traditional economic evaluation methods—such as static payback period, dynamic net present value (NPV), and internal rate of return (IRR)—in the context of green material applications. Building on this, the study develops a comprehensive economic evaluation framework that integrates life cycle cost (LCC) analysis, incremental cost-effectiveness ratio (ICER), sensitivity analysis, and risk-adjusted discount rates. Additionally, for the budgeting process, innovative approaches are proposed, including detailed bill of quantities preparation based on BIM technology, establishment of a green material price database, dynamic price adjustment mechanisms, and contingency fund allocation. The research aims to provide scientific and practical decision-making tools for governments, owners, design units, and construction companies, thereby promoting the scalable and economically viable application of green materials in existing building renovations.

Keywords: existing building renovation; green materials; economic evaluation; budget preparation

Introduction

According to statistics from the United Nations Environment Programme (UNEP), the global construction industry consumes nearly 40% of energy and generates approximately 30% of greenhouse gas emissions. In China, the vast majority of existing buildings were constructed before 2000, and they commonly suffer from issues such as high energy consumption, poor comfort levels, and outdated functionality. Green retrofitting of these existing buildings, rather than large-scale demolition and reconstruction, is an inevitable choice for achieving resource conservation, environmental protection, and sustainable urban development. Green materials—building materials that have minimal environmental impact, low resource and energy consumption, and are harmless to human health throughout their entire lifecycle, from raw material extraction and production to use and disposal—serve as the core enablers of green retrofitting. However, the market premium for green materials (typically 10%–50% higher than conventional materials) has led many potential retrofitting projects to stall due to initial investment pressures. How to scientifically and comprehensively evaluate the long-term economic benefits of green material substitution and, based on this, prepare accurate and reasonable project budgets has become a critical bottleneck hindering the large-scale adoption of green retrofitting for existing buildings. Therefore, this paper aims to develop a rigorous, practical, and integrated methodology for economic assessment and budget preparation to bridge the gap between theory and practice.

1. Application Characteristics of Green Materials in Existing Building Renovation

1.1 Connotation and Classification of Green Materials

Green materials do not refer to a specific product but rather encompass a broad range of categories. Based on their functions in construction, they can be primarily classified into: (1) Enclosure materials: such as high-performance thermal insulation materials (vacuum insulation panels, aerogels), energy-efficient windows and doors (Low-E insulated glass, thermally broken aluminum alloy window frames), reflective thermal insulation coatings, etc. (2) Interior decoration and functional materials: including low-VOC (volatile organic compounds) coatings, formaldehyde-free engineered wood, recycled aggregate concrete, photocatalytic self-cleaning materials, etc. (3) Equipment and system materials: such as high-efficiency HVAC equipment, LED lighting systems, renewable energy integration components (photovoltaic tiles, solar thermal collectors), etc.

1.2 Particularities in the Replacement Process

Unlike new construction, green material replacement in existing building retrofits has distinct characteristics: firstly, strong constraints—limited by the original structural load, spatial dimensions, and pipeline layout, the selection and installation methods of new materials require high adaptability [1]. Secondly, incremental costs are prominent—retrofits typically involve replacing only certain components, making the price difference between green and conventional materials (i.e., incremental cost) a key decision factor. Thirdly, benefits are diversified—advantages extend beyond direct energy savings to include hidden benefits such as health improvements from enhanced indoor environmental quality, increased work efficiency, and added asset value.

2. Economic Evaluation Methodology System for Green Material Substitution

Traditional economic evaluation methods exhibit significant limitations when applied to green materials. For instance, the static payback period method overlooks the time value of capital and the sustained benefits in later project stages, while simplistic cost-benefit ratio approaches struggle to quantify non-monetized environmental and social benefits. To address these gaps, this paper proposes a multidimensional comprehensive evaluation framework.

2.1 Life Cycle Cost (LCC) Analysis

Life Cycle Cost analysis is the cornerstone for assessing the economic viability of green materials. It incorporates the total costs of a project from planning, design, construction, operation, maintenance, through to final demolition, as expressed in the following formula:

$$LCC = C_I + C_R + \sum_{t=1}^{n} \frac{C_{OM,t} + C_E}{(1+r)^t} - \frac{S}{(1+r)^n}$$

among which:

C_I: Initial investment cost (including incremental cost of green materials)

C_R: Renovation Construction Cost

$C_{OM,t}$: Operation and maintenance costs in year t

C_E: Energy cost in year t

S: End-of-period residual value

r: Discount Rate

n: Analysis period (usually 20-30 years)

By comparing the life cycle cost (LCC) of the green material solution with the baseline solution (traditional materials), one can intuitively assess its long-term economic advantages.

2.2 Incremental Cost-Effectiveness Ratio (ICER)

ICER is an indicator that measures the incremental benefits per unit of additional investment, particularly suitable for decision support.

$$\mathrm{ICER} = \frac{\Delta \mathrm{LCC}_{\mathrm{cost}}}{\Delta \mathrm{Benefit}}$$

Here, $\Delta \mathrm{LCC}_{\mathrm{cost}}$ represents the difference in LCC between the two schemes (typically a negative value, indicating cost savings), and ΔBenefit denotes the incremental benefits, which include: (1) Direct benefits: energy cost savings, water resource savings, and reduced maintenance expenses. (2) Indirect benefits: monetized health benefits and productivity improvements, assessed through methods such as Willingness-to-Pay (WTP). (3) External benefits: carbon emission reduction benefits (which can be converted using carbon trading market prices). A smaller (or negative) ICER value indicates better economic performance of the green material scheme.

2.3 Sensitivity Analysis and Monte Carlo Simulation

The economic viability of green material projects is influenced by various uncertainties, such as fluctuations in energy prices, discount rate selection, and material lifespan. Through single-factor or multi-factor sensitivity analysis, key variables with the greatest impact on outcomes can be identified [2]. Furthermore, by employing Monte Carlo simulation, probability distributions are assigned to input variables, and thousands of random sampling calculations are performed to derive the probability distribution of LCC or NPV (Net Present Value). This approach provides decision-makers with risk intervals rather than a single deterministic value.

2.4 Risk-Adjusted Discount Rate

Given the certain market and technological risks associated with green technology, using the social discount rate or industry average discount rate may underestimate these risks. Introducing the Risk-Adjusted Discount Rate (RADR), which incorporates a risk premium into the calculation, can more accurately reflect the economic feasibility of a project.

$$\mathrm{RADR} = r_f+\beta\times(r_m-r_f)+\mathrm{RP}_{\mathrm{tech}}$$

Among them, r_f represents the risk-free interest rate, β denotes the project's systematic risk coefficient, r_m signifies the market return rate, and $\mathrm{RP}_{\mathrm{tech}}$ indicates the unique risk premium associated with green technology.

3. Budget Preparation Method Based on Economic Evaluation

Scientific economic evaluation must be translated into executable budgets to guide engineering practice. The traditional "estimate-budget" model struggles to accommodate the complexity of green retrofit projects.

3.1 BIM-Driven Detailed Bill of Quantities

The accuracy of economic evaluations highly depends on the precision of initial cost data, whereas traditional manual quantity calculations based on 2D drawings often result in significant errors in complex existing building renovation projects. Building Information Modeling (BIM) technology offers a revolutionary solution to this challenge. Through laser scanning or photogrammetry of existing structures, high-fidelity 3D digital twin models can be rapidly constructed. On such models, designers and cost engineers can intuitively and accurately identify all components requiring replacement—whether standardized external windows or irregular roof nodes—while automatically extracting their geometric information and physical properties. When specific green materials (e.g., energy-efficient windows with a U-value of 1.8) are designated, the BIM platform can generate detailed bills of quantities with one click, including material specifications, performance parameters, quantities, and preliminary unit prices [3]. This model-based quantification approach not only significantly enhances the efficiency and accuracy of budget preparation and reduces cost overruns caused by quantity discrepancies but, more importantly, provides structured and traceable data sources for subsequent Life Cycle Cost (LCC) analysis. This achieves end-to-end data integration from design to cost management and operational phases.

3.2 Construction of a Dynamic Green Material Price Database

The green building materials market is currently in a phase of rapid development and iteration, with new products emerging continuously. Prices are influenced by multiple factors such as raw materials, production capacity, and policy subsidies, leading to frequent fluctuations. Relying on outdated quotas or sporadic market inquiries makes it difficult to obtain accurate and comprehensive price information. Therefore, there is an urgent need to establish an authoritative and dynamic price database for green materials.

This database should be led by industry associations, government platforms, or third-party professional institutions, organized by material categories (e.g., doors and windows, insulation, coatings), performance grades, regions, and other dimensions. It should continuously update key information such as historical price trends, mainstream brand price ranges, and additional costs for transportation and installation. Furthermore, the database should integrate the latest fiscal and tax incentive policies, such as immediate VAT refunds and green procurement scoring benefits, to help budget planners comprehensively calculate actual procurement costs. When preparing project budgets, budget personnel can directly retrieve reference prices for similar projects from this database and adjust them based on factors like project scale and procurement timing, thereby establishing a scientific and timely cost baseline that effectively avoids budget distortions caused by information asymmetry.

3.3 Introducing Dynamic Pricing and Contract Mechanisms

Even with precise initial budgets, the volatility of green material prices can still lead to contract disputes or project delays during prolonged procurement and construction cycles. To address this challenge, innovative dynamic price adjustment mechanisms should be incorporated into engineering contracts. Specifically, key bulk commodities that most significantly impact material costs (such as aluminum ingots for window frames and soda ash for glass) can be selected as reference indices [4]. Contracting parties would agree on a baseline price and a reasonable fluctuation threshold (e.g., ±5%). When officially published price indices exceed this threshold during construction, the contract price for materials would be adjusted according to a predefined formula. This "risk-sharing, benefit-sharing" contractual arrangement not only protects contractors from uncontrollable cost surges but also ensures owners do not bear excessive price increases. Consequently, it fosters a more stable and mutually trusting collaborative environment, enabling green retrofit projects to be implemented smoothly and efficiently.

3.4 Reasonable Allocation of Contingency Funds

Existing buildings are akin to "black boxes," where internal conditions often deviate from documented plans. During renovation, unexpected issues such as corroded reinforcement within walls, aging or ruptured concealed pipelines, and insufficient structural load-bearing capacity may arise at any time. These can lead to increased project scope or changes in construction methods, subsequently causing cost overruns. Therefore, scientifically and reasonably allocating contingency fees (or reserve funds) in the budget is a critical aspect of project risk management. This allocation should not be an arbitrary percentage decided impulsively but must be based on a comprehensive evaluation of factors such as the building's age, original design standards, historical maintenance records, and the depth of the current renovation. For older projects with missing documentation and extensive renovation scopes, contingency rates may appropriately be set at 10%-15%; conversely, for others, rates can be controlled at around 5%. Additionally, the budget documentation must clearly define the conditions for using contingency funds and the approval process, ensuring they are reserved exclusively for addressing legitimate unforeseen incremental expenses—not serving as a blanket excuse for poor management.

Conclusion

This paper systematically explores the economic evaluation and budgeting methods for green material replacement in existing building retrofits. The study reveals that relying solely on initial costs for decision-making is highly inadequate, necessitating a life-cycle perspective that integrates direct and indirect benefits while thoroughly assessing risks. The proposed evaluation framework—"LCC + ICER + Sensitivity Analysis"—and the budgeting approach—"BIM + Dynamic Database + Risk-Sharing Contracts"—offer effective pathways to address the economic challenges of green retrofits. Future research could further advance the following areas: first, exploring the inclusion of more non-market ecological benefits (such as biodiversity conservation) into the evaluation system; second, developing intelligent online assessment and budgeting tools to lower application barriers; third, investigating the coupling mechanisms between green finance (e.g., green credit, ESG investment) and project economics to provide stronger capital support for green retrofits. Only by integrating the entire chain of "technical feasibility-economic rationalityfinancial accessibility" can the immense potential of green retrofits for existing buildings be fully unlocked, thereby accelerating the construction sector’s progress toward carbon neutrality goals.

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