An Incremental Cost-Benefit Quantification Model for Passive Houses from a Multidimensional Value Perspective

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Abstract

This paper systematically examines the incremental costs and benefits of passive buildings across all lifecycle stages from a multidimensional value perspective, establishing an incremental cost-benefit assessment model encompassing economic, environmental, and social dimensions. A newly constructed public building in a cold region is used as a case study for validation analysis. The results demonstrate that the incremental benefits of this passive building project exceed its incremental costs throughout the lifecycle, exhibiting sound economic rationality and environmental-social value. The proposed assessment model and evaluation methodology provide theoretical support and a practical basis for green building investment decisions, project optimization design, and policy formulation.

Keywords

Passive House; Incremental Cost; Cost-Benefit Analysis; Multidimensional Value.

1. Introduction

As the global climate change problem becomes increasingly serious, the green and low-carbon transformation in the construction field has become one of the key paths to achieve sustainable development [1]. Passive buildings are gradually becoming an important direction of building transformation due to their high energy efficiency, low operating energy consumption, and strong comfort. Although passive buildings have significant energy-saving and environmental benefits, in the context of the current market mechanism not yet fully reflecting the external benefits of green buildings, cost-benefit analysis of passive buildings from an economic perspective alone is often difficult to fully reflect their multi-dimensional value. Especially in the case of limited user awareness, incremental costs have become an important obstacle to the promotion of passive buildings [2]. Therefore, it is urgent to establish a quantifiable evaluation framework to scientifically evaluate the incremental costs and comprehensive benefits of passive buildings throughout their life cycle. Existing studies have mainly focused on the energy-saving performance analysis of passive buildings [3] and the calculation of economic indicators [4]. The incremental cost-benefit evaluation under the background of their multi-dimensional value is still insufficient. Therefore, this paper constructs an incremental cost-benefit calculation model suitable for passive buildings from a multi-dimensional value perspective.

2. Passive Building Lifecycle Stages

Passive buildings differ significantly from conventional buildings in terms of their phased characteristics and cost structure. Therefore, clarifying the rules for demarcating each stage of the passive building lifecycle is a prerequisite for conducting multidimensional value measurement and incremental benefit analysis. Standards such as the "Green Building Evaluation Standard" (GB/T 50378-2019) and the "Building Carbon Emissions Calculation Standard" (GB/T 51366-2019) clearly define the phase boundaries. Combining full lifecycle theory with practical engineering experience, this article defines the passive building lifecycle into the following five stages.

2.1 Planning and Design Phase

The planning and design phase is a critical stage for determining passive building performance objectives and establishing a technical path. It primarily includes conceptual design, building simulation, construction drawing design, and related performance reviews.

2.2 Construction Phase

The construction phase not only involves conventional civil engineering and equipment installation, but also includes high-tech requirements such as high-performance envelope construction, thermal bridge mitigation, airtightness construction, and comprehensive quality inspections. Furthermore, system commissioning and joint acceptance are essential components.

2.3 Operation and Maintenance Phase

The operation and maintenance phase primarily involves activities such as energy supply, system operation, maintenance, and environmental control during the building's actual use. To maintain high-performance systems, key equipment such as ventilation and control systems require regular maintenance and functional monitoring.

2.4 Modernization and Retrofitting Phase

The modernization and retrofitting phase involves partial replacements, system upgrades, or performance enhancements during the building's operation to address system aging, technological advancements, or performance degradation. 1.5 Demolition and Decommissioning Phase

The demolition and decommissioning phase is the post-life disposal phase for a building, primarily encompassing the dismantling of highly integrated system structures, equipment recycling, disposal of recycled materials and salvage value, and site remediation.

3. Analysis of the Incremental Cost and Benefit Components of Passive Buildings based on a Multidimensional Value Perspective

3.1 Framework for Incremental Cost and Benefit Analysis from a Multidimensional Value Perspective

The life cycle cost of a passive building refers to the sum of direct and indirect costs incurred over the building's entire life cycle. The incremental cost of a passive building can be defined as the additional investment expenditures incurred at each life cycle stage compared to traditional buildings based on incremental cost theory, while still meeting passive building performance standards. Correspondingly, incremental benefits refer to the additional economic, environmental, and social benefits generated by the adoption of passive building design concepts and technological approaches compared to traditional buildings.

To systematically and comprehensively identify and evaluate the incremental cost and benefit components of passive buildings, this paper constructs a multidimensional value analysis framework for the incremental costs and benefits of passive buildings, integrating multidisciplinary theoretical foundations. The core theoretical applications are as follows:

(1) The whole life cycle theory can reveal the structural distribution and time matching of "cost-benefit" at different stages from the perspective of time. Its main role in the analytical framework is to establish the time dimension and stage attribution of the constituent elements. (2) The value engineering theory takes the "function-cost" ratio as its core and achieves a balance between minimizing cost input and maximizing use value through systematic functional analysis. It is used to judge whether the incremental cost input is reasonable and to identify the non-financial benefits of passive buildings in improving health levels. Functional social value does not directly generate cash flow and can be relatively quantified through methods such as willingness to pay and life cycle health

benefit assessment. (3) Transaction cost theory provides an extended dimension for cost identification, mainly used to identify non-market implicit incremental costs and expand the boundaries of traditional financial cost analysis. Traditional building cost analysis focuses on direct financial costs, while passive buildings involve a large number of non-market transaction activities in terms of system adaptation, standard compliance, information coordination, etc. Although they are difficult to measure directly, they constitute important implicit expenses in the building life cycle and need to be considered. (4) Ecological footprint method and carbon value assessment quantifies energy consumption and carbon emissions throughout the building's life cycle, converting carbon emission reduction benefits into economic value. This allows environmental benefits to be directly incorporated into the economic evaluation system, thereby achieving quantification and monetization of environmental benefits.

3.2 Analysis of Incremental Cost Composition

The incremental cost components of passive buildings are as follows based on the definition of technology-specific inputs in incremental cost theory and the dynamic consideration of the full-cycle cost of buildings in the life cycle theory:

(1) Economic incremental costs

1) Planning and design incremental costs

Architectural design and consulting fees: Design and analysis work such as energy consumption simulation, thermal calculation, and airtightness analysis to meet the performance indicators of passive buildings, as well as the costs incurred by entrusting consulting agencies to provide design optimization and performance evaluation.

2) Construction incremental costs

a. Building materials and equipment procurement costs: Mainly the purchase and installation costs of high-performance envelope structures, energy-saving doors and windows, ventilation and heat recovery systems, high-airtightness structural materials and auxiliary equipment.

b. Construction and installation costs: Mainly the costs of various on-site construction and equipment installation such as civil structures and envelope systems, as well as the implementation costs of special technologies such as airtight construction and thermal bridge isolation treatment.

c. Commissioning and management costs: Mainly the costs incurred by commissioning and testing of various systems, functional acceptance, and related management activities such as project management, quality control, and on-site coordination during construction.

3) Operation and maintenance incremental costs

a. Maintenance and upkeep costs: Mainly the costs incurred by regular inspection, maintenance, and upkeep of building envelope structures, door and window systems, ventilation systems, equipment systems, etc.

b. Operation and management expenses: These primarily include management expenses related to daily building operations, including salaries for management personnel, operational monitoring, fault response, and information platform support.

4) Incremental costs for renovation and upgrading

a. Building component replacement costs: These primarily include the replacement of functional components such as door and window seals and sunshades due to aging, wear, or performance degradation.

b. Equipment system upgrade costs: These primarily include the costs of replacing all or part of various systems after they have reached their service life.

c. System optimization and technology upgrade costs: These primarily include system upgrade expenses to improve building operational efficiency.

5) Incremental costs for demolition and decommissioning

Demolition construction costs: These primarily include the labor, machinery, transportation, and on-site safety management costs incurred during the demolition of high-performance building structures, enclosures, and electromechanical equipment.

(2) Environmental incremental costs Environmental incremental costs refer to the additional environmental load and management costs incurred by passive buildings in terms of resource use, material manufacturing and environmental control to achieve environmentally friendly goals throughout their life cycle. The main components include:

1) Carbon emission costs: mainly the environmental management and ecological restoration costs caused by greenhouse gas emissions and pollutant emissions generated during the construction, operation and demolition stages of the building, which can be monetized based on carbon prices or social carbon costs.

2) The increased costs of high-performance materials and equipment production, transportation, installation, maintenance, and environmental treatment of waste after demolition.

3) Environmental expenditures during equipment maintenance: During operation, energy consumption data needs to be monitored, analyzed, and carbon footprints tracked, and the construction and maintenance of environmental monitoring systems form additional investment costs.

(3) Social incremental costs Social incremental costs refer to the implicit or explicit social costs brought about by non-technical factors such as system adaptation, market acceptance, and usage behavior during the promotion and implementation of passive buildings. The main components include:

1) Policy and standard adaptation costs: During the design and construction application process, the policy docking and compliance processing costs incurred to meet the requirements of passive building standards and certification systems in different regions.

2) Personnel Training and Construction Adaptation Costs: Because passive buildings require high construction precision, material compatibility, and process consistency, construction personnel and management personnel require frequent training and on-site coordination, resulting in additional time and financial investment.

3) User Adaptation and Guidance Costs: After a building is operational, users must adjust their habits. This includes behavioral guidance, communication, and after-sales service, which constitute certain operating costs.

3.3 Analysis of Incremental Benefits

(1) Economic benefits

Economic incremental benefits refer to the direct or indirect economic benefits brought about by energy conservation and equipment life extension during the operation and renewal period of the building, mainly including:

1) Energy cost savings: the building envelope system and ventilation heat recovery system effectively reduce the operating energy consumption and save energy expenditure.

2) Reduced operation and maintenance costs: stable equipment operation and reduced maintenance frequency reduce long-term maintenance and replacement costs.

(2) Environmental benefits

Environmental incremental benefits refer to the energy consumption, carbon emissions and resource waste reduced during the construction, operation and decommissioning of the building, mainly including:

1) Carbon emission reduction benefits: the use of high-performance materials and energy-saving systems to reduce carbon emissions throughout the life cycle, and monetize them according to carbon prices.

2) Resource conservation benefits: reducing resource consumption and solid waste emissions through durable building materials, optimized system operation, material recycling design, etc.

3) Environmental protection operation benefits: deploying carbon monitoring and energy consumption platforms helps to control long-term environmental benefits and improve the green level of the project. The realization of benefits depends on the specific application scenario.

(3) Social benefits Social incremental benefits refer to the added value that passive buildings bring to residents' health, comfort, behavior, and social public aspects, mainly including:

1) Health and Comfort Benefits: Stable indoor temperature and humidity, and high air cleanliness help reduce disease risks and improve life satisfaction.

2) Improved User Behavior: The widespread adoption of low-carbon lifestyles enhances user awareness of energy use and green behavior.

3) Social Image and Public Value: Construction companies or developers gain greater social recognition, making it easier for projects to receive policy support.

4. Construction of an Incremental Cost-Benefit Calculation Model for Passive Buildings

4.1 Construction of an Incremental Cost Calculation Model

This paper constructs a passive building incremental cost calculation model based on the above analysis of the incremental cost structure of passive buildings. The incremental cost ΔC_{total} of the passive building over its entire life cycle is:

$$\Delta C_{total} = \Delta C_{ec} + \Delta C_{en} + \Delta C_{s} \tag{1}$$

In the formula, ΔC_{en} is the economic incremental cost, $\Delta C_{ec}$is the environmental incremental cost, and $\Delta C_{s}$is the social incremental cost.

(1) The formula for calculating the economic incremental cost is:

$$\Delta C_{ec} = \sum_{i=1}^{n} \Delta C_{ec}^{i} * (1+r)^{-t_i} \tag{2}$$

Where $\Delta C_{ec}^{i}$is the incremental economic cost of the i stage, $t_i$is the time point (in years) when the cost of the i stage occurs, r is the social discount rate, and n is the number of life cycle stages.

(2) The formula for calculating the incremental environmental cost is:

$$\Delta C_{en} = \sum_{t=1}^{T}\left[\sum_{j=1}^{m}\left(q_{tj} * \sum_{k=1}^{n} a_{jk} * P_{tk} + b_{jk} * E_{tk}\right)\right] * (1+r)^{-t} \tag{3}$$

Where q_{tj} is the increase in the use of the j type of energy due to the use of energy-saving materials/equipment in year t, a_{jk} is the amount of the k type of natural resource consumed in the production of the j type of energy, P_{tk} is the unit price of natural resources in year t, $b_{jk}$is the emission of the k type of pollutant generated per unit of energy, and $E_{tk}$is the cost of pollutant control in year t.

(3) The formula for calculating the social incremental cost is:

$$\Delta C_{s} = \sum_{t=1}^{T}\left(\Delta C_{tr}^{t} + \Delta C_{po}^{t} + \Delta C_{us}^{t}\right) * (1+r)^{-t} \tag{4}$$

In the formula, ΔC_{tr}^{t} represents the training and construction adaptation costs in year t, ΔC_{po}^{t} represents the policy adaptation and compliance expenditures in year t, and ΔC_{us}^{t} represents the user onboarding and follow-up service costs in year t.

4.2 Construction of an Incremental Benefit Calculation Model

This paper constructs an incremental benefit calculation model based on three benefit dimensions: economic, environmental, and social. It also introduces a time value factor to estimate the present value of future benefits. The incremental benefits ΔB_{total} over the entire life cycle of a passive building can be expressed as:

$$\Delta B_{total} = \Delta B_{ec} + \Delta B_{en} + \Delta B_{s} \tag{5}$$

In the formula, ΔB_{ec} is the incremental economic benefit, ΔB_{en} is the incremental environmental benefit, and ΔB_{s} is the incremental social benefit.

(1) The formula for calculating the incremental economic benefit is:

$$\Delta B_{ec} = \sum_{t=1}^{T} (\Delta E_{sa}^{t} + \Delta C_{om}^{t} + \Delta V_{as}^{t}) * (1 + r)^{-t} \tag{6}$$

Where ΔE_{sa}^{t} is the energy cost saved in year t, ΔC_{om}^{t} is the reduction in operation and maintenance expenses in year t, ΔV_{as}^{t} is the potential asset premium or increase in rental and sales income of the building in year t, and r is the social discount rate.

(2) The formula for calculating the incremental environmental benefits is:

$$\Delta B_{en} = \sum_{t=1}^{T} (\Delta CE_{t} * P_{carbon} + \Delta R_{t} * P_{res}) * (1 + r)^{-t} \tag{7}$$

Where ΔCE_{t} is the carbon emission reduction in year t ($kgCO_2$), P_{carbon} is the unit carbon value (yuan/ $kgCO_2$), which can be the current carbon market or social carbon cost value, ΔR_{t} is the saved construction materials or resource consumption (m^3, kg, etc.), and P_{res} is the unit market price of the resource.

(3) The formula for calculating social incremental benefits is:

$$\Delta B_{s} = \sum_{t=1}^{T} (\Delta H_{t} + \Delta S_{t} + \Delta G_{t}) * (1 + r)^{-t} \tag{8}$$

Where ΔH_{t} is the reduction in health expenditure or morbidity loss due to indoor environment improvement in year t (yuan), ΔS_{t} is the gain in work efficiency and learning efficiency resulting from improved user satisfaction, and ΔG_{t} is the indirect incentive brought about by the improvement of green image and social responsibility.

5. Case Study

5.1 Project Overview

A passive building project is located in the cold climate zone of northern my country. The total project site area is approximately 56,000 square meters, with a planned total building area of 183,000 square meters, including approximately 167,000 square meters above ground and 16,000 square meters underground. The project's floor area ratio is 3.0. The building's primary functions include educational and research facilities, offices, and supporting service facilities. Construction strictly adheres to passive ultra-low energy building standards. The total investment budget is approximately 1.52 billion yuan, with an investment per square meter of building area of approximately 8,300 yuan. The project's comprehensive technical approach and sufficient data provide a good foundation for full-lifecycle incremental cost and benefit calculations.

5.2 Incremental Cost Calculation

Incremental costs were quantified based on the project's design, construction, and operation data. This calculation utilizes the discounted cash flow method, assuming a 5% discount rate and a 30-year building lifecycle. Costs are expressed in present value.

(1) Economic incremental cost

In the calculation of economic incremental cost, the incremental cost of planning and design is 58.20 yuan/m², the incremental cost of construction is 1056 yuan/m², the incremental cost of operation and maintenance is 95 yuan/m², the incremental cost of renovation is 110 yuan/m², and the incremental cost of demolition and decommissioning is 32 yuan/m². In summary, the total incremental cost of the economic dimension per unit building area of the project is 1451.2 yuan/m².

(2) Environmental incremental cost

The environmental incremental cost is based on the monetization of carbon emissions and the measurement of environmental loads of resource processing. The high-performance building materials of the project generate additional carbon emissions of approximately 28 $kgCO_2/m^2$ during production and transportation. The carbon emission cost is 2.24 yuan/m² based on the current carbon price of 80 yuan/ton. In addition, the construction and maintenance cost of the environmental monitoring system is approximately 9.6 yuan/m². Therefore, the environmental incremental cost is 11.84 yuan/m².

(3) Social incremental cost

According to project management statistics and data estimation, the incremental cost per unit building area in the social dimension is approximately RMB 26.5/m². In summary, the incremental cost per unit building area over the entire life cycle of the project is RMB 1489.54/m².

5.3 Incremental Benefit Calculation

The incremental benefit calculation is carried out and uniformly discounted to present value based on the project operation simulation and regional reference data.

(1) Economic incremental benefit

In the economic incremental benefit calculation, the average annual operating energy consumption is saved by approximately 65 kWh/m². The annual saving is RMB 58.5/m², and the 30-year discounted present value is approximately RMB 912/m² based on the comprehensive electricity price of RMB 0.9/kWh; the system maintenance expenditure is reduced by approximately RMB 6/m²·year, and the present value is approximately RMB 94/m²; the potential asset premium assessment is increased by 5%, and the unit value is increased by approximately RMB 350/m². Therefore, the economic incremental benefit is RMB 1356/m².

(2) Environmental incremental benefits

In the calculation of environmental incremental benefits, the annual carbon emission reduction during the building operation phase is about 40 $kgCO_2/m^2$, which is a total of 1.2 tons in 30 years. The present value is about 73 yuan/m² based on a carbon price of 80 yuan/ton; the discounted benefit of material waste reduction and water resource conservation during operation is about 15 yuan/m². Therefore, the environmental incremental benefit is 88 yuan/m².

(3) Social incremental benefits

In the calculation of social incremental benefits, the discounted value of the health benefits caused by the improvement of indoor air quality is about 66 yuan/m² based on the reduction of per capita medical expenditure + WTP method, and the user comfort improvement gain is about 48 yuan/m² based on the willingness to pay survey. Therefore, the social incremental benefit is 114 yuan/m².

In summary, the present value of the incremental benefit per unit area is 1558 yuan/m². The comprehensive net benefit of the project is 68.5 yuan/m². The passive building has achieved a positive net benefit, which verifies the applicability and theoretical value of the constructed model in actual engineering.

6. Conclusion

From a full life cycle perspective, this paper systematically analyzes the incremental cost and benefit components of passive buildings throughout their life cycle, constructing an incremental cost-benefit calculation model from a multi-dimensional value perspective. The model's applicability was validated using a new public building in a cold region as an example. The results indicate that the incremental costs of a project are primarily concentrated in the material and equipment procurement and construction phases, while the incremental benefits are reflected in operational energy savings, enhanced environmental value, and comprehensive social impact. Passive buildings exhibit significant economic feasibility and promotional value, with incremental benefits exceeding incremental costs throughout their life cycle. The calculation model and analytical framework proposed in this paper can provide methodological support for investment decisions, policy formulation, and green building value assessment for passive building projects.

References

[1] H. Li, Y. Lu, X. Tian, et al.: Chinese Management Science, (2025) Online, p.1-23. [2025-07-13]
[2] J.Y. Li, L. Chen, J.P. Guo, et al.: Construction Economics, Vol. 44 (2023) Suppl. 1, p.364-366.
[3] Q. Lai, W. Liu, X. Li, et al.: Construction Economics, Vol. 44 (2023) Suppl. 1, p.391-396.
[4] Y.C. Qi, X.L. Li: Construction Economics, Vol. 42 (2021) No. 7, p.100-104.