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Study on Whole-Life-Cycle Management of Green Building Projects

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Abstract: With the deepening of global sustainable development concepts, green buildings have demonstrated significant value in energy conservation, emission reduction, efficient resource utilization, and environmental friendliness. However, traditional project management often focuses on a single phase and lacks systematic control spanning from planning and design through operation and decommissioning. Based on Life Cycle Management (LCM) theory, this paper constructs a whole-life-cycle management framework covering four stages — planning and design, construction implementation, operation and maintenance, and decommissioning and recycling — and proposes key methods such as target setting, performance monitoring, cost control, and risk management. Through case studies of representative domestic and international green building projects, the effectiveness of the proposed indicator system and management strategies in controlling energy consumption, reducing carbon emissions, and optimizing economic benefits is demonstrated. The study shows that whole-life-cycle management not only enhances the overall performance of green buildings, but also promotes industry standardization and technological innovation, providing decision-making references and practical guidelines for governments, owners, and design-build teams.

Keywords: green building; whole-life-cycle management; performance evaluation; cost control; risk management

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1. Introduction

As global climate change intensifies and resource constraints become more pronounced, the construction industry has become a major consumer of energy and emitter of carbon. Statistics show that energy use during the construction and operation phases accounts for about 40% of global consumption, with nearly one-third of total carbon emissions. Traditional project management tends to focus only on design or construction, failing to consider resource efficiency and environmental impact across the entire life cycle. Consequently, many green targets cannot be sustained after project completion. Meanwhile, standards such as LEED, BREEAM, and GB/T 50378 set quantitative design-stage criteria but rarely extend requirements into operation, maintenance, and decommissioning, leading to long payback periods for incremental green investments and accumulated systemic risks. Therefore, there is an urgent need for a systematic management model that runs through planning and design, construction, operation and maintenance, and decommissioning, to achieve a low-carbon, efficient, and sustainable closed loop for green buildings.

This study, grounded in Life Cycle Management theory, aims to develop a theoretically robust yet practically applicable whole-life-cycle management framework for green building projects. First, it reviews domestic and international green building standards and LCM models to define key performance indicators for energy saving, water conservation, carbon emissions, and material recycling. Next, leveraging BIM, digital twins, and IoT technologies, it designs methods for target decomposition, real-time monitoring, and closed-loop optimization. Finally, it conducts case studies of typical green building projects to validate the framework's effectiveness in controlling energy use, reducing emissions, and improving economic returns, from which replicable lessons and recommendations are distilled. A mixed-methods approach — combining literature review, quantitative modeling, and qualitative interviews — is adopted to provide systematic decision support and implementation guidance for policymakers, owners, and design-build teams.

2. Theoretical Foundations and Concept Definitions

2.1. Core Concepts and Evaluation Standards of Green Buildings

The core concept of green building is to achieve harmonious co-existence of resources, environment, and people throughout the building's life cycle. First, green buildings emphasize resource conservation and recycling by optimizing design, using high-efficiency energy-saving equipment, and selecting renewable materials to reduce natural resource consumption. Second, they focus on environmental friendliness and ecological protection, requiring site selection and construction to minimize impacts on existing ecosystems, land, water bodies, and biodiversity. Third, green buildings prioritize indoor environmental quality — ventilation, natural lighting, acoustics, thermal comfort, and air pollution control — to create healthy and comfortable living and working spaces. In summary, green buildings aim for an integrated "low carbon, energy saving, environmental protection, health, and comfort" approach, achieving maximum social and economic benefits with minimal environmental cost. To assess the effectiveness and level of green building practices, various evaluation standards and certification systems have been established globally. Internationally, the most representative are the U.S. LEED (Leadership in Energy and Environmental Design) and the U.K. BREEAM (Building Research Establishment Environmental Assessment Method). LEED uses a points-based system across five categories — sustainable sites, water efficiency, energy and atmosphere, materials and resources, and indoor environmental quality — and awards Certified, Silver, Gold, or Platinum levels. BREEAM evaluates management, health and well-being, energy, transport, water, materials, waste, and ecology in the context of regional climate and regulations, emphasizing environmental performance control throughout the process. In China, the "Green Building Evaluation Standard" (GB/T 50378) and its star-rating system provide technical guidelines and regulatory norms [1]. This standard defines one-, two-, and three-star levels based on six criteria: building energy efficiency; land use and outdoor environment; water conservation; materials and resources; indoor environmental quality; and operation management. Specialized standards also exist for high-rise residential buildings, public buildings, and renovation projects. As policies and market demand evolve, these evaluation standards have been continuously refined, introducing performance acceptance and dynamic monitoring mechanisms during construction and operation, enabling ongoing tracking and optimization of green indicators. Overall, the core concepts and evaluation standards of green buildings offer clear value goals and technical pathways, laying the assessment foundation for whole-life-cycle management. Subsequent chapters will build on this theoretical base to explore how to implement these green evaluation elements in planning and design, construction, and operation and decommissioning stages, achieving a sustainable closed-loop for building projects [2].

2.2. Life Cycle Management Theory and Models

Life Cycle Management (LCM) theory emerged as a response to the limitations of traditional Life Cycle Assessment (LCA), which primarily focused on quantifying environmental impacts such as greenhouse-gas emissions or resource depletion. Whereas

LCA often stops at impact measurement, LCM extends the scope by embedding these assessments within a broader decision-making framework that integrates resource efficiency, environmental stewardship, economic viability, and social responsibility. At its core, LCM treats a product — or, in the case of buildings, a project — as a system whose inputs, processes, outputs, and eventual end-of-life must be managed holistically. This holistic orientation recognizes that choices made during material sourcing or design can propagate through construction, operation, maintenance, and decommissioning phases, amplifying or mitigating overall sustainability outcomes. The theoretical underpinnings of LCM draw on a melding of ecological flow analysis, systems thinking, and established project management methodologies such as those outlined in the PMBOK (Project Management Body of Knowledge). From ecology, LCM inherits the concept of material and energy throughput — tracking how raw resources move through extraction, fabrication, assembly, use, and disposal [3]. From systems theory, it borrows the feedback-loop construct, acknowledging that real-time data and stakeholder feedback at later stages should inform adaptive adjustments to earlier decisions. From project management, it adopts process groups and knowledge areas — scope, schedule, cost, quality, integration, and stakeholder management — so that sustainability objectives are woven into mainstream planning and control mechanisms rather than treated as add-on considerations. In practice, LCM models often revolve around the "3R" principles — Reduce, Reuse, Recycle — augmented by two complementary paradigms: "Cradle to Grave", which emphasizes minimizing negative impacts through to final disposal, and "Cradle to Cradle", which aspires to design all materials for perpetual reuse or safe return to the biosphere. Within the construction sector, these paradigms translate into specific strategies at each life-cycle stage. During planning and design, they encourage selection of low-impact materials, modular or prefabricated components, and forms that facilitate passive heating, cooling, or natural daylighting. In construction, they guide waste segregation, on-site recycling, and mechanized processes that reduce energy consumption and emissions. During operation and maintenance, they inform predictive maintenance schedules, sub-metering of building systems, and occupant behavior programs to curb energy and water use [4]. Finally, at decommissioning, they support dismantling methods that preserve component integrity for reuse, and material recovery protocols that maximize recycling rates. Digital technologies — most notably Building Information Modeling (BIM) and digital-twin platforms — have become enablers of LCM by providing integrated repositories where energy-use data, carbon-footprint metrics, material-flow diagrams, and cost-benefit analyses coalesce into real-time dashboards. These tools allow project teams to simulate "what-if" scenarios (for example, comparing the carbon and cost impacts of alternative façade systems), monitor performance against design targets during construction, and continuously optimize operations based on actual sensor data. When combined with environmental management systems such as ISO 14001 and national standards like China's GB/T 50378 for green buildings, LCM fosters parallel tracking of traditional project constraints (time, scope, budget, quality, and safety) alongside environmental KPIs, embedded within a unified governance structure. By operationalizing LCM, the construction industry gains not only the ability to deliver individual projects with demonstrably lower life-cycle impacts but also the framework to replicate best practices across diverse building types and geographic contexts. Standardized templates for material databases, waste-tracking logs, performance-monitoring dashboards, and risk-assessment matrices become organizational assets that drive continuous improvement. Moreover, LCM's emphasis on stakeholder collaboration — engaging owners, designers, contractors, facility managers, regulators, and end users — ensures that sustainability goals remain aligned with economic objectives and community needs. Subsequent chapters will build on this theoretical and methodological foundation to detail specific strategies for implementing LCM in planning and design, construction execution, and operation and decommissioning of green building projects [5].

3. Project Life Cycle Stage Division and Management Strategies

3.1. Planning and Design Stage Management

The planning and design stage marks the starting point of whole-life-cycle management for green buildings. Site selection should consider geography, climate, and ecological sensitivity, prioritizing plots with favorable solar exposure, wind patterns, and water resources, while conducting ecological impact assessments to protect existing vegetation and water systems. During design, digital tools such as energy simulations, daylight analysis, and carbon footprint calculations enable iterative optimization of building form, orientation, envelope, and window-to-wall ratios to minimize heating, cooling, and lighting loads. Material selection must meet structural safety and durability requirements, while favoring low-footprint, renewable, or highly recyclable green materials and leveraging local supply chains to reduce transportation emissions [6].

Technologically, BIM and digital twins should integrate structural, MEP, HVAC, and plumbing models in a unified information environment. Clash detection and energy simulations facilitate interdisciplinary optimization, and pre-defined KPIs — such as energy use intensity, material green score, and life-cycle carbon emissions — enable quantitative comparison during design reviews [7]. A multi-stakeholder coordination mechanism, including owner, designers, energy consultants, and regulators, should convene regular green-target alignment meetings to ensure consistency with local (GB/T 50378) or international (LEED, BREEAM) standards. This systematic approach lays a robust indicator and data foundation for subsequent construction and operation stages, supporting closed-loop optimization.

3.2. Construction and Operation Stage Management

The construction phase is critical for translating green design into reality. The construction plan must specify green methods and standards, strictly control waste sorting and recycling to meet recovery targets, and employ advanced techniques — such as pumped grout and prefabricated components — to reduce dust and noise. Major construction machinery should be retrofitted for energy efficiency or powered by new energy sources, with real-time monitoring of energy use and emissions. Water usage requires metering and reuse, utilizing rainwater harvesting and wash-water recycling systems to further conserve resources. A green performance evaluation system, integrated into construction progress and quality acceptance, combined with third-party environmental audits, ensures that design goals for energy, water, and material reuse are achieved on site [8].

In the operation stage, smart operations platforms and Building Management Systems (BMS) continually monitor energy use, indoor environment quality, and equipment status to identify deviations and trigger fault alerts for targeted maintenance. Operation strategies cover HVAC, lighting, and water systems, combining scheduled inspections with predictive maintenance to optimize performance. Sub-metering devices collect operational data for comparison with design simulations, and data-driven energy optimization models propose tuning measures. For high-use or aging equipment, techniques such as variable-frequency drives, system retrofits, and intelligent algorithms boost efficiency and extend service life. Operation management also addresses occupant comfort and health — monitoring air quality, adjusting daylight, and optimizing acoustics — to ensure low energy use and a safe, healthy, and comfortable indoor environment throughout the building's life [9].

4. Key Management Elements and Methods

4.1. Performance Evaluation and Monitoring Mechanism

Within a whole-life-cycle management framework, establishing a rigorous performance evaluation and monitoring system is crucial. First, a multi-dimensional indicator set should be defined — covering environmental benefits, energy-use intensity, carbon emissions, water-use efficiency, and material recycling rates — and these key performance indicators (KPIs) must be aligned with project objectives. Each indicator should be both quantifiable and actionable; for example, annual energy use per square meter, whole-life-cycle carbon footprint, and construction-phase waste-recovery rate can serve as core metrics, with specific numerical thresholds set for each project stage. By defining baseline and target values during the design phase, subsequent monitoring can quickly flag deviations. To ensure real-time, reliable data collection, IoT and digital technologies must be fully leveraged. Sensor networks can monitor energy-consuming equipment, indoor-environment parameters, and water systems online, feeding data into the Building Management System (BMS) or a digital-twin platform [10]. During construction, on-site environmental monitors record machinery energy use, emissions levels, and waste removal; during operation and maintenance, sub-metering and precise monitoring gather equipment-performance data, which is compared against design-stage simulations. All monitoring data converge on a visual dashboard that supports daily, weekly, and monthly queries and trend analyses, with a rules engine triggering automatic alerts to aid managerial decision-making. Performance monitoring is more than static reporting — it enables continuous, closed-loop improvement. Based on collected data and analysis, regular multi-stakeholder review meetings should be held to compare actual performance against targets, diagnose root causes of discrepancies, and develop corrective measures. When high-energy-use areas or environmental risks are identified, targeted optimization initiatives can be launched immediately; digital-twin simulations can validate proposed solutions before implementation, and the resulting improvements are incorporated into the monitoring metrics. By iterating indicator sets and monitoring methods — drawing on lessons from exemplary cases and standardizing processes — green-building performance management evolves into a dynamic, closed-loop system that can serve as a benchmark for industry-wide sustainable development.

4.2. Cost Control and Risk Management

In green-building whole-life-cycle management, cost control extends beyond initial investment to encompass total life-cycle expenditures. First, a life-cycle cost analysis should be performed during the planning and design phase, incorporating projected expenses for design, construction, operation and maintenance, and decommissioning into a unified model. Comparing total cost and benefit across different design options — by quantifying energy-savings from green technologies and materials in simulated and operational models — allows assessment of payback periods for incremental investments. Market research and supply-chain analysis guide the selection of locally sourced green materials and renewable-energy equipment, reducing procurement and transportation costs to achieve an optimal "low investment, high return" cost structure. During construction, cost control must be embedded in project management through bill-of-quantities tracking, cost-component analysis, and contract-incentive mechanisms, enabling dynamic cost monitoring and optimization. Prefabricated building and modular-component techniques should be promoted to reduce on-site labor and schedule risks, thereby lowering site-management expenses. Major work packages should adopt target-cost management, with progress controls triggering cost-variance alerts to ensure subcontractors meet green-construction standards without exceeding budgets. In operation and maintenance, precise metering and on-demand maintenance tie equipment-performance parameters to maintenance expenditures, avoiding unnecessary replacements or over-servicing, extending equipment life, and stabilizing long-term costs.

Risk management requires a comprehensive identification and evaluation system at project outset, covering technical, market, policy, and environmental risks. Technical risks include green-technology applicability and integration challenges; market risks involve green-product premium and demand fluctuations; policy risks stem from changes in certification standards or subsidy schemes; environmental risks relate to extreme weather or site-condition variability. After qualitative and quantitative assessment, appropriate mitigation measures are defined — for instance, pilot trials or simulations to address technical uncertainty; ongoing dialogue with regulators and reserved compliance budgets for policy shifts; diversified revenue models to hedge market risk. Integrating cost control with risk management creates a closed-loop feedback mechanism. At each performance-review meeting, cost-execution status and risk profiles are reported together; any budget overruns or emerging risks prompt corrective actions whose impacts on future cost and risk are evaluated. Through digital-twin and BIM integration, budget, schedule, and risk-alert data are compared in real time, enabling multi-dimensional, multi-stakeholder collaborative decision-making. Ultimately, this approach reduces incremental green investment costs while containing risks to acceptable levels, ensuring sustainable economic returns and stable management across the building's entire life cycle.

5. Case Analysis and Practical Insights

5.1. Typical Whole-Life-Cycle Management Case

The Tencent Binhai Tower in Shenzhen's Qianhai Cooperation Zone exemplifies whole-life-cycle green-building management. From the planning and design phase, the project set dual goals of "zero energy" and "ecological synergy". The design team used regional data on sunlight, wind, and rainfall to run BIM-based energy simulations, comparing multiple massing and orientation options. They ultimately adopted natural-ventilation corridors and a double-skin facade. For materials, locally produced high-performance insulated glass and low-carbon concrete were prioritized, reducing transport-related emissions, and suppliers' environmental footprints were pre-screened via a third-party green-materials database. During construction, green-building standards were contractual requirements. Prefabricated components and modular construction shortened the schedule by 30% and cut onsite waste by over 20%. Sensors for environmental monitoring and energy-use data collection were installed to track dust, noise, and CO_2 emissions in real time. A digital-twin platform visualized these metrics, enabling dynamic optimization of landscaping, rainwater harvesting, and wastewater treatment processes. The project achieved China's three-star green-building rating, LEED Platinum, and the highest SKA accreditation. In operation, the maintenance team leveraged IoT technology to sub-meter the HVAC and lighting systems, comparing monthly operational data against the initial simulations. Big-data analysis identified primary energy-use discrepancies, prompting targeted retrofits — such as variable-air-volume terminal upgrades — and optimizations of the predictive maintenance algorithms on the central controllers. Since commissioning, the building's annual energy use per square meter is 42% below industry benchmarks, indoor-air-quality indices remain in the "excellent" range, and occupant surveys rate thermal comfort and daylighting above 88 out of 100. This case validates the whole-life-cycle framework: quantifying sustainability targets in design, embedding them through construction and operation, and using digital tools for continuous data-driven optimization. Contractual and organizational mechanisms tightly integrate cost control and risk management, delivering environmental, economic, and occupant-experience benefits. Its practices and methods offer a replicable blueprint for other large-scale public and office buildings.

5.2. Lessons Learned and Challenges

The Tencent Binhai Tower demonstrates that a top-down, integrated whole-life-cycle approach is essential for meeting green-building goals. In design, quantified KPIs and multi-stakeholder collaboration laid clear pathways for subsequent phases; in construction, prefabrication and real-time monitoring compressed schedules and ensured waste-reduction targets; in operation, sub-metering and big-data analytics enabled ongoing performance tuning, yielding a healthy, comfortable indoor environment. Embedding green objectives, performance monitoring, cost control, and risk management throughout the life cycle not only boosts overall project value but also creates a standardized, transferable management model.

However, several challenges remain. First, management indicators and data are often siloed across multiple systems, lacking unified standards and efficient sharing mechanisms, which undermines real-time decision precision. Second, while digital tools are gaining traction in large projects, their cost and complexity limit adoption in small or retrofit projects. Third, green technologies and materials vary in market maturity; many innovations still require long-term performance validation, which current contracts and cost models inadequately address. Finally, stronger coordination and clearer incentive structures among owners, designers, contractors, and operators are needed to sustain green objectives amid competing interests. Going forward, industry-wide data-standardization platforms and policy incentives for green technology and financing should be advanced to scale and normalize whole-life-cycle management in green buildings.

6. Conclusion

This study, grounded in Life Cycle Management theory, has developed a green-building whole-life-cycle management framework covering planning and design, construction implementation, operation and maintenance, and decommissioning and recycling. Key methods include sustainability-target setting, performance monitoring, cost control, and risk management. By reviewing LEED, BREEAM, and GB/T 50378 standards, the framework aligns stage-specific indicators. Leveraging BIM, digital twins, and IoT technologies, it establishes a real-time feedback loop between design simulations and operational data. The Tencent Binhai Tower case illustrates how prefabrication, sub-metering, and data-driven optimization can be effectively applied in practice. Results show that this integrated approach dramatically reduces operational energy use and carbon emissions while enabling rapid payback on green investments, offering a practical pathway for owners and decision-makers. Although the framework has proven successful in large public and office buildings, digital-technology costs and technical barriers remain high for smaller projects and retrofits. Future research should explore lightweight digital platforms and sensor networks to lower these barriers and promote data standardization and interoperability across stages and stakeholders. As new materials and intelligent-maintenance technologies evolve, long-term verification of their reliability and economic benefits will refine life-cycle cost models. Finally, integrating carbon-neutral targets with green-finance and insurance tools can further advance sustainable, scalable green-building whole-life-cycle management.

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