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Systematic Review of Cost Optimization Models for Green Building Construction Projects

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Abstract- Green building construction projects are increasingly recognized as essential for advancing environmental sustainability and reducing the ecological footprint of the built environment. However, the perception of higher upfront costs remains a barrier to their widespread adoption. Cost optimization models provide a pathway to balance financial viability with sustainability goals, making them a critical focus for both researchers and practitioners. This synthesizes the existing body of knowledge on cost optimization models applied to green building construction projects, with the objective of identifying prevailing approaches, evaluating their effectiveness, and highlighting areas for future advancement. This followed PRISMA guidelines, with searches conducted across major scientific databases to capture peer-reviewed articles, case studies, and technical reports published over the past two decades. Inclusion criteria focused on studies addressing explicit cost optimization strategies, economic evaluation methods, or decision-support frameworks in the context of certified or sustainability-oriented building projects. Models identified were categorized into economic and financial models (e.g., life cycle costing, net present value analysis), operational and resource-based approaches (e.g., value engineering, lean construction), technology-driven solutions (e.g., BIM-enabled cost simulations, machine learning forecasting), and integrated multi-criteria decision-making frameworks. Comparative analysis revealed that while economic and financial models remain foundational, emerging digital technologies and hybrid optimization techniques offer greater potential for achieving both cost efficiency and long-term environmental benefits. Findings also indicate persistent challenges, including limited empirical validation of models in real-world projects, regional disparities in adoption, and insufficient integration with advanced digital technologies. This concludes that cost optimization for green building construction requires multi-disciplinary collaboration, policy support, and stronger links between financial modeling and sustainability outcomes. Future research should focus on AI-enhanced decision tools, renewable energy integration, and context-sensitive frameworks that align cost efficiency with global sustainability targets.

Index Terms- Cost Optimization, Green Building, Construction Projects, Sustainable Design, Energy Efficiency, Lifecycle Cost Analysis, Resource Management, Budget Planning, Financial Modeling, Project Performance, Risk Mitigation, Sustainability Metrics

I. INTRODUCTION

The construction industry is one of the largest contributors to global energy consumption, resource depletion, and greenhouse gas emissions (Akan *et al*., 2017; Huang *et al*., 2018). In response to the urgent need for sustainable development, the concept of green building construction has emerged as a transformative approach to minimize environmental impacts while enhancing occupant well-being and operational efficiency. Green buildings integrate principles of energy efficiency, renewable energy utilization, water conservation, material optimization, and waste reduction into the design, construction, and operational phases (Masood *et al*., 2017; Isopescu, 2018). Although the adoption of green construction practices has accelerated globally, a persistent challenge lies in the perception of higher upfront capital costs compared to conventional building projects (Chan *et al*., 2017; Darko *et al*., 2017). This cost premium often deters developers, investors, and policymakers, despite evidence that long-term operational savings and enhanced asset value frequently outweigh initial expenditures (Ng and Tao, 2016; Megginson and Fotak, 2016).

The economic implications of green building construction are therefore central to its widespread acceptance. While these projects often promise significant savings in energy and maintenance costs across their life cycle, realizing such benefits requires careful financial planning and strategic decision-making at the project's early stages (Crawford *et al*., 2016; Ford and Despeisse, 2016). Cost optimization becomes a crucial mechanism for bridging the gap between sustainability goals and financial feasibility. By employing systematic methodologies such as life cycle costing, value engineering, lean construction, and simulation-based modeling, project stakeholders can evaluate trade-offs, identify cost-saving opportunities, and achieve both economic and environmental performance targets (Mostafa *et al*., 2016; Al-Zwainy *et al*., 2016). Effective cost optimization not only enhances affordability but also strengthens the case for mainstreaming green construction as a viable pathway toward sustainable urban development (Gelband *et al*., 2016; Celestin, 2018).

Given the diversity of approaches and models available, there is a pressing need to consolidate and critically examine the evidence on cost optimization strategies in green building construction. This provides a rigorous method to synthesize existing knowledge, evaluate the effectiveness of different models, and identify patterns, gaps, and emerging trends in the literature (Pollock and Berge, 2018; Munn *et al*., 2018). Unlike narrative reviews, systematic reviews follow transparent protocols for study selection, data extraction, and analysis, thereby ensuring objectivity and reproducibility. This is particularly relevant in the construction field, where fragmented research outputs and context-specific case studies can make it difficult to derive generalized insights.

The objectives of this are fourfold. First, it seeks to categorize and analyze the various cost optimization models applied to green building construction, ranging from financial evaluation frameworks to technology-driven simulations and integrated decision-making tools. Second, it aims to assess the effectiveness and limitations of these models in achieving cost efficiency while maintaining sustainability performance. Third, this intends to highlight regional, sectoral, and methodological variations in the adoption of cost optimization strategies. Finally, it endeavors to identify research gaps and propose directions for future inquiry, particularly in light of digital transformation, artificial intelligence, and evolving policy frameworks.

The guiding questions that structure this are: (1) What types of cost optimization models have been developed and applied in green building construction projects? (2) How effective are these models in balancing upfront costs with long-term sustainability benefits? (3) What contextual factors influence the adoption and success of these models? and (4) What future directions are most promising for advancing cost optimization in sustainable construction?

Through addressing these questions, this aims to contribute to both academic scholarship and practical decision-making in the pursuit of economically viable and environmentally responsible built environments.

II. METHODOLOGY

The methodology of this systematic review was developed in alignment with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, ensuring transparency, rigor, and replicability. A comprehensive search strategy was employed to identify relevant studies on cost optimization models in green building construction projects. The search was conducted across leading academic databases, including Scopus, Web of Science, ScienceDirect, and Google Scholar, covering publications from 2000 to 2025 to capture both foundational models and recent advancements. Search terms combined keywords such as "green building," "sustainable construction," "cost optimization," "life cycle costing," "value engineering," "lean construction," and "decision-making models," using Boolean operators to refine results.

The selection process followed a multi-stage screening approach. First, duplicate records were removed, and titles and abstracts were screened for relevance to the research objectives. Full-text articles were then evaluated against predefined eligibility criteria. Studies were included if they explicitly examined cost optimization strategies or models within the context of green building or sustainability-oriented construction projects. Both qualitative and quantitative studies, including empirical case studies, simulation-based analyses, and conceptual frameworks, were considered. Exclusion criteria eliminated articles that focused solely on environmental performance without addressing cost optimization, publications not available in English, and non-peer-reviewed sources lacking methodological rigor.

Data extraction was performed using a structured template to ensure consistency. Key variables included study objectives, geographic context, type of building project, cost optimization model applied, methodological approach, and reported outcomes in terms of cost savings, efficiency, or sustainability performance. This enabled a systematic synthesis of findings across diverse contexts. To enhance the reliability of the review, two independent reviewers conducted the screening and extraction processes, with discrepancies resolved through consensus.

Quality assessment of included studies was carried out using a combination of criteria adapted from established appraisal tools, focusing on methodological transparency, robustness of data, and practical applicability of findings. Studies were graded as high, medium, or low quality to provide nuanced insights into the strength of the available evidence. The synthesis of results combined narrative analysis with thematic categorization of cost optimization models, enabling the identification of prevailing approaches, comparative strengths, limitations, and areas requiring further research.

This process is illustrated through a PRISMA flow diagram, which traces the number of records identified, screened, excluded, and finally included in the synthesis. By adhering to this structured methodology, this ensures that conclusions drawn are evidence-based, systematically derived, and relevant to both academic inquiry and professional practice in sustainable construction.

2.1 Theoretical Background

The pursuit of sustainable construction has transformed the traditional paradigm of building design and delivery, positioning cost optimization as a fundamental driver of decision-making. As green buildings gain prominence in response to global environmental challenges, understanding the theoretical underpinnings of cost optimization within the sustainability context becomes essential (Kibert, 2016; Zhang *et al*., 2018). This background section explores the concept of cost optimization in construction, reviews the principles of green building and their associated certification systems, and examines the intricate relationship between sustainability objectives and cost management strategies.

The concept of cost optimization in construction refers to the systematic process of achieving maximum value for resources invested in a project by minimizing costs while maintaining or enhancing quality, functionality, and performance. Unlike cost-cutting, which often compromises outcomes, cost optimization seeks a balance between financial efficiency and long-term benefits. In construction, this involves evaluating different design alternatives, material selections, technological applications, and project delivery methods to identify solutions that deliver economic efficiency without undermining durability, safety, or sustainability. Techniques such as life cycle costing (LCC), net present value (NPV), value engineering (VE), and lean construction principles are central to this pursuit. These methodologies extend beyond immediate capital expenditures to encompass operational, maintenance, and decommissioning costs, enabling stakeholders to understand the full financial trajectory of a building project. Cost optimization is therefore not a singular event but an iterative process spanning the planning, design, construction, and operational phases, guided by multi-criteria decision-making frameworks that integrate economic, social, and environmental dimensions (Tapia and Padgett, 2016; Formisano *et al*., 2017).

Green building principles reinforce this shift toward holistic value creation by embedding sustainability at the core of construction practices. A green building is designed, constructed, and operated to reduce negative environmental impacts, enhance resource efficiency, and improve the quality of life for occupants (Arif *et al*., 2016; Singh, 2018). Fundamental principles include energy efficiency, water conservation, the use of environmentally responsible materials, waste reduction, indoor environmental quality, and adaptability to climate conditions. These principles are operationalized and standardized through internationally recognized certification systems, which provide structured frameworks for evaluating and benchmarking building performance.

Leadership in Energy and Environmental Design (LEED), developed by the U.S. Green Building Council, is among the most widely adopted certification systems. LEED evaluates projects across categories such as sustainable site development, energy and water efficiency, materials selection, and indoor environmental quality, offering certification levels ranging from Certified to Platinum. Similarly, the Building Research Establishment Environmental Assessment Method (BREEAM), originating in the United Kingdom, is a pioneering sustainability assessment method that emphasizes categories including energy use, health and well-being, transport, materials, waste, and management practices. More recently, the Excellence in Design for Greater Efficiencies (EDGE) system, developed by the International Finance Corporation (IFC), has gained traction in emerging economies due to its streamlined, cost-effective approach. EDGE focuses on resource efficiency in energy, water, and embodied materials, making it accessible to developers in contexts where affordability is critical. These certification systems not only establish performance benchmarks but also incentivize innovation by linking environmental outcomes with market recognition and financial benefits (Lanahan and Armanios, 2018; Darko and Chan, 2018).

The relationship between sustainability and cost management in construction is both complementary and complex. On one hand, green buildings are often perceived as more expensive due to higher initial investment requirements for advanced materials, technologies, and design processes. This perception presents a significant barrier to adoption, particularly in cost-sensitive markets. On the other hand, a growing body of evidence demonstrates that when assessed across the building life cycle, green buildings frequently outperform conventional ones in terms of cost-effectiveness. Reduced energy and water bills, lower maintenance costs, enhanced occupant productivity, and increased asset valuation contribute to long-term economic gains that offset the initial premium (Kholodilin *et al*., 2017; Carlson and Pressnail, 2018). This underscores the importance of adopting life cycle perspectives in cost management rather than focusing narrowly on upfront capital expenditures.

Cost optimization acts as the bridge that aligns sustainability objectives with financial feasibility. By systematically analyzing trade-offs, optimization models help stakeholders prioritize interventions that deliver the greatest return on investment in both monetary and environmental terms. For example, simulation-based modeling tools allow designers to evaluate multiple design scenarios, quantifying the cost implications of choices such as building orientation, insulation levels, or renewable energy integration. Similarly, value engineering processes identify design alternatives that achieve functional requirements with lower costs or higher sustainability outcomes. In practice, these approaches not only reduce financial risks but also build confidence among investors and clients that sustainability does not equate to excessive cost.

Moreover, the integration of digital technologies such as Building Information Modeling (BIM), artificial intelligence (AI), and data analytics is revolutionizing the synergy between sustainability and cost management. BIM-enabled cost simulations allow for real-time analysis of design changes and their cost implications, while AI-driven predictive models enhance accuracy in forecasting life cycle costs and potential savings. These innovations expand the capacity of cost optimization to address complex sustainability requirements, moving beyond traditional accounting toward dynamic, evidence-based decision-making (Adams *et al*., 2016; França *et al*., 2017).

In essence, the theoretical background of this review situates cost optimization as an indispensable enabler of sustainable construction. Green building principles establish the environmental and social imperatives, certification systems provide structured frameworks for accountability, and cost optimization models operationalize the balance between financial constraints and sustainability aspirations. Understanding this relationship is critical for evaluating existing models and for guiding future innovations that will define the economic viability of sustainable construction on a global scale.

2.1 Types of Cost Optimization Models Identified

The pursuit of cost efficiency in green building construction has given rise to diverse optimization models that balance financial feasibility with sustainability performance (Shan *et al.*, 2017; Sagbansua and Balo, 2017). These models can be broadly categorized into economic and financial frameworks, operational and resource-focused approaches, technology-driven tools, and hybrid or integrated methodologies as shown in figure 1. Each category reflects different theoretical foundations and practical applications, but all converge on the goal of minimizing costs without compromising environmental and social benefits.

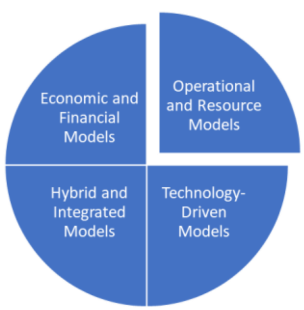

Figure 1: Types of Cost Optimization Models Identified

Among the most established cost optimization approaches are economic and financial models, which provide structured techniques for evaluating the long-term value of green building investments. Life cycle costing (LCC) is a particularly influential tool, offering a holistic perspective by accounting for all costs associated with a building over its entire lifespan. This includes initial capital expenditure, operation and maintenance costs, replacement expenses, and eventual decommissioning. LCC is essential for green projects because it captures the financial benefits of energy efficiency measures, reduced water consumption, and lower maintenance requirements, which often offset higher upfront investments.

Closely related are net present value (NPV) and return on investment (ROI) models, which apply discounted cash flow techniques to evaluate financial performance. NPV calculates the present value of expected future cash flows relative to initial investment, while ROI expresses profitability as a percentage. These models are critical in demonstrating the economic viability of green construction to investors and developers. For example, incorporating renewable energy systems may increase capital costs but yield substantial savings over time. By quantifying such trade-offs, NPV and ROI models provide evidence-based justification for sustainable investments, thereby enhancing stakeholder confidence.

While financial models emphasize long-term economic feasibility, operational and resource-focused models address the efficiency of construction processes and material utilization (Lake *et al.*, 2017; Aid *et al.*, 2017). Value engineering (VE) and lean construction are two widely applied approaches in this category. VE systematically evaluates project functions to identify alternatives that achieve equivalent or superior performance at lower cost. In green building projects, VE may involve substituting conventional materials with sustainable alternatives that deliver similar structural performance but at reduced environmental and financial costs.

Lean construction, derived from lean manufacturing principles, seeks to eliminate waste, improve workflow, and maximize value delivery across project phases. By minimizing inefficiencies such as rework, delays, and resource misallocation, lean practices directly contribute to cost optimization while enhancing sustainability outcomes. For instance, just-in-time material delivery reduces both storage costs and on-site waste generation, aligning operational efficiency with environmental goals.

Complementary to these approaches are material optimization and waste reduction models. These emphasize the selection of durable, recyclable, and locally sourced materials, alongside strategies for minimizing construction and demolition waste. Computational tools and databases are increasingly used to evaluate material options based on life cycle impacts and costs, ensuring that resource efficiency translates into both environmental benefits and financial savings.

Advances in digital technology have significantly expanded the scope of cost optimization in green construction. Building Information Modeling (BIM) integration has emerged as a transformative tool, enabling stakeholders to simulate, visualize, and analyze project performance across design, construction, and operation phases. BIM allows for real-time cost estimation and clash detection, reducing the risk of costly design errors and construction delays. Furthermore, BIM platforms can integrate sustainability metrics, enabling designers to assess the cost implications of energy efficiency measures or material substitutions early in the project lifecycle.

Beyond BIM, simulation and artificial intelligence (AI)-based cost prediction models are gaining traction. Simulation tools enable scenario analysis, allowing stakeholders to test different design strategies and evaluate their financial and sustainability outcomes (Cairns *et al*., 2016; Fauré *et al*., 2017). For instance, energy simulation software can estimate long-term operational savings from various insulation levels or HVAC configurations, providing a robust basis for cost-benefit decisions. AI techniques, particularly machine learning, enhance predictive accuracy by analyzing large datasets of past project costs, construction timelines, and performance outcomes. These models not only improve cost forecasting but also adapt to project-specific contexts, offering tailored optimization strategies.

Recognizing the multifaceted nature of cost optimization in green construction, hybrid and integrated models combine elements from multiple approaches to provide comprehensive decision-support frameworks. Multi-criteria decision-making (MCDM) frameworks such as the Analytic Hierarchy Process (AHP) and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) are widely employed in this regard. These frameworks enable stakeholders to evaluate trade-offs among diverse criteria, including cost, energy performance, environmental impact, and social acceptability. By quantifying and prioritizing competing objectives, MCDM tools facilitate balanced decision-making in complex green building projects.

Optimization algorithms further enhance integration by applying mathematical and computational methods to balance cost efficiency with sustainability targets. For example, genetic algorithms, linear programming, and fuzzy logic models have been applied to optimize design variables such as building orientation, envelope characteristics, and renewable energy integration. These algorithms provide solutions that minimize costs while simultaneously maximizing energy savings or reducing carbon emissions. The adaptability of such models makes them particularly valuable in contexts where project conditions, regulatory frameworks, and stakeholder priorities vary widely.

Taken together, these categories of cost optimization models represent complementary pathways for advancing the financial viability of green building construction. Economic and financial models emphasize long-term value, operational approaches target process efficiency, technology-driven tools expand predictive and analytical capacity, and integrated frameworks reconcile multiple objectives within complex decision environments. The diversity of models underscores the importance of a tailored approach, where the choice of optimization strategy depends on project scale, regional context, stakeholder priorities, and available technological capacity (Djenontin *et al*., 2018; Radner *et al*., 2018). Collectively, these models demonstrate that sustainability and cost efficiency are not mutually exclusive but can be harmonized through systematic, evidence-based methodologies.

2.3 Comparative Analysis of Models

The identification of diverse cost optimization models in green building construction provides an important foundation for understanding their relative strengths, weaknesses, and suitability under varying conditions (Shi *et al*., 2016; Khoshbakht *et al*., 2017). However, the real value of these models lies in their comparative effectiveness, particularly when assessed against the criteria of cost savings, applicability across project phases, scalability in different socio-economic contexts, and the inherent trade-offs between economic and sustainability objectives. A comparative analysis provides clarity on how these models perform in practice and guides stakeholders in selecting the most appropriate strategies for their projects as shown in figure 2.

Economic and financial models such as life cycle costing (LCC), net present value (NPV), and return on investment (ROI) have demonstrated consistent effectiveness in quantifying long-term financial benefits. Their strength lies in capturing operational savings derived from reduced energy consumption, lower maintenance costs, and enhanced asset durability. For instance, LCC effectively highlights the value of renewable energy installations, showing how the initial investment can be offset by long-term savings. However, these models may underrepresent intangible benefits such as occupant productivity or reduced environmental externalities, potentially limiting their holistic applicability.

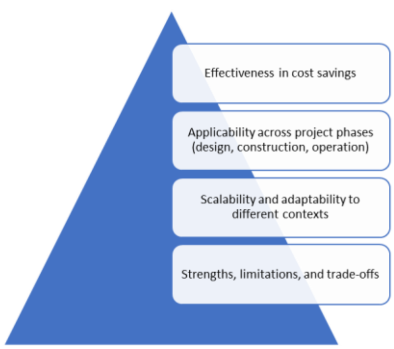

Figure 2: Comparative Analysis of Models

Operational and resource models like value engineering (VE) and lean construction are more effective in generating immediate cost savings during the construction phase by minimizing waste, streamlining processes, and improving resource allocation. Their ability to identify functional alternatives and eliminate inefficiencies has led to substantial reductions in material and labor costs. Nevertheless, the cost savings from operational models may not always translate into significant long-term benefits if not complemented by lifecycle considerations.

Technology-driven models, particularly Building Information Modeling (BIM) and simulation tools, demonstrate high effectiveness in cost avoidance rather than direct savings. By enabling early detection of design errors, clash detection, and performance simulations, these models reduce the likelihood of costly rework and ensure that sustainability features are integrated efficiently. Artificial intelligence (AI)-based prediction models further enhance this effectiveness by improving the accuracy of cost forecasting. Although their initial implementation can be expensive, the long-term benefits often outweigh the costs, particularly in complex projects.

Hybrid and integrated models, including multi-criteria decision-making frameworks and optimization algorithms, are effective in achieving balanced outcomes rather than maximizing cost savings alone. Their capacity to integrate financial, environmental, and social criteria allows stakeholders to identify strategies that achieve broader sustainability goals with acceptable cost implications. While they may not always deliver the greatest short-term savings, their effectiveness lies in optimizing trade-offs and ensuring long-term value.

The applicability of cost optimization models varies significantly across design, construction, and operation phases. Economic and financial models are particularly valuable during the early design and planning stages, when long-term costs and benefits must be projected to guide investment decisions. Operational and resource models, on the other hand, are most relevant during the construction phase, where process efficiency and material optimization can be directly implemented (Knoeri *et al*., 2016; Erol *et al*., 2016).

Technology-driven models such as BIM span multiple phases, offering value during design (through simulations and clash detection), construction (through coordination and scheduling), and operation (through facility management applications). Similarly, AI-based models can enhance both construction planning and operational performance forecasting. Hybrid models, with their multi-criteria frameworks, demonstrate cross-phase applicability by supporting integrated decision-making from concept design to post-occupancy evaluation.

The scalability of these models is heavily influenced by economic, technological, and institutional contexts. In developed economies, advanced technology-driven models such as BIM and AI are increasingly feasible due to access to digital infrastructure, skilled personnel, and regulatory incentives. Their scalability is evident in large-scale projects and urban development programs where sophisticated tools can be deployed effectively.

In developing economies, however, the adoption of technology-intensive models is often constrained by limited resources and technical expertise. Simpler economic and operational models such as LCC, VE, and material optimization are more adaptable in such contexts, offering immediate benefits without significant infrastructure requirements. EDGE certification, for example, aligns well with resource-constrained settings by providing streamlined cost and efficiency evaluations. Nevertheless, the growing availability of cloud-based platforms and international knowledge transfer is gradually expanding the scalability of advanced models to emerging markets.

Each model category carries distinct strengths and limitations. Economic and financial models excel in demonstrating investment viability but risk oversimplification if intangible or non-financial sustainability benefits are excluded. Operational models provide tangible short-term savings but may fall short of addressing long-term performance unless integrated with lifecycle analysis. Technology-driven models offer unparalleled precision and predictive capability but require substantial upfront investment and expertise, which may limit accessibility. Hybrid models provide the most holistic decision-making frameworks but often demand complex data inputs and advanced analytical skills, potentially complicating their use in resource-limited settings (Galvis, 2018; Androutsopoulou and Charalabidis, 2018).

Trade-offs are inherent in all models. For instance, maximizing short-term cost savings through lean construction may conflict with sustainability investments that require higher initial expenditure but deliver long-term benefits. Similarly, prioritizing environmental performance in multi-criteria decision frameworks may reduce immediate ROI, raising concerns among cost-sensitive investors. Effective application of these models requires acknowledging such trade-offs and aligning them with project-specific priorities and stakeholder expectations.

In comparative perspective, no single model emerges as universally superior; instead, their value lies in complementarity. Economic models establish financial justification, operational models ensure efficiency during implementation, technology-driven models enhance accuracy and integration, and hybrid frameworks reconcile competing objectives. The choice of model should therefore be informed by project phase, regional context, resource availability, and strategic goals. Ultimately, the comparative analysis demonstrates that cost optimization in green building construction is not a singular process but a dynamic interplay of models that must be selected and adapted to achieve the dual goals of economic efficiency and sustainability performance.

2.4 Key Findings and Trends

The systematic review of cost optimization models in green building construction reveals several important findings that shed light on prevailing practices, emerging innovations, regional and sectoral dynamics, and the measurable impacts of these models on project performance, affordability, and sustainability. These findings provide an evidence-based foundation for understanding both the current state of research and its implications for practice.

Across the reviewed literature, economic and financial models—particularly life cycle costing (LCC), net present value (NPV), and return on investment (ROI)—emerge as the most widely applied approaches. Their prominence reflects the need for clear financial justification in green building projects, where upfront costs often present barriers to adoption. LCC consistently demonstrates that investments in energy-efficient technologies, sustainable materials, and renewable energy systems generate long-term savings that outweigh initial expenditures. NPV and ROI further strengthen investment cases by quantifying profitability and payback periods, enabling developers and investors to assess economic viability (Tao and Finenko, 2016; Contestabile *et al.*, 2016). Outcomes from these models show that, on average, green buildings deliver lower operating costs, improved asset values, and enhanced competitiveness in the real estate market.

Operational and resource-based models, such as value engineering (VE) and lean construction, are also widely adopted, especially during the construction phase. These models contribute to measurable reductions in material waste, labor inefficiencies, and project delays. Case studies highlight that VE, when applied in the design stage, often results in cost savings of 10–15% without compromising performance, while lean practices enhance workflow efficiency and minimize rework. Together, these outcomes demonstrate that operational models directly address cost challenges during project execution, complementing the long-term financial benefits captured by economic models.

Recent years have witnessed a surge in technology-driven innovations that are reshaping the cost optimization landscape. Building Information Modeling (BIM) has become a central tool, enabling stakeholders to simulate design alternatives, conduct clash detection, and perform real-time cost estimation. By integrating sustainability metrics into digital models, BIM ensures that cost and environmental performance are evaluated simultaneously, thereby reducing the risk of late-stage design changes. Artificial intelligence (AI) and machine learning further extend this potential by improving predictive accuracy in cost forecasting and identifying optimization strategies from large datasets of past projects.

Simulation-based approaches also represent a key innovation, allowing for the evaluation of multiple design and operational scenarios. Energy and environmental simulations quantify the long-term cost savings associated with different building configurations, insulation levels, or renewable energy integration. Optimization algorithms, such as genetic algorithms and fuzzy logic, are increasingly employed to balance cost efficiency with energy savings and carbon reduction targets (Starkey *et al*., 2016; Dhodiya and Tailor, 2016). These innovations highlight a clear trend toward data-driven, computationally advanced methods that expand the precision and adaptability of cost optimization in green construction.

The adoption of cost optimization models varies significantly across regions and sectors, reflecting differences in economic development, regulatory frameworks, and institutional capacity. In developed economies such as the United States and Western Europe, advanced technology-driven models like BIM, AI-based forecasting, and integrated simulation tools are widely implemented due to strong digital infrastructure, skilled labor availability, and supportive policy environments. Certification systems like LEED and BREEAM reinforce this adoption by embedding cost optimization within broader sustainability assessments.

In contrast, developing economies often rely more heavily on simpler models such as LCC, VE, and material optimization due to limited resources and technical expertise. For instance, the EDGE certification system developed by the International Finance Corporation (IFC) has gained traction in Africa, Asia, and Latin America, where affordability and resource efficiency are paramount. Sectoral differences are also evident: commercial real estate projects in global cities frequently employ advanced hybrid models to balance investor expectations and sustainability goals, whereas public housing and small-scale residential projects in emerging markets tend to prioritize resource-based and financial models for affordability.

Evidence from empirical studies strongly indicates that cost optimization models enhance project performance by reducing delays, minimizing rework, and improving design efficiency (Chidiebere and Idiake, 2018; Karimi *et al*., 2018). Operational models, particularly lean construction, are associated with improved schedule adherence and productivity, while financial models such as LCC ensure better alignment between design decisions and long-term economic outcomes.

In terms of affordability, cost optimization plays a critical role in overcoming the perception of green buildings as prohibitively expensive. By demonstrating payback periods, ROI, and long-term savings, models provide confidence to both investors and end-users. This is particularly significant in low- and middle-income contexts, where upfront cost concerns are most acute. Cost optimization strategies enable broader access to sustainable construction, thereby contributing to more inclusive urban development.

Sustainability outcomes are also enhanced through the integration of cost optimization models. For instance, material optimization reduces embodied carbon by prioritizing recyclable and locally sourced materials, while simulation models enable designs that maximize energy savings and minimize operational emissions. Hybrid models, in particular, ensure that sustainability metrics are considered alongside cost, thereby aligning project decisions with broader environmental and social goals. Collectively, the evidence underscores that cost optimization is not merely a financial exercise but a critical enabler of holistic sustainability performance.

Overall, the key findings and trends reveal a dual trajectory in cost optimization research and practice. On one hand, established financial and operational models continue to dominate due to their accessibility and proven effectiveness. On the other hand, a wave of digital and computational innovations is expanding the frontiers of cost optimization, offering unprecedented levels of precision and integration. Regional and sectoral variations highlight that no single model fits all contexts; instead, adaptability and alignment with local conditions remain essential (Exner *et al*., 2016; Bradford, 2017). The evidence clearly demonstrates that cost optimization models not only improve economic outcomes but also reinforce the affordability and sustainability of green building construction, thereby strengthening the business case for sustainable development worldwide.

2.5 Research Gaps and Challenges

The systematic review of cost optimization models in green building construction reveals substantial progress in developing frameworks, tools, and strategies to balance economic and sustainability objectives. However, despite the diversity of models and promising outcomes, several gaps and challenges persist that limit their applicability, reliability, and broader adoption. These challenges are particularly evident in the areas of empirical validation, integration with digital and smart technologies, contextual barriers related to policy, finance, and skills, and insufficient lifecycle-based approaches. Addressing these shortcomings is essential for advancing both academic research and practical implementation in sustainable construction.

One of the most significant gaps is the limited empirical validation of cost optimization models in actual construction projects (Xue *et al*., 2018; Arashpour *et al*., 2018). Much of the existing research is conceptual or simulation-based, relying on theoretical assumptions, laboratory experiments, or small-scale case studies. While such studies provide valuable insights, they often fail to capture the complexities, uncertainties, and dynamic conditions of real-world construction environments. For instance, life cycle costing (LCC) models frequently assume idealized cost trajectories and predictable performance outcomes, whereas in practice, fluctuations in energy prices, material availability, and user behavior significantly affect long-term costs. Similarly, simulation models may produce technically optimal solutions that are difficult to implement due to stakeholder resistance or logistical constraints.

The absence of robust field-based evidence limits the credibility of these models among practitioners, investors, and policymakers. Without empirical demonstration of their accuracy and effectiveness, models risk being dismissed as academic exercises rather than actionable tools. This gap underscores the need for longitudinal studies, post-occupancy evaluations, and collaborative research partnerships between academia and industry to validate models against real project outcomes. Empirical data would also enable the refinement of assumptions, improve predictive accuracy, and enhance stakeholder confidence in adopting cost optimization strategies.

Although technological advancements such as Building Information Modeling (BIM), artificial intelligence (AI), and the Internet of Things (IoT) have demonstrated significant potential in enhancing cost optimization, their integration into existing models remains limited. Most cost optimization frameworks still rely on conventional methods of financial analysis, operational efficiency, and scenario simulation, often isolated from real-time data and digital tools. For example, while BIM platforms are increasingly used for design coordination and cost estimation, their integration with lifecycle cost optimization and sustainability metrics is underdeveloped. Similarly, AI-driven predictive analytics, which could enhance the accuracy of cost forecasts and identify hidden optimization opportunities, are still in experimental stages with limited mainstream application.

The slow adoption of digital integration reflects both technical and institutional barriers. On the technical side, challenges include interoperability issues between software platforms, the high cost of implementing advanced digital tools, and data management complexities. Institutionally, there is often resistance to change among stakeholders accustomed to traditional methods, as well as a shortage of skilled professionals capable of leveraging these technologies effectively. The lack of integration reduces the ability of cost optimization models to deliver dynamic, adaptive, and evidence-based insights in rapidly evolving construction contexts.

Another critical challenge lies in the contextual factors that influence the applicability and success of cost optimization models. Policy environments vary widely across regions, shaping incentives, regulations, and institutional support for sustainable construction. In developed economies, supportive policies such as tax incentives, green building codes, and certification schemes facilitate the adoption of advanced optimization models. In contrast, in many developing economies, weak regulatory frameworks, fragmented governance structures, and insufficient enforcement mechanisms hinder the uptake of cost optimization strategies.

Financial constraints also play a central role. The higher upfront costs of digital tools, certification systems, and sustainable technologies can deter developers, particularly in resource-constrained contexts (Dahlman *et al*., 2016; Gupta *et al*., 2017). Even when models demonstrate long-term savings, access to financing mechanisms remains limited, restricting their practical adoption. Additionally, skills shortages represent a significant barrier. Many regions lack professionals trained in advanced methodologies such as LCC analysis, BIM integration, or optimization algorithms. Without adequate technical expertise, models remain underutilized or improperly applied, undermining their effectiveness.

A further gap lies in the limited development and application of lifecycle-based cost optimization approaches. While life cycle costing has been widely promoted, most models focus narrowly on initial capital expenditure or operational costs, neglecting other critical lifecycle stages such as maintenance, refurbishment, and end-of-life management. This partial perspective results in an incomplete understanding of long-term economic and environmental performance. For example, models often fail to account for the costs and benefits of material recyclability, building adaptability, or eventual deconstruction, which are increasingly important in circular economy frameworks.

Moreover, lifecycle-based models face methodological challenges in data availability, uncertainty management, and stakeholder engagement. Reliable data on material durability, operational performance, and decommissioning costs are often scarce or inconsistent, making lifecycle analysis difficult to conduct with precision. The uncertainty inherent in projecting costs and performance over decades also complicates the reliability of such models. Furthermore, lifecycle approaches require collaboration across multiple stakeholders—designers, contractors, facility managers, and policymakers—who may have divergent priorities and limited incentives to participate. These challenges limit the ability of lifecycle-based optimization to fully inform sustainable construction decisions.

While cost optimization models have advanced significantly, key research gaps and challenges persist. The lack of empirical validation undermines credibility and limits adoption in practice. Insufficient integration with digital and smart technologies prevents models from leveraging real-time data and advanced analytics. Contextual challenges related to policy, finance, and skills constrain their applicability, particularly in developing economies. Finally, lifecycle-based approaches remain underdeveloped, often failing to capture the full spectrum of costs and benefits associated with sustainable construction (Iacovidou *et al*., 2017; Hasan, 2017). Addressing these gaps requires a concerted effort to ground models in empirical evidence, embrace digital transformation, build institutional capacity, and expand lifecycle perspectives. By overcoming these challenges, cost optimization models can evolve from conceptual tools into robust, practical instruments that drive the global transition toward economically viable and environmentally responsible building practices.

2.6 Future Directions

The evolution of cost optimization models in green building construction reflects a broader shift toward integrating financial viability with sustainability imperatives. While significant progress has been made, the rapid advancement of digital technologies, the global emphasis on decarbonization, and the need for resilient urban development point to several promising avenues for future research and practice as shown in figure 3 (Scott *et al*., 2016; Rockström *et al*., 2017). These directions encompass the application of artificial intelligence (AI), machine learning, and digital twin technologies; the integration of renewable energy and smart grid cost models; enhanced global collaboration for knowledge sharing; and the development of policy and industry-driven incentives that can accelerate the mainstreaming of green cost optimization.

The growing availability of big data in construction and building operations creates opportunities for AI and machine learning (ML) to transform cost optimization. Traditional models often rely on static assumptions and limited datasets, reducing their ability to account for complex variables such as fluctuating material costs, changing occupant behavior, or evolving environmental conditions. AI and ML can address this limitation by analyzing vast datasets from past projects, energy performance records, and supply chain dynamics to predict costs with greater accuracy. Machine learning algorithms are particularly effective at identifying hidden patterns, enabling the detection of cost-saving opportunities that conventional methods may overlook.

Digital twins—virtual replicas of physical buildings—represent another frontier in cost optimization. By integrating real-time data from sensors, IoT devices, and building management systems, digital twins allow stakeholders to simulate and evaluate the economic and environmental impacts of different design and operational strategies throughout the building's lifecycle. They provide dynamic, adaptive platforms for cost forecasting, enabling decision-makers to continuously optimize building performance in response to actual conditions. The combination of AI, ML, and digital twins holds immense potential for moving cost optimization beyond theoretical models into practical, continuously evolving tools that directly inform construction and operational decisions.

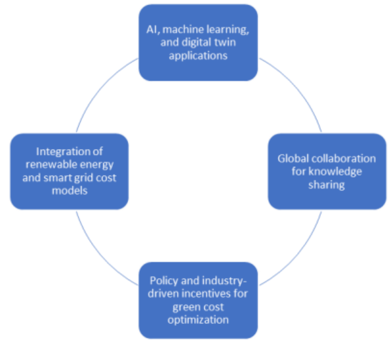

Figure 3: Future Directions

The transition toward low-carbon energy systems further underscores the importance of integrating renewable energy and smart grid models into cost optimization frameworks. Green buildings are increasingly incorporating renewable technologies such as solar photovoltaics, wind turbines, and geothermal systems, but their financial feasibility is influenced by local energy markets, grid integration policies, and storage capacities. Traditional cost models often treat these systems as isolated investments, failing to capture their dynamic interactions with broader energy networks.

Future cost optimization models must incorporate smart grid dynamics, enabling buildings to function as active participants in decentralized energy systems. This includes evaluating costs and benefits of demand response strategies, energy storage, and peer-to-peer energy trading. For instance, a building equipped with rooftop solar panels and battery storage may reduce operational costs by storing surplus energy during off-peak hours and selling excess capacity back to the grid during peak demand. By integrating these dynamics, cost models can more accurately reflect the economic value of renewable energy systems while also promoting resilience and sustainability (Liu and Zeng, 2017; Pietzcker *et al*., 2017).

Cost optimization in green building construction is inherently context-specific, shaped by regional economic conditions, regulatory frameworks, and cultural practices. Nevertheless, global collaboration is essential for accelerating innovation and ensuring equitable access to best practices. Current research reveals fragmented adoption patterns, with advanced models concentrated in developed economies while simpler approaches dominate in developing regions. Bridging this divide requires mechanisms for international knowledge exchange, capacity building, and technology transfer.

Global platforms supported by international organizations, professional associations, and academic networks can play a pivotal role. By creating open-access databases of case studies, cost benchmarks, and validated models, stakeholders across regions can learn from each other's experiences. Collaborative research projects that pair institutions from developed and developing contexts can also generate adaptable models that address diverse socio-economic conditions. Furthermore, harmonizing certification systems and performance metrics at the international level would facilitate comparability and encourage broader adoption of cost optimization strategies.

The widespread adoption of cost optimization models also depends on the presence of enabling policy and industry frameworks. Even the most advanced models cannot achieve impact without supportive incentives that encourage stakeholders to integrate them into decision-making. Governments and industry bodies must therefore play an active role in driving adoption through targeted interventions.

Policy incentives can include tax credits, subsidies, or low-interest financing for projects that demonstrate optimized lifecycle costs in line with sustainability goals. Regulatory measures such as mandatory energy performance disclosure or lifecycle cost reporting can further embed cost optimization into mainstream practice. Industry-driven initiatives, including voluntary standards, green procurement practices, and professional training programs, can complement these efforts by fostering a culture of financial and environmental accountability. Importantly, incentives should not only promote adoption in advanced markets but also support resource-constrained contexts where upfront costs present significant barriers. For example, expanding micro-finance and blended finance models for green housing projects in developing economies would enable broader application of cost optimization strategies.

Looking ahead, the future of cost optimization in green building construction lies in the convergence of digital innovation, renewable energy integration, global collaboration, and supportive institutional frameworks. AI, machine learning, and digital twins will provide unprecedented precision and adaptability, enabling continuous and dynamic optimization across building lifecycles. Renewable energy and smart grid integration will expand the economic and environmental scope of cost models, aligning building performance with global decarbonization targets (Borlase, 2017; Geels *et al*., 2017). International collaboration will democratize access to knowledge and ensure that cost optimization benefits extend to both developed and developing regions. Finally, policy and industry incentives will provide the critical enabling environment to embed these models into practice at scale. Together, these directions offer a roadmap for transforming cost optimization into a cornerstone of sustainable construction, driving the global transition toward affordable, resilient, and environmentally responsible built environments.

CONCLUSION

This systematic review examined the diverse landscape of cost optimization models applied to green building construction projects, highlighting their role in reconciling economic efficiency with environmental sustainability. This identified four major categories of models: economic and financial frameworks such as life cycle costing and net present value analysis; operational and resource approaches including value engineering and lean construction; technology-driven models based on Building Information Modeling (BIM), simulation, and artificial intelligence; and hybrid, multi-criteria decision-making frameworks. Collectively, these models demonstrate significant potential in reducing costs, enhancing resource efficiency, and improving project affordability while maintaining high sustainability performance.

Key insights reveal, however, that most models remain underutilized in real-world projects due to limited empirical validation, insufficient integration with digital and smart technologies, and contextual barriers linked to policy, finance, and skills. Furthermore, lifecycle-based optimization remains fragmented, with many approaches neglecting end-of-life and circular economy considerations. These findings underscore the importance of advancing beyond conceptual frameworks toward validated, adaptive, and context-sensitive models that can guide decision-making throughout the entire building lifecycle.

The implications of these findings are far-reaching. For policymakers, supportive regulations, incentives, and financing mechanisms are essential to mainstream cost optimization strategies in green construction. For practitioners, integrating advanced digital tools and lifecycle perspectives into project planning and delivery can enhance competitiveness and long-term value. For researchers, future work should prioritize empirical validation, AI-enabled decision tools, and comparative studies across different regional and sectoral contexts.

Ultimately, cost optimization in green building construction requires a multi-disciplinary and multi-stakeholder approach. Collaboration among engineers, architects, economists, policymakers, and technology developers is vital to designing models that are both financially robust and environmentally transformative. Such collective action will accelerate the global transition toward sustainable, affordable, and resilient built environments.

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