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Research on Cost Estimation Optimization of International Engineering Projects Based on Life Cycle Cost Concept

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Abstract: Against the complex and volatile external environment of international engineering projects, this study constructs an optimized cost estimation system by applying the Life Cycle Cost (LCC) concept, which comprehensively covers the full cycle of planning, design, demolition, construction, operation, maintenance, and disposal. International engineering projects frequently encounter multifaceted risks, including geopolitical shifts, economic fluctuations, and supply chain disruptions, rendering traditional cost estimation methods inadequate. These conventional approaches often suffer from one-sided estimating scopes and inaccurate predictions caused by uncertain external factors, primarily focusing on the construction phase while neglecting long-term operational and maintenance expenditures. To address these critical gaps, this research clarifies the LCC core calculation formulas and integrates dynamic variables to account for external uncertainties. By establishing a robust mathematical framework, the proposed model facilitates a more holistic financial assessment from project inception to final decommissioning. The research finds that the LCC concept effectively compensates for the inherent defect of overemphasizing construction-stage costs, providing stakeholders with a transparent and sustainable financial outlook. Furthermore, empirical validation demonstrates that the optimized system significantly improves the comprehensiveness, reliability, and accuracy of cost estimation for international engineering projects. Ultimately, this study offers valuable theoretical insights and practical guidelines for project managers and investors aiming to enhance cost control, mitigate financial risks, and ensure the long-term economic viability of large-scale global infrastructure developments.

Keywords: international engineering; life cycle cost; cost estimation; dynamic calculation; uncertainty control; project management

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1. Introduction

The acceleration of globalization, coupled with rapid regional population growth and intensified human activity, has substantially heightened the demand for infrastructure connectivity across national borders. Despite these growing needs, numerous underdeveloped regions and countries have yet to fully embrace advanced construction technologies or modern infrastructure development methodologies. Consequently, the pursuit of external expertise and support has emerged as a pivotal strategy to address these challenges. The proliferation of international engineering projects has become a significant catalyst for fostering cross-border economic and technological collaboration, particularly in critical sectors such as transportation, energy, and municipal infrastructure [1]. However, compared to domestic projects, international engineering endeavors are subject to far more intricate and unpredictable external conditions. These complexities encompass disparities in economic systems, fluctuations in exchange rates, shifts in political and legal frameworks, divergent construction standards, and cultural differences among participating nations.

These multifaceted factors considerably amplify the difficulty of accurately estimating project costs. Inadequate cost estimates frequently lead to budget overruns, construction delays, and, in extreme cases, the complete failure of projects. Such outcomes can have profound adverse effects on the profitability and market competitiveness of the involved stakeholders. The ability to anticipate and mitigate these risks is therefore critical for ensuring the successful execution of international engineering projects [2, 3].

In this context, the concept of Life Cycle Cost (LCC) has garnered increasing attention within the international engineering industry. LCC emphasizes the comprehensive evaluation of a project's total cost throughout its entire life cycle, encompassing planning, design, construction, operation, maintenance, and eventual demolition or disposal. Traditional cost estimation methods for international engineering projects often prioritize the construction phase and the speed of project delivery, while neglecting long-term operational, maintenance, and end-of-life costs. This narrow focus can result in incomplete and overly simplistic cost assessments that fail to capture the true overall financial implications of a project [1, 4]. By adopting LCC principles, stakeholders can achieve a more holistic understanding of project costs, enabling better decision-making and resource allocation to enhance long-term sustainability and efficiency.

2. Relevant Theoretical Foundations

2.1. Life Cycle Cost (LCC) Concept

The Life Cycle Cost (LCC) concept emerged in the United States during the 1960s, initially within the domain of military equipment management, before gradually expanding into civilian industries and other sectors [4]. LCC encompasses the total economic cost incurred throughout the entire life cycle of a project or product. This includes expenses related to planning, design, material procurement, construction, installation, operation, maintenance, demolition, disposal, and environmental restoration. By addressing all these phases comprehensively, the LCC framework provides a holistic view of the financial implications associated with a project or product over its entire lifespan.

The fundamental principle of LCC is to assess a project from a long-term perspective, taking into account its entire life cycle rather than focusing solely on a single phase or short-term construction costs. This approach prioritizes long-term economic performance and sustainability, thereby mitigating the risks of "tunnel vision" that arise from concentrating exclusively on one stage of a project, such as construction or initial implementation. By adopting this broader perspective, LCC enables a more accurate and comprehensive evaluation of a project's true overall cost and economic value. Furthermore, this methodology supports decision-making processes that are grounded in a scientific and systematic understanding of cost dynamics across all stages of a project’s life cycle [5, 6] (As shown in Figure 1).

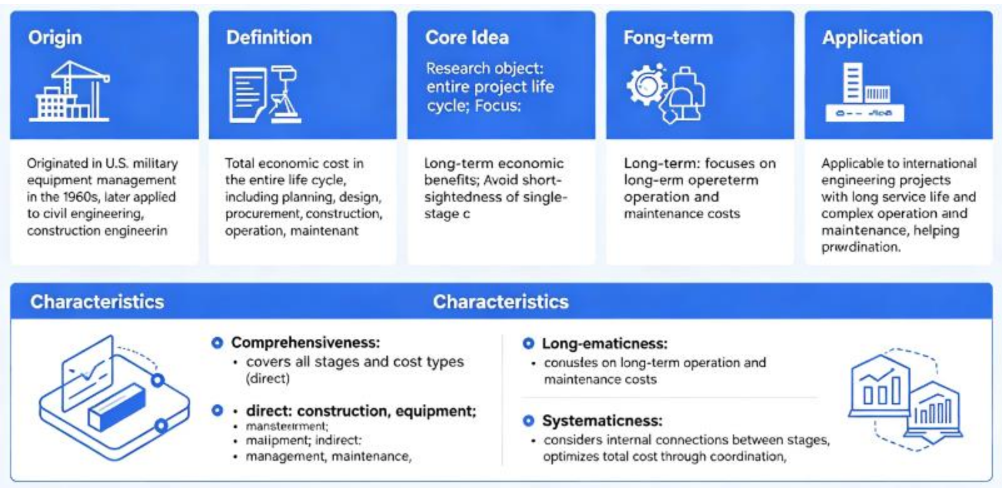

Figure 1. Life Cycle Cost (LCC) Concept

The LCC concept is distinguished by its comprehensiveness, longevity, and systematicness [7]. Comprehensiveness signifies that it encompasses all stages of a project's life cycle and all categories of costs, including direct costs such as construction and equipment expenses, as well as indirect costs like management, maintenance, and environmental expenditures. Longevity highlights the focus on long-term operation and maintenance costs, extending beyond the completion date and into the full service life of the asset. Systematicness reflects the integration of internal connections between each stage of a project's life cycle, ensuring the optimization and overall management of total costs. This involves allocating resources and funds appropriately across different phases, trades, and scopes to achieve balanced and efficient cost distribution. By addressing these dimensions, the LCC framework provides a robust foundation for managing complex projects with extended service lives and intricate operational requirements.

For international engineering projects, which often feature extended service lives and intricate operation and maintenance demands, the application of the LCC concept offers significant advantages. It enables project managers to gain a more comprehensive understanding of the overall budget, encompassing both immediate and long-term financial implications. Additionally, the LCC approach facilitates informed decision-making by providing a scientifically grounded framework for evaluating costs and resource allocation. This ensures that projects are not only economically viable but also sustainable over their entire operational lifespan, thereby enhancing their overall value and effectiveness in meeting global engineering standards [8].

2.2. Relevant Theories for Cost Estimation of International Engineering Projects

Cost estimation of international engineering projects is a multifaceted and systematic endeavor that integrates various theories and methodologies, including engineering economics, project management, and international trade. Engineering economics serves as the foundational framework for practical cost estimation, utilizing economic evaluation techniques such as cost-benefit analysis and discounting methods. These approaches assess the economic feasibility of project costs and provide a quantitative basis for selecting appropriate estimation methods. Project management theory, on the other hand, emphasizes the comprehensive management of project costs throughout the lifecycle of the project [9]. This includes dynamic cost control during implementation phases to ensure that expenditures remain within the predefined budgetary limits. By combining these theoretical perspectives, practitioners can achieve a balanced approach to cost estimation that accounts for both economic rationality and effective cost control mechanisms. Figure 2 illustrates the relevant theories applied in the cost estimation of international engineering projects.

Figure 2. Relevant Theories for Cost Estimation of International Engineering Projects

3. Current Situation and Problematic Analysis of Cost Estimation for International Engineering Projects

3.1. Current Status of Cost Estimation for International Engineering Projects

In recent years, the continuous growth and steady expansion of large-scale international engineering projects have significantly increased their complexity. This has necessitated advancements in cost estimation practices to meet the demands of these intricate projects [9]. Many international engineering enterprises have responded by developing relatively mature cost estimation systems, incorporating advanced software and tools designed to improve both efficiency and accuracy. These systems enable project managers and engineers to better predict financial requirements and allocate resources effectively, thereby reducing risks associated with budget overruns and unforeseen expenses. Furthermore, the integration of cutting-edge technologies, such as artificial intelligence and big data analytics, has further enhanced the precision of cost estimation processes, ensuring that estimates align closely with actual project outcomes.

Simultaneously, the widespread adoption of international engineering standards and norms has played a pivotal role in standardizing cost estimation methods [10]. This standardization has led to greater comparability and scientific rigor in the results, allowing stakeholders to make more informed decisions based on reliable data. By adhering to these established norms, enterprises can ensure consistency across projects, regardless of geographical location or industry sector. Additionally, the harmonization of methodologies facilitates cross-border collaboration and benchmarking, enabling organizations to identify best practices and optimize their cost estimation strategies. These advancements contribute to the overall improvement of project management efficiency and the successful execution of complex international engineering endeavors.

3.2. Core Issues in Cost Estimation of International Engineering Projects

One of the significant challenges in the cost estimation of international engineering projects is the limited scope often applied during the estimation process. Many current practices focus predominantly on specific construction stages, while overlooking costs associated with other critical phases of the project life cycle. These phases include the planning and design stage, the operation and maintenance stage, and the demolition and disposal stage. This narrow focus can result in an underestimation of the total project cost. As the project progresses, these omissions may necessitate substantial additional budget allocations, leading to unexpected cost overruns. Such financial discrepancies can disrupt project timelines and strain resources, ultimately impacting the overall feasibility and success of the project. A comprehensive approach to cost estimation that accounts for all life-cycle stages is essential to mitigate these risks and ensure financial predictability.

For instance, international infrastructure projects frequently incur higher operation and maintenance costs during later stages. These elevated costs can be attributed to various factors, including local construction policies, regulatory requirements for maintenance and operation, and the salaries of local workers and staff. Additionally, the cost of consumable materials, which often varies significantly from the country of origin, can further inflate expenses. If these factors are not adequately considered during the initial cost estimation process, the project may face severe economic challenges. Such oversight can lead to financial strain, necessitating unplanned budget adjustments and potentially jeopardizing the project's financial viability. Therefore, a more holistic and detailed approach to cost estimation is critical to account for these variables and ensure the long-term economic sustainability of international engineering projects.

3.3. The Necessity of Applying the Life-Cycle Cost Concept to Cost Estimation

The application of the Life Cycle Cost (LCC) concept is an effective approach to addressing the challenges associated with cost estimation in international engineering projects. By requiring consideration of the total cost across the entire life cycle of a project, the LCC concept compensates for the limitations of traditional cost estimation methods, which often focus narrowly on specific construction stages. This broader perspective enables project managers to develop a more accurate and comprehensive understanding of the true budget requirements. Furthermore, the LCC concept emphasizes the importance of long-term budget management and systematic control, allowing project managers to proactively anticipate and mitigate uncertainties at each stage of the project's life cycle. This proactive approach reduces the potential impact of unforeseen factors on project costs, thereby enhancing the precision and reliability of cost estimation processes. Additionally, the integration of the LCC concept into cost estimation practices fosters a more strategic approach to financial planning, ensuring that resources are allocated efficiently and effectively throughout the project's duration.

Moreover, the adoption of the Life Cycle Cost (LCC) concept can significantly benefit international engineering enterprises by optimizing project design and construction strategies. This optimization not only reduces long-term operation and maintenance expenses but also contributes to the overall economic efficiency of the project. By minimizing unnecessary expenditures and enhancing resource utilization, enterprises can achieve greater financial sustainability and improve their market competitiveness. The LCC approach encourages a forward-looking perspective, enabling organizations to identify cost-saving opportunities during the early stages of project planning and execution. This strategic focus on long-term benefits ensures that projects are not only economically viable but also capable of delivering sustained value over time. As a result, the application of the LCC concept serves as a critical tool for enhancing the financial performance and competitive positioning of engineering projects in the global marketplace [11].

4. Optimization Plan for Cost Estimation of International Engineering Projects Based on the Concept of Life Cycle Cost

4.1. Optimization Ideas and Basic Principles

The optimization of cost estimation can be effectively achieved by adopting the concept of Life Cycle Cost (LCC). For international engineering projects, it is essential to view the project life cycle as an integrated whole while simultaneously breaking it down into detailed and manageable components [12]. Traditional estimation methods often focus on isolated stages, which can lead to inefficiencies and overlooked costs. To address this, the process should be divided into smaller, well-defined sections and managed through a structured, layered, and top-down approach. This method ensures that each phase of the project is thoroughly analyzed, allowing for a more accurate and comprehensive cost estimation process. By systematically addressing each segment, potential cost-saving opportunities can be identified and leveraged, ultimately enhancing the overall financial efficiency of the project.

The primary advantage of this detailed management approach lies in its ability to uncover and account for costs that might otherwise be neglected or underestimated. Establishing a comprehensive, systematic, and dynamic cost estimation system is crucial for achieving this goal. This involves clearly defining the cost components associated with each stage of the project life cycle, ensuring that all relevant data is meticulously collected and organized. Furthermore, the system must be designed to adapt and improve continuously, incorporating feedback and lessons learned from previous projects. By refining cost estimation methods over time, the accuracy and reliability of the system can be significantly enhanced. This iterative process not only reduces the likelihood of unexpected expenses but also provides a robust framework for financial planning and decision-making in complex international engineering projects [13].

4.2. Construction of Cost Estimation System Based on LCC

The construction of a cost estimation system grounded in the Life Cycle Cost (LCC) concept is a pivotal component for optimizing estimation processes in international engineering projects. This system encompasses defining the scope of cost estimation, systematically collecting and organizing relevant data, and refining cost estimation methodologies. The scope of cost estimation must comprehensively address all phases of the project's life cycle, including planning, design, construction, operation and maintenance, as well as demolition and disposal. Each phase should be meticulously analyzed to identify all associated cost elements, ensuring the estimation process is exhaustive and precise.

The systematic collection and organization of cost data serve as the foundation for the effective operation of the cost estimation system. Data acquisition should include information from analogous international engineering projects, alongside critical factors such as currency exchange rates, raw material costs, labor expenses, and other economic variables specific to the host country. This data must be categorized and structured into a robust cost database, which should be continuously updated to reflect fluctuations in market conditions and project developments. Real-time updates to the database are essential for maintaining the accuracy and reliability of cost estimations. Furthermore, integrating the LCC concept into traditional estimation methods allows for the refinement of these methodologies, enhancing their scientific validity and precision [10].

$$LCC = C_P + C_D + C_C + C_O + C_{Dp}$$

Within this framework, LCC represents the aggregate cost incurred throughout the entire life cycle of an international engineering project. (C_P) denotes the planning stage costs, encompassing expenses related to feasibility studies, investigations, and surveys. (C_D) pertains to the design stage costs, including expenditures for conceptual design, detailed design, and design reviews. (C_C) captures the construction stage costs, which include costs for construction materials, equipment, labor, and management. (C_O) reflects the operation and maintenance stage costs, covering equipment upkeep, personnel management, and energy consumption. Finally, (C_{Dp}) represents the demolition and disposal stage costs, which include building demolition, waste management, and environmental restoration.

$$C_t = C_0 \times (1 + r)^t$$

Additionally, (C_t) signifies the cost incurred during the t-th year within a specific stage of the project's life cycle, while (C_0) represents the initial cost of that stage. The variable (r) indicates the annual cost increase rate, accounting for factors such as inflation and market price variations, and (t) denotes the duration in years for the stage under consideration. This formula facilitates the calculation of dynamic costs for each stage, enabling a comprehensive understanding of how price changes influence project expenditures over time. By employing this approach, the cost estimation system can provide a more accurate and adaptive financial analysis for international engineering projects.

4.3. Optimization of Cost Estimation for Each Lifecycle Stage

Based on the needs of the LCC concept, the optimization of cost estimation in international engineering projects requires integrating the characteristics of each life cycle stage. To address the key issues in cost estimation at each stage and achieve optimization of the total life-cycle cost, the planning and design stage is a critical link [10]. The cost determined during this stage constitutes a significant proportion of the total life-cycle cost. Therefore, cost estimation optimization at this stage should prioritize improving the project scheme and selecting the option with the lowest total life-cycle cost through comprehensive multi-scheme comparisons. Sharing resources among designers, management teams, and budget engineers during the early design phase can lead to substantial savings by avoiding unnecessary expenditures. Additionally, collaboration among these three parties facilitates the early identification of cost risks and potential issues that may arise in future project management. This proactive approach ensures that the project is aligned with cost efficiency goals from the outset.

The construction stage is where project costs are directly incurred, making cost control during this phase crucial to the overall life-cycle cost [1]. Cost estimation optimization at this stage should emphasize the accurate calculation of construction costs while strengthening control over material prices and labor costs. Effective cost management can be achieved through the application of professional management skills and the implementation of an efficient hierarchical management mechanism. Such measures can significantly reduce resource waste and prevent cost overruns caused by construction errors. By closely monitoring material procurement and labor allocation, project managers can ensure that expenditures remain within budgetary constraints. Furthermore, adopting advanced construction technologies and methodologies can enhance efficiency and minimize unnecessary expenses, contributing to the overall cost optimization of the project.

The operation and maintenance stage is the longest and often the most complex phase in a project's life cycle. Cost estimation optimization during this stage should focus on predictive approaches informed by past experience. Managers must anticipate and mitigate potential risks and oversights during operation and maintenance by employing proactive strategies [14]. Optimizing processes requires a thorough understanding of local laws, regulations, and customs to ensure compliance and efficiency. Establishing a scientific operation and maintenance cost prediction model is essential for accurately forecasting expenses. Additionally, reducing operation and maintenance costs can be achieved by refining maintenance strategies, such as implementing condition-based maintenance or predictive maintenance techniques. These approaches not only enhance the reliability of the project but also contribute to long-term cost savings by minimizing unexpected failures and associated repair costs.

$$C_{D,opt} = \min\left(C_{D,i} + \sum_{t=1}^{n} C_{O,it} \times (P/F, r, t)\right)$$

Among them, $(C_{D,opt})$ represents the optimal design stage cost; $(C_{D,i})$ represents the design cost of the i-th design scheme; $(C_{O,it})$ represents the operation and maintenance cost of the i-th design scheme in the t-th year; $(P/F, r, t)$ represents the present value factor, (r) represents the discount rate, and (n) represents the operation and maintenance period. This formula is utilized to select the optimal design scheme by comparing the total cost of the design stage and the operation and maintenance stage across different design schemes. By integrating these variables, decision-makers can identify the most cost-effective solution that balances initial design expenditures with long-term operational efficiency.

$$C_{C,est} = \sum_{i=1}^{m} Q_i \times P_i \times (1 + k)$$

Among them, $(C_{C,est})$ represents the estimated construction stage cost; (Q_i) represents the quantity of the i-th construction material or engineering quantity; (P_i) represents the unit price of the i-th construction material or engineering quantity (considering exchange rate and international market price); (k) represents the comprehensive cost coefficient (including management fees, taxes, risks, etc.). This formula is applied to accurately estimate the construction stage cost by accounting for the quantity, unit price, and comprehensive cost of each construction item. By incorporating these factors, project managers can ensure that cost estimations are precise and reflective of real-world conditions, thereby minimizing the likelihood of budgetary discrepancies and enhancing overall financial planning.

5. Case Analysis

5.1. Overview of Case Projects

The case selected involves a 150-kilometer cross-border railway project managed by a Chinese contractor in a South Asian country. This project, classified as a key infrastructure initiative, has a construction period of four years and a 30-year operation and maintenance cycle. The project encompasses significant engineering challenges, including the construction of 12 bridges and 3 tunnels, as well as the procurement of cross-border steel materials. Additionally, it requires strict adherence to local environmental and construction standards. The initial cost estimation for this project, which focused solely on the construction phase, projected an investment of 520 million USD. However, this traditional approach failed to account for long-term operation and maintenance expenses, as well as external economic factors such as local exchange rate fluctuations (±4–6% annually) and raw material price increases (3.1% annual growth rate). These omissions highlight the limitations of conventional cost estimation methods in addressing the comprehensive financial demands of such large-scale international projects.

Before optimization, the project's cost estimation process was hindered by the absence of a systematic regional cost database. Instead, it relied heavily on subjective experience and comparisons with similar projects [13]. This approach introduced significant risks, as evidenced by a preliminary risk assessment that projected a potential cost overrun of 20–25% during later stages. Critical cost components, such as equipment maintenance, environmental restoration, and waste disposal, were entirely excluded from the estimation scope. These omissions underscore the inadequacies of traditional international engineering cost estimation practices, which often fail to incorporate comprehensive risk assessments and long-term financial planning. By neglecting these essential factors, the project faced heightened financial uncertainty, particularly in the context of fluctuating economic conditions and evolving regulatory requirements. This analysis highlights the urgent need for more robust and systematic cost estimation methodologies to ensure the financial sustainability of international infrastructure projects.

5.2. Optimization Effect Analysis and Verification

By utilizing the LCC-based cost estimation optimization system alongside the core dynamic calculation formulas introduced in this study, the full life-cycle cost of the South Asian cross-border railway project was recalculated with enhanced precision. This optimization approach integrated multi-stage cost components, establishing a localized regional cost database tailored to the project's unique geographical and economic context. Furthermore, it dynamically adjusted costs to account for inflationary pressures and fluctuations in exchange rates, effectively addressing the inherent limitations of traditional estimation methodologies [15]. The system's adaptability ensures that cost projections remain robust and reflective of real-world economic conditions, thereby improving the reliability of financial planning for large-scale international engineering projects.

The data presented in Table 1 highlights the significant discrepancies between traditional estimation methods and the LCC-based optimized approach. Traditional methods primarily focused on construction and preliminary design costs, leading to a 26.7% underestimation of the total life-cycle cost when compared to the optimized results. In contrast, the LCC-based estimation incorporated long-term cost factors, with operation and maintenance expenses constituting 20.1% of the total life-cycle cost, thereby emerging as a critical cost component [16]. Additionally, the multi-scheme optimization applied during the planning and design stages resulted in an 18.5% increase in upfront costs. However, this proactive investment substantially mitigated the project's potential cost overrun risk, reducing it to a range of 7–9%. These findings underscore the scientific rigor and enhanced reliability of the LCC concept in refining cost estimation practices for international engineering projects, ensuring more accurate financial forecasting and risk management.

Table 1. Comparison of Traditional and LCC-Based Optimized Cost Estimation Results

Estimation Type	Planning & Design Cost	Construction Cost	Operation & Maintenance Cost	Demolition & Disposal Cost	Total Life Cycle Cost
Traditional Cost Estimation	30.8	489.2	0 (Ignored)	0 (Ignored)	520.0
LCC-Based Optimized Estimation	36.5	507.8	142.6	22.1	709.0

6. Conclusion

This study systematically examines how to optimize cost estimation for international engineering projects using the Life Cycle Cost (LCC) approach. By developing a comprehensive estimation framework, the study delineates cost components for each project phase and integrates dynamic calculation models to enhance precision. The framework's effectiveness is validated through a detailed case study of a cross-border railway project, showcasing its practical applicability. This structured approach ensures that all cost elements, including initial investment, operational expenses, and decommissioning costs, are accounted for, thereby addressing gaps in traditional estimation methods. The study emphasizes the importance of adopting such methodologies to improve financial predictability and project sustainability in the global engineering sector.

The case results reveal that the LCC-based estimation framework significantly mitigates the limitations and inaccuracies inherent in conventional methods. Specifically, the total life cycle cost of the project was calculated at approximately USD 709 million, which exceeded the estimate produced by traditional methods by USD 189 million. This discrepancy highlights the underestimation risks associated with conventional approaches. Furthermore, the framework demonstrated its capacity to reduce the likelihood of cost overruns by over 12 percentage points, underscoring its reliability in managing financial risks. These findings suggest that the LCC approach not only enhances cost accuracy but also provides a robust foundation for strategic decision-making in complex international projects.

The findings underscore the transformative potential of the LCC approach in improving the accuracy and comprehensiveness of cost estimation for international engineering projects. By enabling firms to optimize project planning and manage long-term costs more effectively, this methodology contributes to better resource allocation and financial sustainability. Additionally, the study highlights the broader implications of adopting LCC frameworks, including fostering innovation in cost management practices and promoting the sustainable development of engineering projects on a global scale. Future research could explore the integration of advanced technologies, such as artificial intelligence and machine learning, to further refine LCC models and enhance their predictive capabilities. Such advancements would provide even greater support for decision-makers in navigating the complexities of international project management.

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