Optimizing Railway Track Management through Life Cycle Cost Analysis: A Comprehensive Review

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DOI: https://doi.org/10.31284/j.jtm.2024.v5i2.5935
Received 22 April 2024; Received in revised 15 May 2024; Accepted 16 May 2024; Available online 12 June 2024

Abstract

This research presents a comprehensive analysis of the application of life cycle cost (LCC) analysis to railway track systems, aiming to optimize the economic and operational performance of railway infrastructure throughout its lifespan. The study explores existing LCC models and their application in railway track analysis, emphasizing the importance of LCC as a decision-making tool for infrastructure management. Furthermore, the research delves into the integration of degradation models for key track components such as ballast, rails, and sleepers, and their contribution to more accurate and effective LCC analysis. Several case studies are reviewed to illustrate the practical application of LCC analysis in real-world scenarios, including the analysis of alternative track support materials for the Sydney Harbour Bridge, the evaluation of monoblock sleeper systems for the Indonesian Urban Metro Railway Project under uncertainty, and the assessment of life cycle costs, energy, and carbon for the Beijing-Shanghai High-Speed Railway. The findings from this research highlight the importance of LCC analysis in guiding maintenance and renewal policies for railway tracks, ensuring cost-effectiveness while maintaining safety and reliability. The research concludes with recommendations for the adoption of advanced LCC models and maintenance strategies, as well as the need for future research to address uncertainties in system performance and refine models for better decision-making in railway track management.

Keywords: *Life Cycle Cost, Railway*

1. Introduction

The railway system in Indonesia faces several significant challenges that impact its efficiency, safety, and sustainability. One of the primary issues is the continuous degradation of railway track components due to operational stresses and environmental factors, which necessitates regular maintenance and eventual renewal to ensure ongoing reliability and safety [1]. The maintenance management system in Indonesia has been found lacking when compared to more advanced systems like that of the United Kingdom's Network Rail. Key problems identified include financial management issues, organizational structure inefficiencies, and inadequate asset management. Additionally, the Indonesian railway network suffers from a lack of proper maintenance windows, leading to difficulties in scheduling necessary upkeep without disrupting services. The infrastructure itself is often outdated, with many tracks being relics from the Dutch colonial era, requiring intensive handling and modernization [2].

The high-speed rail projects, such as the Jakarta-Bandung line, have faced numerous setbacks including cost overruns, environmental concerns, and poor management practices, which have raised questions about their long-term viability and safety. The government has also struggled with land acquisition and clearance, further complicating infrastructure projects and leading to significant delays and increased costs. These issues highlight the need for comprehensive reforms in maintenance management, investment in modern infrastructure, and better project planning and execution to improve the overall performance of Indonesia's railway system.. This reality brings to the forefront the concept of Life Cycle Cost (LCC) analysis in railway track management, a methodology that assesses the total cost associated with the lifecycle of railway track components from acquisition through to disposal [3][4]. LCC analysis is pivotal for making informed decisions that optimize the economic and operational performance of railway tracks over their entire lifespan [5].

LCC analysis in railway track management involves the comprehensive assessment of all costs associated with the construction, maintenance, operation, and eventual decommissioning of track systems [6]. By quantifying these costs, LCC analysis helps identify the most cost-effective strategies for maintaining track integrity and performance. This approach is particularly important in the face of increasing demands on rail infrastructure, where the need to maximize the efficiency of financial investments while ensuring safety and reliability cannot be overstated [7].Railway tracks comprise various components, including rails, sleepers, ballast, and fastenings, each with its unique degradation mechanisms and maintenance requirements [8]. Factors such as traffic load, environmental conditions, and material properties influence the rate of degradation, necessitating a nuanced understanding of these components and their interactions. Effective LCC analysis, therefore, requires not only a grasp of the economic aspects but also a deep technical knowledge of railway track systems and their behavior under operational stresses [9] [4].

Given the complexity of railway track systems and the diverse factors influencing their performance and costs, there is a pressing need for optimization models that can minimize LCC while ensuring the safety and reliability of rail transport [3]. These models must account for the dynamic nature of track degradation, incorporating predictive maintenance strategies and innovative materials to extend the lifespan of track components [10]. By integrating such models into railway infrastructure management, stakeholders can achieve a balance between operational efficiency, economic viability, and environmental sustainability, paving the way for a more resilient and cost-effective railway system [11][4].

In conclusion, the paper the application of Life Cycle Cost (LCC) analysis to railway track systems is an indispensable strategy for railway infrastructure management. It provides a framework for understanding and optimizing the costs associated with the entire lifespan of railway tracks, from initial construction to eventual decommissioning. By incorporating technical knowledge of track degradation and maintenance requirements, LCC analysis enables infrastructure managers to make decisions that enhance the safety, reliability, and cost-effectiveness of rail transport. The development and implementation of sophisticated optimization models that address the dynamic and complex nature of railway tracks are crucial for the sustainable advancement of the global railway network. As the demand on railway systems continues to grow, the integration of LCC analysis into railway management practices will be vital for ensuring the long-term economic and operational success of this essential mode of transportation.

2. Literature Review

2.1. Summary of Existing LCC Models and Their Applications in Railway Track Analysis of RAMS Concepts

Life Cycle Cost (LCC) analysis has been extensively applied in railway track management to optimize the cost and performance of railway infrastructure. Various models have been developed to address different aspects of railway track LCC. For instance, some models focus on the direct costs associated with construction, maintenance, and renewal, while others incorporate broader economic factors, including downtime and user costs during maintenance periods. These models are crucial for railway administrators and policymakers to make informed decisions that balance cost, performance, and safety. For example, the application of LCC models in the Lisbon–Porto line demonstrated significant cost savings by optimizing the timing and nature of maintenance interventions.

2.2. Integration of Degradation Models for Ballast, Rail, and Sleepers in LCC Analysis

The integration of degradation models into LCC analysis is critical for accurately predicting the maintenance needs and lifecycle costs of railway tracks. Degradation models for ballast, rail, and sleepers take into account the wear and tear that these components undergo due to mechanical stresses and environmental conditions. These models help in predicting the deterioration rate of track components, which is essential for planning maintenance and renewal activities in a cost-effective manner. For instance, advanced degradation models consider the impact of repeated load cycles on rails and the compaction of ballast over time, which are key factors in determining the frequency and type of maintenance required.

2.3 Review of Case Studies Focusing on Specific Railway Lines and Their LCC Optimization

Several case studies have been conducted to demonstrate the practical application and benefits of LCC analysis in railway track management. These include:

- Lisbon–Porto Line: The LCC analysis conducted on the Lisbon–Porto line utilized a comprehensive model that incorporated both the initial construction costs and the ongoing maintenance and renewal costs, as seen in Figure 1 [12]. The study highlighted the potential for reducing overall lifecycle costs through the strategic timing of track renewals and the use of more durable materials.
- Sydney Harbour Bridge: The Sydney Harbour Bridge case study focused on the replacement of traditional timber sleepers with more durable steel one, as seen in Figure 2. The LCC analysis showed that despite the higher initial cost, steel sleepers offered lower lifecycle costs due to their longer lifespan and reduced maintenance requirements [13].
- Indonesian Urban Metro Railway Project: In this project, LCC analysis was used to evaluate different track designs and materials for an urban metro system, as seen in Figure 3. The study explored various scenarios under different traffic conditions and maintenance strategies, providing insights into the most cost-effective options for the metro system [14].

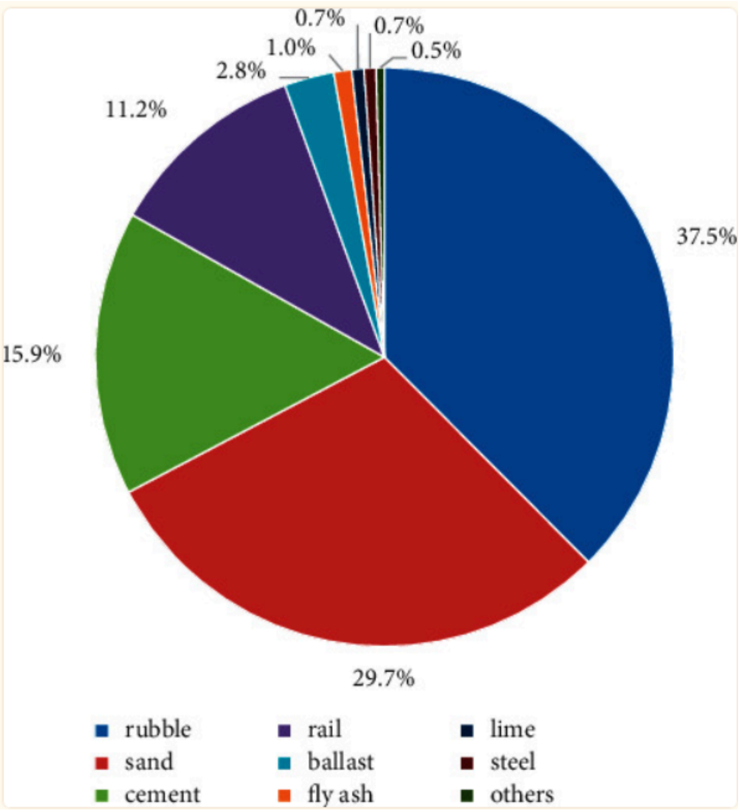

Figure 1. Proportion of life-cycle CDW generated from various construction materials [12]

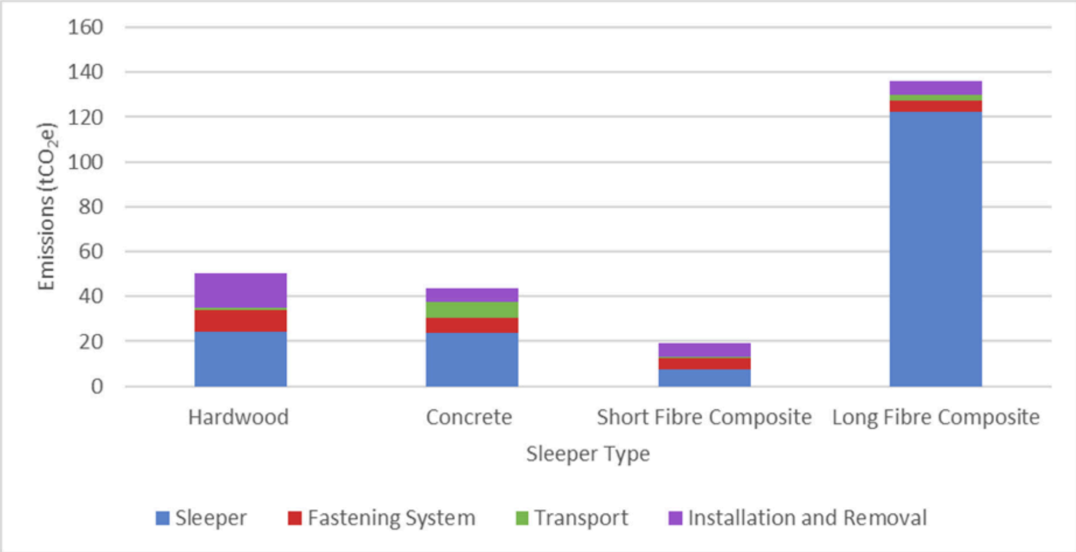

Figure 2 Total embodied emissions for sleepers with 50% fastening reuse and material reclaiming [13]

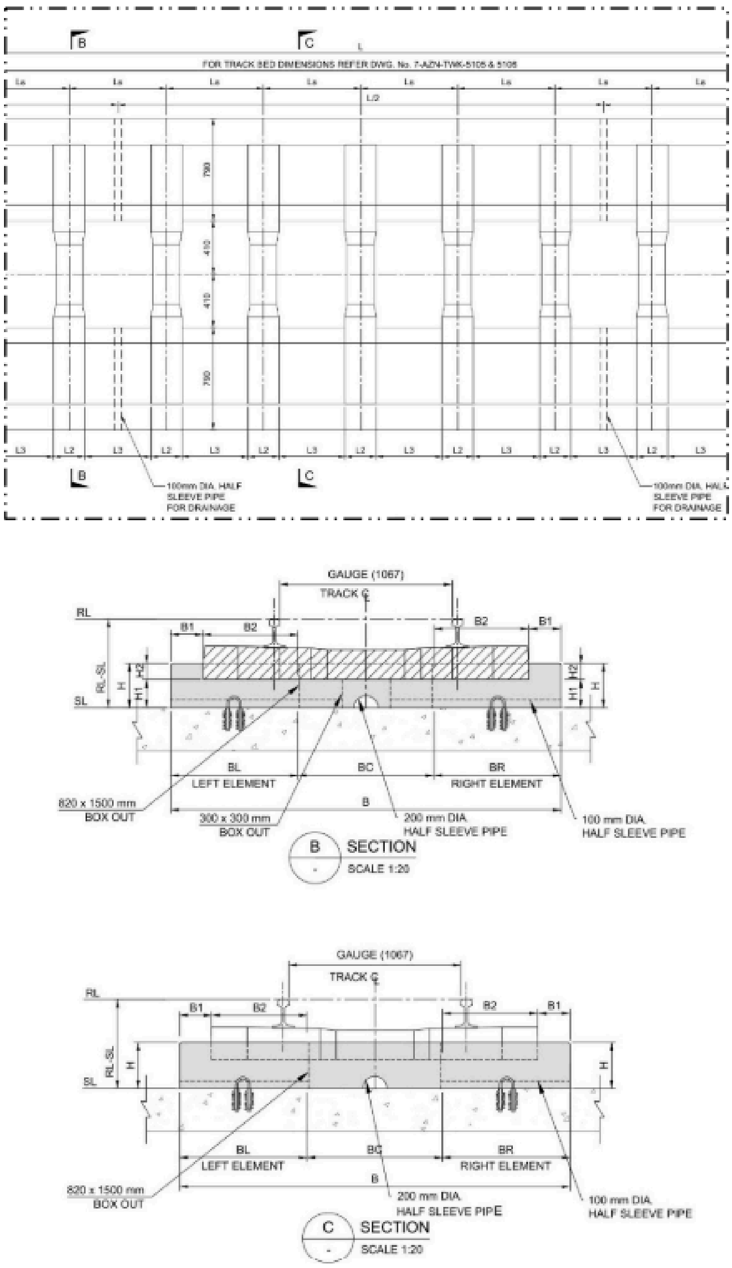

Figure 3. Technical detail of railway slab track for the Jakarta MRT Project [14].

These case studies illustrate the effectiveness of LCC analysis in guiding the decision-making process for railway track maintenance and renewal. By considering the total costs over the life of the track, railway managers can optimize their investments and achieve a balance between cost, performance, and safety.

3. Methodology

3.1. Mixed Integer Linear Programming Model for Optimizing Railway Track Renewal Operations

The methodology employs a mixed integer linear programming (MILP) model to optimize the scheduling and allocation of resources for railway track renewal operations [15]. This model is designed to minimize the total cost of renewals while ensuring that the track remains in a state that meets safety and performance standards. The MILP model incorporates various constraints, including budget limitations, track downtime, and the availability of maintenance crews and equipment. It also considers the degradation rate of track components to determine the optimal timing for renewal interventions. This approach allows for the strategic planning of renewals, which can significantly reduce the life cycle costs associated with railway tracks. The model's effectiveness is demonstrated through a case study on the Lisbon–Porto railway line in Portugal, showing potential cost savings in track renewals [16].

3.2. Assessment of the Life Cycle, Energy, and Carbon Footprint of High-Speed Railways

The methodology also involves an assessment of the life cycle, energy, and carbon footprint of high-speed railways, with a specific focus on the Beijing-Shanghai High-Speed Railway [17]. This analysis considers all stages of the railway's life cycle, from construction to operation and eventual decommissioning. The assessment quantifies the energy consumption and carbon emissions associated with each stage, providing a comprehensive overview of the environmental impact of high-speed rail operations. This information is crucial for making decisions that not only consider economic and operational efficiency but also environmental sustainability. The findings from the Beijing-Shanghai High-Speed Railway serve as a case study to illustrate the potential environmental benefits of high-speed rail compared to other modes of transportation.

3.3 Markov Forecast Model for Maintenance Decisions Based on Track Recording Machine Data

The methodology includes the use of a Markov forecast model to make informed maintenance decisions based on data collected from track recording machines [4]. These machines provide critical data on track conditions, such as geometry and rail wear, which are used to predict the future state of the track components. The Markov model assesses the probability of different degradation states over time, allowing maintenance planners to anticipate when interventions will be necessary. By using this predictive model, railway operators can schedule maintenance activities more efficiently, reducing the risk of unexpected track failures and the associated costs.

4. Case study

The Sydney Harbour Bridge serves as a pivotal case study for the life cycle cost analysis (LCC) of alternative railway track support materials, as explored in the research conducted by Sepani Senaratne and colleagues. This investigation is paramount in addressing the pressing need for cost-effective, maintenance-efficient, and environmentally sustainable solutions within railway infrastructure, particularly for iconic and heavily utilized structures such as the Sydney Harbour Bridge. The study meticulously evaluates three distinct materials for railway transoms: precast conventional composite concrete-steel panel, precast prestressed composite concrete-steel panel, and fiber composite panel, covering various life cycle phases including manufacturing, installation, maintenance, and end-of-life disposal. The primary aim is to ascertain which material presents the most financially viable option over a projected lifespan of 100 years, taking into account both direct costs and the implications of maintenance and replacements [9].

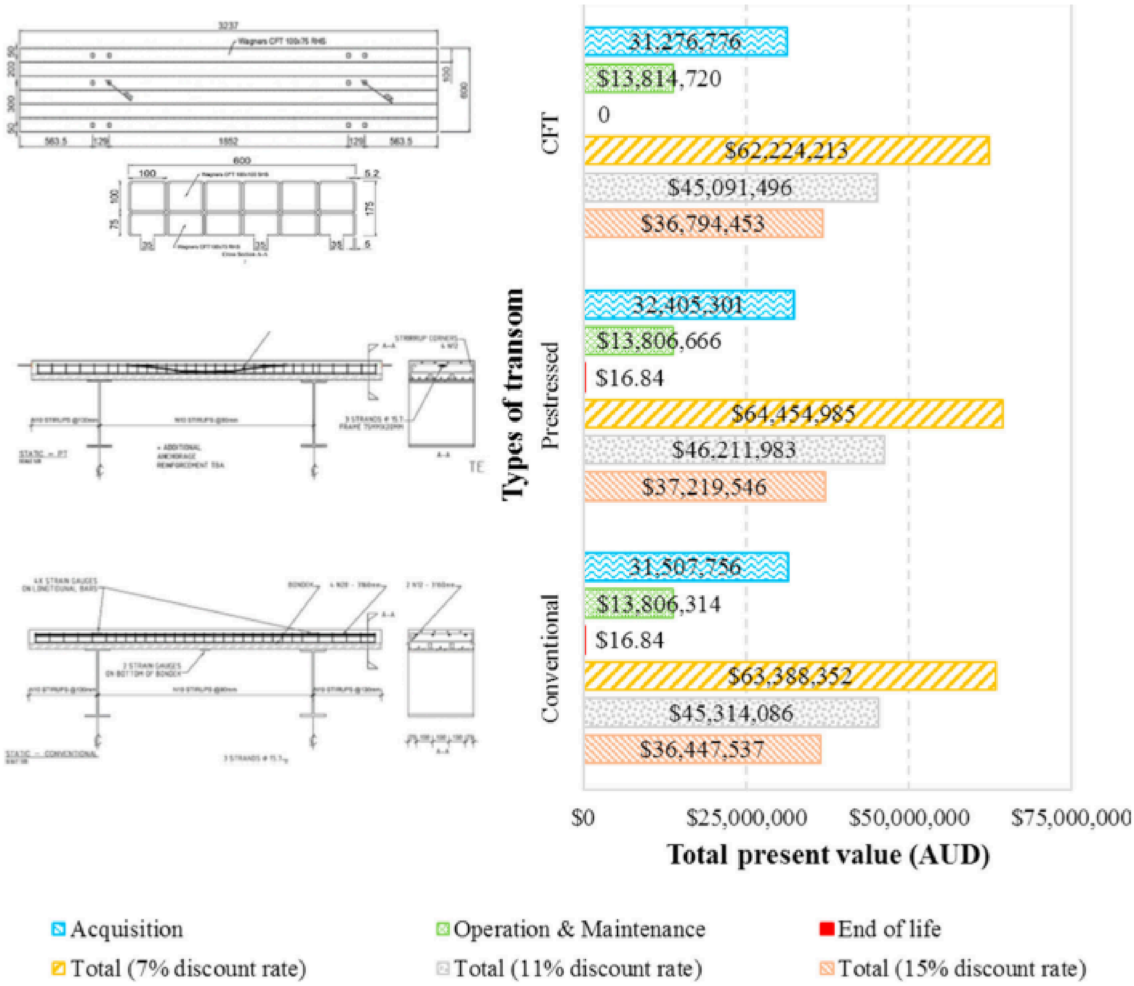

Figure 4. Overall life cycle cost comparison using lift installation method

The outcomes of the case study underscore the fiber composite panels as the most financially advantageous option in the long term, despite their higher initial cost. This advantage is attributed mainly to their reduced maintenance needs and extended lifespan compared to the other materials evaluated. The application of Monte Carlo Simulation to factor in uncertainty within the life cycle cost analysis enhances the depth of understanding regarding the potential financial risks associated with each material option. This case study is of critical importance to decision-makers within the railway industry, offering empirical data and a comprehensive financial analysis to support the shift towards more sustainable and cost-effective materials in railway infrastructure projects. The insights derived from this study are instrumental in guiding future projects, not only for the Sydney Harbour Bridge but also for similar applications globally, thereby advocating for a transition towards more sustainable practices in the construction and maintenance of railway systems [18], [19], [20].

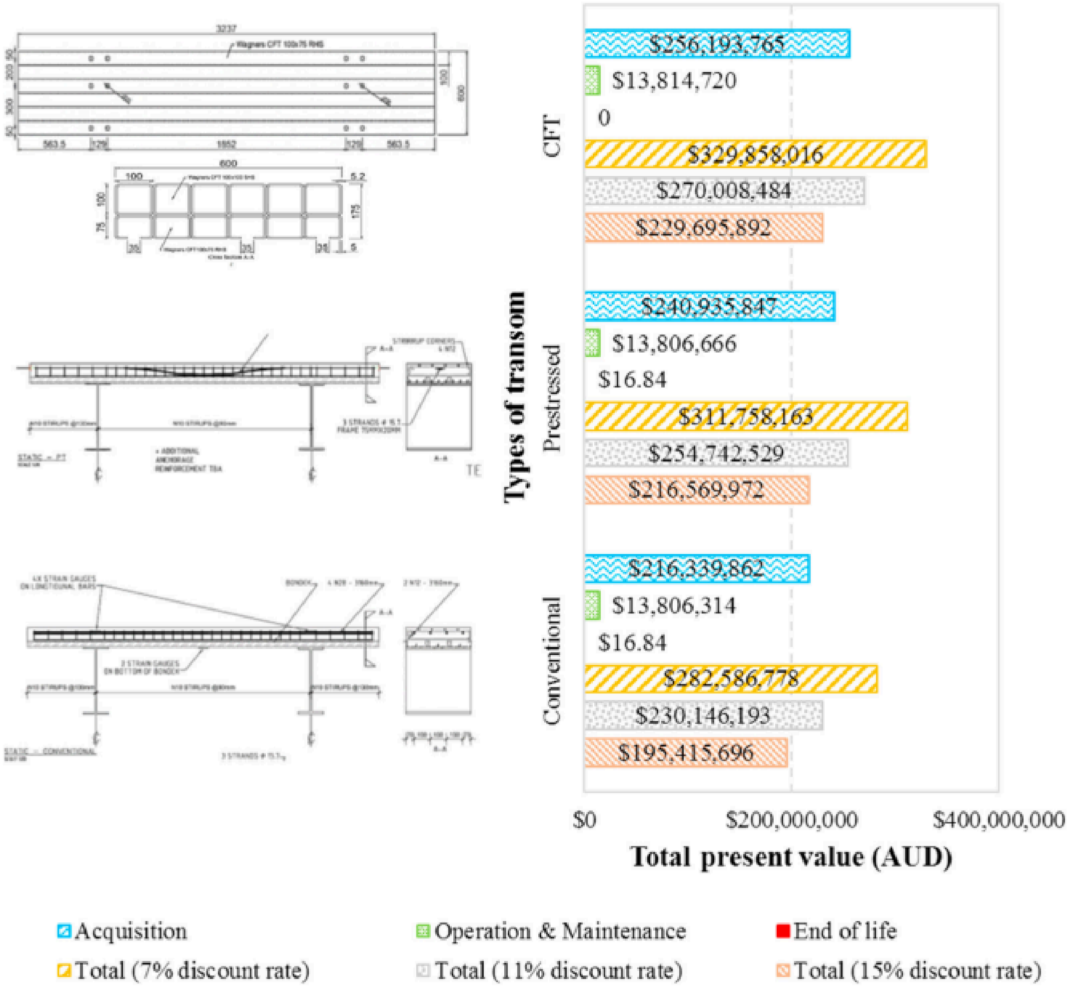

Figure 5. Overall life cycle cost comparison using full modular method

The Indonesian Urban Metro Railway Project, particularly the Jakarta Mass Rapid Transit (MRT) and Light Rail Transit (LRT) systems, exemplifies the implementation of a slab track monoblock sleeper system, a pivotal innovation in urban rail infrastructure. This system, as detailed in the study by K Usman et al., is chosen for its potential to meet the demanding criteria of modern urban rail systems, including sustainability, reliability, and reduced life cycle costs under conditions of uncertainty. The slab track system, characterized by its use of precast concrete sleepers with integrated anti-vibration systems, offers significant advantages over traditional ballasted tracks, such as enhanced durability and lower maintenance requirements, which are crucial in the context of Jakarta's challenging geohazards and climate conditions [21].

The life cycle cost analysis of this project, utilizing Monte Carlo Simulation (MCS), reveals critical insights into the risk management of railway infrastructure. For instance, the Jakarta MRT Project Phase 1, which includes both underground and elevated sections, employs Type 1 Railway Slab Track (RST) where the anti-vibration system is mounted underneath the sleepers. This configuration is specifically designed to mitigate vibrations, enhancing passenger comfort and structural integrity. Conversely, the Jakarta LRT Project Corridor 1 (Phase 1) utilizes Type 2 RST, integrating the anti-vibration system within the rail fastening systems, suitable for elevated tracks where stability and vibration reduction are paramount. Both cases underscore the importance of incorporating performance uncertainty into planning and operational strategies to manage potential defects or failures effectively, thereby ensuring the system's long-term sustainability and efficiency [20], [21].

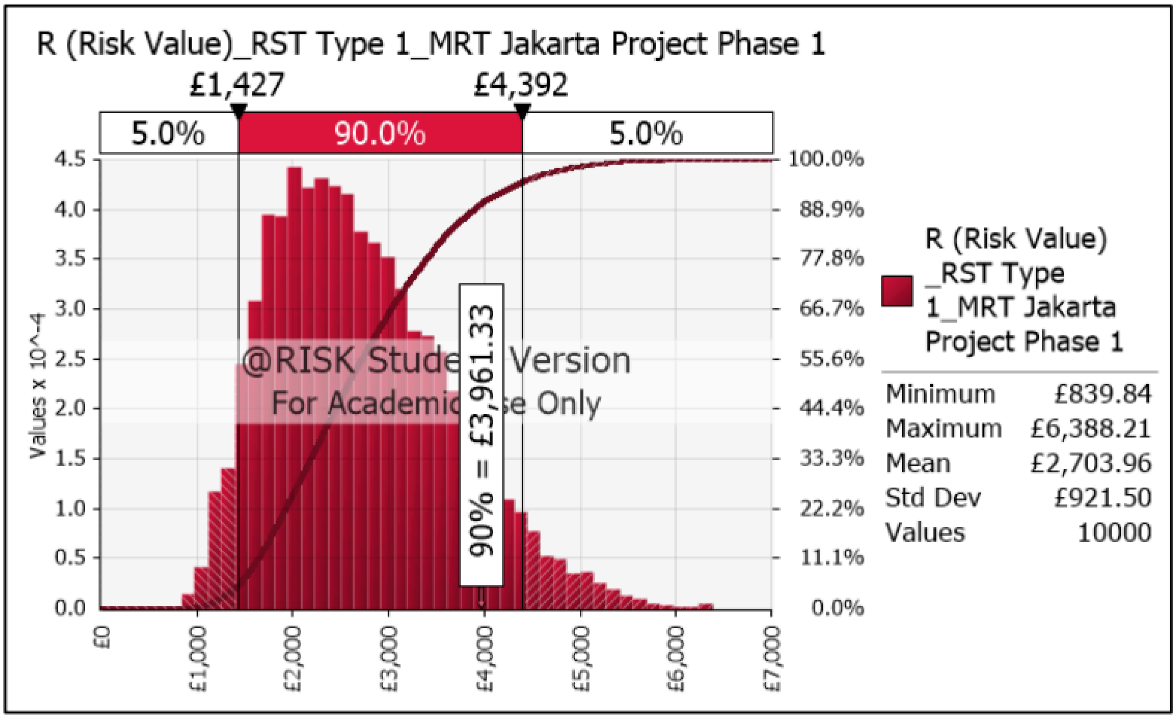

Figure 6. The Risk Value (R) associated with defective or failed type 1 railway slab track (RST) implemented in phase 1 of the MRT Jakarta project

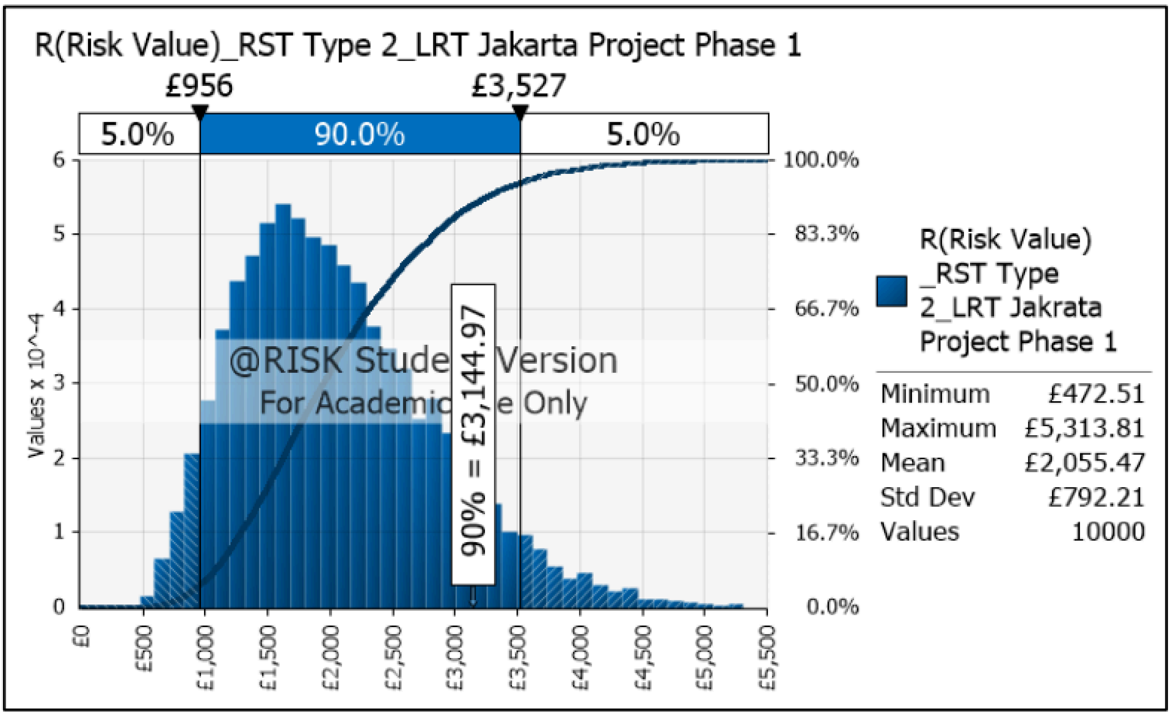

Figure 7. The Risk Value (R) associated with defective or failed type 1 railway slab track (RST) implemented in phase 1 of the LRT Jakarta project

The Beijing-Shanghai High-Speed Railway (HSR) case study uses life cycle assessment (LCA) and life cycle cost (LCC) methods to evaluate the energy consumption, carbon emissions, and overall costs from conception through disposal. The majority of carbon emissions (64.86%) and energy consumption (54.31%) occur during the construction phase, primarily due to the use of cement [17]. The operation and maintenance phase follows, highlighting the ongoing costs and environmental impacts during the railway's functional life. This study provides a detailed breakdown of costs, with the construction stage being the most expensive. It offers suggestions for reducing environmental impacts, such as adopting cleaner energy sources and improving material efficiency. This case study illustrates the critical need for comprehensive planning and evaluation of environmental impacts in large-scale infrastructure projects [22].

Table 1. Carbon emissions and energy usage of the track, earthwork, and the complete rail system across four stages

Stages	Track		Earthwork		*Entire Rail System*	
	CO2	Energy	CO2	Energy	CO2	Energy
Conception	35.59	382.22	35.59	382.22	71.18	764.44
Construction	1547.5	15,908.26	8317.33	43,546.72	9964.83	59,454.98
Operation and Maintenance	1990.18	20,956.20	2864.48	17,713.92	4854.66	38,670.12
Disposal	20.75	369.04	451.29	10,214.50	472.04	10,583.54
Total	3694.02	37,615.72	11,668.68	71,857.36	15,362.70	109,473.08

5. Discussion

The three LCC models under consideration offer insights into the cost-effectiveness of different railway track support materials and systems. The Sydney Harbour Bridge study focuses on the replacement of timber transoms with steel-concrete composites, which, despite higher initial costs, offer long-term financial benefits due to reduced maintenance and longer service life. The Indonesian Urban Metro Railway Project evaluates slab track monoblock sleepers, which are more resilient to extreme weather and geohazards, potentially reducing unexpected maintenance costs. The Beijing-Shanghai High-Speed Railway analysis incorporates energy and carbon costs, revealing that the majority of the LCC is incurred during the construction phase, with significant environmental impacts.

Each model has practical implications for railway infrastructure management. The Sydney Harbour Bridge case demonstrates the potential for significant cost savings over time through the use of durable materials that align with the existing infrastructure. The Indonesian case underscores the importance of selecting systems that are adaptable to local environmental conditions, which can lead to more predictable LCC outcomes. The Beijing-Shanghai HSR case illustrates the need for upfront investment in sustainable construction practices to minimize long-term energy and carbon costs.

Environmental sustainability is becoming an integral part of LCC analysis for railway track systems. The Sydney Harbour Bridge study shows that material choices not only affect financial costs but also environmental outcomes, with composite materials offering a reduction in greenhouse gas emissions compared to traditional timber. The Indonesian project's focus on slab track systems reflects a growing awareness of the need for infrastructure resilience in the face of climate change and extreme weather events. The Beijing-Shanghai HSR case explicitly includes energy and carbon assessments, highlighting the environmental costs associated with construction and emphasizing the potential for cleaner energy sources and material efficiency.

These cases collectively suggest that LCC analysis must evolve to incorporate environmental considerations alongside financial ones. By doing so, railway managers can make more informed decisions that align with global sustainability goals and potentially benefit from regulatory incentives or avoid future environmental liabilities.

Budget constraints are a critical factor influencing LCC outcomes and decision-making in railway track management. The Sydney Harbour Bridge case illustrates how initial budget constraints might limit the adoption of more expensive but environmentally friendly materials, despite their lower long-term costs. The Indonesian project highlights the challenge of selecting a track system that balances cost, performance, and adaptability within budgetary limits. The

Beijing-Shanghai HSR case shows that while construction costs are high, long-term savings can be achieved through energy-efficient and low-carbon solutions.

These LCC models demonstrate that budget constraints can either drive or hinder innovation in railway track systems. Decision-makers must carefully weigh the short-term financial pressures against the long-term cost savings and environmental benefits. This often requires a shift in perspective from immediate cost minimization to a broader view of value creation over the lifecycle of the railway track system.

In conclusion, the comparative analysis of these LCC models reveals the complexity of optimizing railway track systems. It underscores the need for a holistic approach that considers financial, operational, and environmental factors. By integrating these considerations, railway infrastructure managers can make decisions that not only meet immediate budgetary requirements but also contribute to the long-term sustainability and efficiency of the railway network.

6. Conclusion

The comprehensive review of Life Cycle Cost (LCC) analysis within railway track management, as explored through literature reviews and detailed case studies, underscores its critical role in the strategic planning and sustainable management of railway infrastructure. This research has highlighted several key findings:

Material Innovations and Cost Efficiency: Innovations such as the use of steel-concrete composites, as demonstrated in the Sydney Harbour Bridge case study, offer not only cost savings but also environmental benefits over traditional materials.

Adaptability to Environmental Conditions: The importance of selecting infrastructure that withstands local environmental conditions, as seen in the Indonesian Urban Metro Railway Project, is crucial for reducing maintenance costs and enhancing system resilience.

Environmental Impact and Sustainability: The analysis of the Beijing-Shanghai High-Speed Railway has shown that incorporating environmental costs into LCC can highlight significant impacts and opportunities for sustainable practices during the construction phase.

Based on these insights, this paper recommends the development of integrated LCC models that encompass financial, environmental, and technical parameters, the undertaking of longitudinal studies on material performance, enhancement of predictive maintenance technologies, and further research into the effects of policy on LCC outcomes.

LCC analysis is indispensable not only for ensuring cost-effectiveness and operational efficiency but also for enhancing the safety and reliability of railway systems. It supports strategic decision-making that balances short-term expenditures with long-term benefits, promoting the sustainable growth of railway networks. As the global demand for sustainable and efficient transportation solutions continues to grow, the role of LCC analysis becomes increasingly vital. Future advancements in LCC methodologies should aim to incorporate broader sustainability metrics, refining the approach to meet the evolving needs of the transportation sector and contributing to the overarching goals of global sustainability.

Acknowledgments

The authors gratefully acknowledge the financial and other support received from the Indonesia Railway Company (PT. Kereta Api Indonesia).

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How to cite this article:

Indrakusuma R, Budiwantoro B, Wicaksono S. Optimizing Railway Track Management through Life Cycle Cost Analysis: A Comprehensive Review. *Jurnal Teknologi dan Manajemen*. 2024 July; 5(2):127-139. DOI: 10.31284/j.jtm.2024.v5i2.5935