Decision Support to Improve Railway Track Maintenance in Indonesia: A Life Cycle Cost Approach

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Abstrak

Infrastruktur kereta api adalah aset yang kompleks dan harus memiliki masa pakai yang panjang. Oleh karena itu, metode pemeliharaan yang efektif diperlukan untuk mencapai hasil optimal sepanjang siklus hidup. Life Cycle Cost (LCC) adalah metode evaluasi total biaya yang terkait dengan masa pakai sistem dan juga dapat digunakan untuk menentukan metode yang paling hemat biaya dalam jangka panjang. Penelitian ini dimulai dengan membahas kegagalan komponen jalur utama seperti rel, bantalan, dan balast. Dengan studi literatur, model degradasi komponen jalur kritis dapat dikembangkan untuk mengidentifikasi penyebab kegagalan. Analisis pemilihan material digunakan untuk memastikan pemilihan yang optimal dalam hal biaya dan kinerja. Jenis pemeliharaan yang tepat ditentukan untuk memastikan operasi yang benar dan aman dari sistem jalur kereta api. Tujuan utama dari makalah ini adalah untuk menentukan metode yang efektif dan efisien untuk pemeliharaan jalur kereta api di Indonesia. Dalam studi ini, model degradasi perkiraan komponen jalur digunakan sebagai dasar untuk menentukan pemilihan material komponen. Jenis pemeliharaan kereta api yang ada dibahas dan melibatkan penentuan jenis pemeliharaan berdasarkan analisis LCC untuk mencapai metode yang paling hemat biaya.

Kata kunci: Infrastruktur, Biaya Siklus Hidup, Kereta Api, RAMS

Abstract

Railway infrastructure is a complex asset and must have a long service life. Therefore, effective maintenance methods are required to achieve optimal results throughout the life cycle. Life Cycle Cost (LCC) is a method of evaluating the total cost associated with the service life of a system and can also be used to determine the most cost-effective method in the long term. This research begins by discussing the failure of major track components such as rails, sleepers and ballast. With the literature study, critical track component degradation models can be developed to identify the causes of failures. Material selection analyses are used to ensure optimal selection in terms of cost and performance. The appropriate type of maintenance is determined to ensure proper and safe operation of the railway track system. The main purpose of this paper is to determine the effective and efficient methods for maintaining railway tracks in Indonesia. In this study, the estimated degradation models of track components are used as the basis for determining component material selection. Existing types of railway maintenance are discussed and involve determining the type of maintenance based on LCC analysis to achieve the most cost-effective method.

Keywords: Infrastructure, Life Cycle Cost, Maintenance, Railway

1. Introduction

Railway infrastructure is a complex asset that should have a long life, and therefore, an effective maintenance method is required to provide optimal results during its life cycle. In Indonesia, railway infrastructure assets are divided into several systems, such as buildings, signaling, and tracks. Among these systems, the track is an essential part of the railway infrastructure, and proper maintenance planning is needed to maintain the reliability and safety of train travel.

Railway track maintenance requires large resources and budget. Track maintenance has a broad scope, which makes this asset tend to be difficult to maintain, affected by internal factors such as complexity, as well as external factors such as weather variations and the surrounding environment. For instance, in Europe, the allocation of annual costs needed to carry out maintenance of railway tracks is around 15-25 billion EUR or around 70,000 EUR per km per year [1]. Meanwhile, PT. Kereta Api Indonesia (Persero) only allocates costs for track maintenance of around 1,500 billion Rupiahs per year or around 500 million Rupiahs per km per year, which is only 30% of the maintenance cost allocations compared to Europe [2]. This underlies the emergence of questions related to the maintenance of railway tracks in Indonesia, one of which is the problem of track reliability and safety.

The advent of the railway revolutionized transportation, making it possible to move goods and passengers over long distances efficiently. Over the centuries, railways have evolved in response to changing technological capabilities and societal needs [5]. The first rail systems, utilizing horse-drawn wagons on wooden or metal tracks, have transformed into today's high-speed rail networks operating on complex track systems with advanced signaling and control technologies. The constant need for safer, more reliable, and more efficient transport systems necessitates continuous improvements and developments in railway infrastructure [6].

In today's world, railway infrastructure forms the backbone of many countries' transportation systems. It includes tracks, bridges, tunnels, signaling systems, and stations, each of which plays a critical role in ensuring smooth, efficient operations [7]. However, maintaining this vast and complex infrastructure presents significant challenges. Aging infrastructure, increasing passenger and freight demands, and the pressure to maintain safety and efficiency all contribute to the complexities of modern railway infrastructure management.

Track maintenance in the area of PT. Kereta Api Indonesia (Persero) now uses a track maintenance approach based on the company's past knowledge and experience rather than a reliability and risk-based approach. To determine the reliability or risk-based maintenance methods known to be cost-effective and efficient, the so-called Reliability, Availability, Maintainability and Safety (RAMS) or Life Cycle Cost (LCC) approach, which is economically viable, must be implemented to optimize asset performance [3].

LCC is a method to assess the total cost associated with the lifetime of the system. In addition, LCC can also be used as a basis for decision-making on the most cost-effective method in the long term, starting from the investment, operation and maintenance stages, and disturbances that occur during the asset life cycle [4]. Therefore, one of the ways to optimize maintenance costs can be carried out by calculating the estimated degradation of a system or asset.

In this review paper, LCC approaches that have been carried out previously are discussed to determine the effective and efficient methods for maintaining railway tracks in Indonesia. The literature study will begin by studying the system degradation estimation, which will be linked to the material selection in the LCC design phase. Next, the types of maintenance that can be applied to railway track infrastructure assets will be discussed in more detail to support the decision-making for maintenance activities based on the LCC approach that has been carried out. In the end, this study is expected to provide recommendations and shed light on how to obtain effective and efficient maintenance methods based on reliability and safety, which can be further applied in PT. Kereta Api Indonesia (Persero).

2. Methods

This research was conducted by exploring existing journals as references. It begins with a discussion on the failure or degradation of mainline components such as rails, sleepers, and ballast, which are crucial in the development of railroad systems. A mainline component degradation model can be developed to determine the causes of failure or degradation affecting track component performance. Furthermore, based on many previously developed LCC analyses, material selection for the railroad system is performed to ensure optimal selection in terms of cost and performance. Once the materials are selected, the appropriate type of maintenance must be determined to keep the railroad system operating properly and safely. Maintenance of the railroad system is essential to ensure that the components can last for a long time. The results of the literature study obtained are then used as a reference to determine the type of maintenance that is suitable for railroad systems in Indonesia, thereby producing a safe, reliable, and efficient railway system.

3. Result And Discussion

The comprehensive analysis presented in the provided sources delves into various aspects of railway track maintenance in Indonesia, focusing on the application of Life Cycle Cost (LCC) approaches and comparing them with other maintenance strategies. This section synthesizes the key findings and discussions from the sources, highlighting the effectiveness of LCC in optimizing railway track maintenance.

3.1. Degradation and Components Selection

Degradation of track components must be well controlled to avoid failure or derailment. If component degradation is not handled with an effective maintenance strategy, the impact is not only delayed time and financial losses but also on passenger safety. The way to control track component's condition is by routine inspections. By carrying out routine inspections, the condition of the components will be recorded properly and then a maintenance or repair strategy can be planned.

3.1.1. Rail component

Rail is a track component that has direct contact with the rail vehicle wheels. In its lifetime, rail components often have failures that are generally caused by fatigue, failure in weld joints and other failures that originate from surface damage such as wear. Although the failure level of rail components is lower than other components, rail failure will greatly affect other component's failure, especially whose structures are underneath this component. Analysis of the various factors that cause rail failure is important to be able to determine the impact caused by mismanagement of failure which will be related to the LCC of the rail component.

Many studies have developed various models to evaluate the economic life of the rail. Rail degradation modeling is a key element in the development of rail maintenance and renewal strategies. The results of model development with stochastic analysis, and mechanistic models until Artificial intelligence (AI) models such as machine learning have been proven to contribute to determining the type and timing of appropriate maintenance on the economic life of the rail [8], [9]. Each model has advantages and disadvantages, for instance, mechanistic models can show the relationship between forces and track components clearly but it cannot be used for decision-making because these models do not employ the uncertainty factors in the process. Statistical models can be used to model degradation based on descriptive factors. Deterministic models, especially linear regression, have lower capability and accuracy in modeling highly complex degradation. While AI and machine learning models can provide higher accuracy than other models. However, to predict rail degradation, it is not enough to use a single model, because the track system is complex and many factors can affect component degradation, so modeling rail degradation requires a comparison of various types of models depending on the application.

Another failure mode in rail components that often occurs is a failure in welded joints. According to the data in Figure 1., Welded joint failures accounted for 930 instances of all failures that occurred in 2022 [2]. This is a very high percentage compared to other types of faults such as geometry failure and rail buckling.

Sudden failures in welded joints can be caused by errors in welding methods such as early removal of molds and improper surface finishing that produce unwanted stress concentrations in the weld area [10], [11]. This error should get more attention so that companies can develop new welding procedures and surface finishing techniques to improve the fatigue resistance in weld joints. Detection of defects in welded joints before they become critical, can be done by routine inspection or by performing non-destructive testing (NDT) techniques. Image processing-based inspection can be used for early detection of rail defects and can help prevent rail failures that can result in operating delays, maintenance costs and safety risks [12], [13]. Therefore recommended to conduct inspections with advanced non-destructive testing techniques to detect and monitor the development of rail defects, especially NDT with ultrasonic technology has significantly advanced in rail defect detection [14].

3.1.2. Sleeper component

Sleepers have the main function of distributing the lateral and longitudinal loads of the train to the underlying layers. Sleepers also serve to maintain a consistent width between the two rails or become a fixation point on the railway track [15]. Sleeper materials have undergone many developments, until now there are several alternative materials ranging from wood, iron, and concrete to fiber composites, each of which has its characteristics.

Failure of sleeper components can be influenced by external and internal factors. External factors include axle load, facility condition, ballast condition and subgrade condition [16]. This study analyzed the causes of sleeper component failure and concluded some factors such the axle loads exceeding design, facility conditions especially wheel damage, ballast conditions that do not meet specifications such as grain size and subgrade conditions with non-uniform bearing capacity can cause deeper failure. Meanwhile, internal factors that affect the damage of sleeper components come from the natural form of the material [17]. In wooden sleepers, fungal decay, cleavage at the sleeper ends, and termites were identified as the main causes of failure. In concrete sleepers, damage on the rail seat affected by axle loads and cracks was identified as a potential failure-causing issue. In steel sleepers, corrosion, cracks and warping were potential causes of failure. Therefore, it is necessary to develop new materials as effective alternatives to replace sleepers with traditional materials such as wood, steel and concrete.

Based on sleepers materials research in 2020 by Senaratne et al [18], the characteristics of different materials are shown in Table 1.

Figure SEQ Gambar * ARABIC 1. Cause of track failure data ADDIN CSL_CITATION {"citationItems":[{"id":"ITEM-1","itemData":{"author":[{"dropping-particle":"","family":"PT. Kereta Api Indonesia (Persero)","given":"","non-dropping-particle":"","parse-names":false,"suffix":""}],"id":"ITEM-1","issued":{"date-parts":[["2021"]]},"title":"Annual and Sustainability Report","type":"report"},"uris":["http://www.mendeley.com/documents/?uuid=469c026d-da87-4a6c-ba7f-3e135993260a"]}],"mendeley":{"formattedCitation":"[2]","plainTextFormattedCitation":"[2]","previouslyFormattedCitation":"[2]"},"properties":{"noteIndex":0},"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"}[2]

Table 1. Comparison of the sleeper material characteristics [18], [19]

Criteria	Timber Sleepers		Concrete Sleepers		Composite Fibre Sleepers	
	Advan-tages	Disadvan-tages	Advan-tages	Disadvan-tages	Advan-tages	Disadvan-tages
Properties	Good mechanical behaviour Light-weight	Prone to cracking/ splitting Experience fungal decay Termite attack	Monolithic structural action	Experience cracking Experience breakage due to high dynamic loading	Good mechanical behaviour for trains (similar to timber) Lightweight and corrosion resistance	Degrades strength when exposed to direct sunlight Protective paint required to limit solar exposure
Durability	Durable in optimum location	Often incapable of meeting design life (20 years)	Durable (capable of meeting 50-year design life)	-	Durable (expected 100-year design life)	-
Cost	Cheap in capital cost	High maintenance cost	Precast manufactu-ring for efficient transporta-tion	High capital cost to purchase	Precast manufactu-ring for efficient transporta-tion	High capital cost to purchased
Sustainability aspects (emissions, resources & usability)	Re-usable for other applications (landscaping, building, etc.)	Declining volume of hardwood available to meet the rate of renewal	Constructed from recyclable materials	High carbon emissions during manufacturing	Readily available resources	Limited use due to emerging nature

Composite materials have the best life cycle cost due to a more efficient installation process that is 14% faster than concrete and wood materials [18], [19]. Besides the efficient installation costs, composite materials have a higher design life of 100 years and less maintenance is needed. Although these materials require a higher initial cost, application of these materials is considered more advantageous than other materials that are cheaper but need more maintenance and certainly require high labor to maintain. While wood material requires low acquisition and end-life costs, it requires high maintenance and periodic replacement making it the most expensive alternative material in the LCC analysis. This makes composite materials the recommended and most effective option in the long term with the LCC analysis approach [20].

3.1.3. Ballast component

Ballast is a component of the railway track to keeps the sleepers in position and provides lateral support and stiffness to the track. Continuous loading from trains, external contamination, accumulation of ballast damage and degradation of ballast particles will cause degradation in ballast resistance. Degradation of ballast aggregate occurs due to the breakage of single particles as well as angular abrasion of the ballast [21]. When the ballast is contaminated with sand, the behavior will be very different. Ballast contaminated with sand can reduce stiffness, increase settlement, and decrease the angle of material grains [22]. The highest contribution of

contamination is provided by particle damage and wear affected by traffic and maintenance loads. When the contamination level reaches a critical limit, the ballast layer needs to be replaced with new ballast. Treatment by tamping can cause ballast damage, thereby significantly reducing the strength of the ballast. Based on laboratory test results, ballast damage caused by tamping operations mostly occurs during the tamping insertion stage. The tamping vibration can obtain 4 kg of fine particles/ sleeper/ tamping [23].

Ballasted track is generally used around the world because of its low construction cost and ease of maintenance and repair. However, the degradation of ballast components due to increasing traffic loads is a common problem that requires a lot of maintenance activities and high costs. Moreover, the indicators number and type of ballast quality selection criteria and testing methods around the world vary considerably to the material type and local geology [24]. This encourages further studies on the causes of ballast degradation according to the type of material and geological conditions of each country due to tamping and dynamic loads of passing trains. In addition, it is necessary to discuss the development of technology in ballast for the future, such as the use of recycled ballast, the utilization of asphalt materials for ballast reinforcement and improved ballast adhesion.

Several studies have been conducted to select ballast construction designs based on RAMS analysis and LCC to evaluate the impact on the environment. The analysis was conducted by measuring the overall parameters and indicators of RAMS and evaluating the total cost to assess the environmental impact. The result is that slab track is the best solution based on RAMS, LCC and LCA analysis for the long term with a design life of 100 years [25], [26]. The study stated that the most influential factor in the design of ballasted track and slab track is in the Maintenance and Renewal (M&R) phase. However, if the design life is only 50-60 years, it is stated that the ballasted track has lower performance and environmental impact than the slab track.

3.2. Maintenance on Railway Track

Maintenance is a series of activities, technical, administrative, and managerial carried out during the life cycle of a component, sub-system or system including its facilities and infrastructure, to maintain or restore the value of an asset. The value in question includes reliability, availability, productivity, and market value. Maintenance activities consist of several stages including planning, coordination, financing, and operations. Maintenance is a multidisciplinary activity involving spare parts and human-machine tool information. The main purpose of maintenance is to ensure asset reliability and availability. The importance of maintenance has been proven in various fields such as construction, transportation, aviation, power, and manufacturing industries. There are various maintenance strategies developed such as preventive maintenance, corrective maintenance, condition-based maintenance and so on. Each strategy plays an important role in reducing the occurrence of failures and functional degradation that cause unplanned unavailability resulting in high operating and recovery costs.

3.2.1. Corrective Maintenance

Corrective maintenance (CM) is an action to restore a failed system to its normal function through the repair or replacement of failed components. CM is usually carried out after damage or failure of the system or component is recognized. This CM activity can consume a lot of resources and takes a long time so CM is often applied to low-cost and non-critical components to minimize maintenance costs and resources [27].

Railway transportation requires a high level of operation and punctuality to provide quality services for its users so it is important to maintain and inspect the railway infrastructure regularly. An integer programming model in scheduling corrective maintenance activities can effectively reduce train travel delays caused by maintenance activities [28]. In addition, the ability of technicians to respond to failure signals and perform railway track repairs also determines the downtime in rail operations [29]. Therefore, factors that directly affect the downtime of the railway

track such as the level of damage, the number of maintenance teams and the performance of the maintenance team must be seriously considered to avoid delays in train travel.

Another important thing in implementing a CM strategy is the availability of high-quality data. With the availability of high-quality data, the prediction and visualization of failure forms can be processed into an alarm so that CM activities can be planned effectively and efficiently. Using a Building Information Model (BIM) approach linked to a Computerized Maintenance Management System (CMMS) can improve the quality of data for corrective maintenance actions [30]. In addition, quality data can be used to create a complete CM scheme to determine not only the probability but also the failure detection and severity to determine the failure sequence, such as Failure Mode Effect Critical Analysis (FMECA), Failure Propagation Model (FPM), and Risk Evaluation Number (REN) [31]. However, it should be considered that the failure of one component can lead to the failure of other components. Therefore, detailed analysis is required to avoid false positives of errors that have occurred.

3.2.2. Preventive Maintenance

Preventive maintenance (PM) is performed according to a specified time, use, or condition criteria and is intended to reduce the likelihood of failure or deterioration of an item [32]. PM is carried out when a system is not operating. These PM activities aim to increase the service life and/or reliability of a system. PM activities usually include relatively small service activities that require short downtime, such as visual inspection, lubrication, replacing planned parts or components, and so on. However, PM activities can also be major inspections that require significant operational downtime, proper planning and adequate resources.

In the railway sector, especially railway track infrastructure, preventive maintenance is very important to ensure the reliability, availability and safety of rail transportation. Another goal for the company is to minimize overall maintenance costs while ensuring good service in terms of timeliness, safety, and efficient train operation. For this reason, a method or model related to preventive maintenance scheduling is needed as a strategy for achieving the objectives mentioned. Various algorithm models such as Variable Neighborhood Search (VNS) and Ant Colony Optimisation (ACO) have been developed and proven effective in minimizing the overall cost of maintenance [33]. These algorithms are used in scheduling preventive maintenance on railway infrastructure to keep the railway infrastructure in good operating condition at a low cost. Even with these algorithms, scheduling can be planned optimally considering the limited human resources (crew) available [34]. However, other constraint factors such as weather conditions and train travel frequency have not been accommodated in this scheduling modeling so further studies are needed to further improve the effectiveness of the maintenance program.

From a technical perspective on railway tracks, preventive maintenance must be linked to other factors such as track degradation over time, track layout, and track quality limits. This must be considered to guarantee the safety, security and comfort of passengers. One form of preventive maintenance is the operation of tamping on a ballasted track. Tamping is the most common method used to improve track geometry conditions that affect the safety and comfort of train travel. Preventive maintenance by optimizing tamping activities on ballasted tracks can reduce maintenance costs [35], [36]. Moreover, when combined with a ballast cleaning and renewal strategy based on the ballast deterioration index, it will help optimize track maintenance costs [37]. In addition, opportunistic preventive maintenance scheduling by scheduling tamping based on track degradation levels can reduce overall maintenance costs while ensuring track safety and reliability [38]. The most important thing in this opportunistic preventive maintenance is the ability to identify the level of track degradation so that scheduling can be done accurately.

3.2.3. Condition-Based Maintenance

Condition-based maintenance (CBM) is performed after checking the operational status of equipment to prevent failure. In this maintenance, the most important factor is the ability to identify parameters in the system that correlate between measured values and degradation. This maintenance involves a combination of understanding the failure mechanism, availability of appropriate measurement technology, and adequate analysis tools. An illustration of the CBM concept is shown in Figure 2.

Degradation is monitored periodically at times t1, t2, and so on. The check at time ta is the first time after crossing the threshold and tp is the possible time to take CBM measures and tf is the failure time if CBM measures have not been taken by then. After tf, it is necessary to perform CM which usually costs much more than prevention by taking appropriate action [27].

The condition of railway tracks is always affected by axle loads and traffic, so it is very important to manage its performance to ensure the desired level of quality. This underlies the importance of monitoring and maintenance with CBM. To obtain an efficient CBM maintenance schedule, Model Predictive Control (MPC) and Time Instant Optimization (TIO) approaches can be used [39], [40]. These approaches can balance maintenance costs and track performance and can help railway track operators make the right maintenance decisions to improve reliability and safety.

For continuous monitoring of rail tracks, accelerometer technology can be used to measure vibration and provide track condition estimation [41]. In addition, video image processing technology can be used to provide information on the actual condition of rails that can reduce surface defect detection errors to support maintenance decisions [42]. The utilization of the developed technology has the potential to increase the effectiveness of track maintenance and reduce downtime due to track failure as well as efficiently perform condition-based maintenance decision-making. Meanwhile, to maximize monitoring with consideration of technical factors such as track deterioration and track quality thresholds, the Mixed Integer Linear Programming (MILP) model can be used to determine when to perform tamping [43]. Furthermore, the researched model and technology utilization should be integrated with other maintenance to develop a comprehensive maintenance plan for railway tracks.

3.3. Railway Track Life Cycle Cost (LCC)

LCC is defined as the economic assessment of an item, system, or facility by considering all significant costs over its economic life [44]. Figure 3. shows the life cycle of an asset starting

Figure 3. Total asset life-cycle ADDIN CSL_CITATION {"citationItems":[{"id":"ITEM-1","itemData":{"ISBN":"9780849303241","author":[{"dropping-particle":"","family":"McGlynn","given":"Joel","non-dropping-particle":"","parse-names":false,"suffix":""},{"dropping-particle":"","family":"Campbell","given":"John D.","non-dropping-particle":"","parse-names":false,"suffix":""},{"dropping-particle":"","family":"Jardine","given":"Andrew

Figure 2. Condition-Based Maintenance Concept ss-names":false,"suffix":""}],"CSL_CITATION {"citationItems":[{"id":"ITEM-1","itemData":{"ISBN 9781118487198","author":[{"dropping-particle":"","family":"Kurma","given":"U.","non-droppin g-particle":"","parse-names":false,"suffix":""},{"dr opping-particle":"","family":"Rumar","given":"U.","non-dropping-particle":"","parse-names":false,"s uffix":""},{"dropping-particle":"","family":"Murthy","given":"D.N.P.","non-dropping-particle":"","parse -names":false,"suffix":""}],"id":"ITEM-1","issued":{"date-parts":[[2016]]}},"publisher":"John Wiley & Sons, Ltd.","title":"Complex system maintenance engineering: modelling, optimization and management","type":"book"},"uris":["http://www.mendeley.com/documents/?uuid=ef9f98e0-1603-4822-8e3c-0750ab1a4a7a"]}],"mendeley":{"formatte dCitation":"[27]","plainTextFormattedCitation":"[27]","previouslyFormattedCitation":"[27]"},"propert ies":{"noteIndex":0},"schema":"https://github.com /citation-style-language/schema/raw/master/csl-cit ation.json"}[27]

from identifying customer needs which are then developed in the design/planning phase, procurement and construction or acquisition process, asset operation, maintenance and

development, and finally decommissioning or disposal phase. LCC analysis can be used as a basis for evaluating the economic and technical performance of assets, such as machinery, equipment and production systems. It is often being projected as an economic tool, in addition, LCC can also be the basis for improving system effectiveness and making it beneficial for selecting equipment and production systems. LCC analysis can also be used to select alternative production schemes, determine modifications to existing systems, make investments in new technologies and select machinery or equipment from different suppliers [45].

In Life Cycle Cost (LCC), the costs of each phase can affect each other. A change in costs in one phase can have an impact on the costs of other phases. For example, low initial costs and efficient design can reduce subsequent production and operating costs. Similarly, high operation and maintenance costs can be an indicator of problems in the design or production phase. Figure 4. shows typical characteristic curves of costs incurred during the product life cycle.

As seen in Figure 4. initial costs can influence subsequent production and operating costs. This is because good quality initial design and development can reduce the risk of failure and maintenance costs in the future. Production costs can be influenced by initial costs such as efficient design or the use of appropriate technology. In addition, good management in the production phase can affect future operation and maintenance costs. Furthermore, operation and maintenance costs can be influenced by design quality, the use of quality raw materials, and the reliability and efficiency of the product or asset being operated. Finally, disposal costs can be influenced by initial design decisions, material selection, and maintenance policies implemented during the operational life.

Several steps can be taken in calculating costs in Life Cycle Cost (LCC) analysis. The first step in calculating costs in LCC is to identify the cost components associated with the product life cycle. Cost components generally include initial cost, production cost, operation and maintenance cost, and dismantling or disposal cost [46]. In general, LCC can be formulated as the Equation (1).

$$CC = cost_{Initial} + cost_{production} + cost_{O\&M} + cost_{disposal} \tag{1}$$

Figure 4. Cost typical characteristic curves incurred the life cycle of an asset ADDIN CSL_CITATION

{"citationItems":[{"id":"ITEM-1","itemData":{"author":[{"dropping-particle":"","family":"Alavizadeh","given":"Ali","non-dropping-particle":"","parse-names":false,"suffix":""}],"container-title":"INTERNATIONAL JOURNAL OF MODERN ENGINEERING","id":"ITEM-1","issued":{"date-parts":[["2010"]]},"page":"76-83","title":"USAGE OF AXIOMATIC DESIGN METHODOLOGY IN THE U.S. INDUSTRIES","type":"article-journal","volume":"10"},"uris":["http://www.mendeley.com/documents/?uuid=68081942-a8e0-44f3-9ecd-c8608e4d0b6f"]}],"mendeley":{"formattedCitation":"[67]","plainTextFormattedCitation":"[67]","previouslyFormattedCitation":"[67]"},"properties":{"noteIndex":0},"schema":"https://github.com/citation-style-language/schema/raw/master/csl-citation.json"}[67]

The next step is to determine the appropriate calculation method to estimate the costs in each life cycle phase. Commonly used methods in LCC include cost-benefit analysis, cost-effectiveness analysis, and Monte Carlo simulation to include uncertainty in future costs [47]. After the calculation method is determined, the next step is to perform cost calculations based on the data that has been collected. Cost calculations are performed for each cost component and include initial cost estimates, operation and maintenance costs, and dismantling or retirement costs.

The last step is to analyze and interpret the results of the cost calculation in LCC. The results of the calculation can be used to identify the most significant costs in the product life cycle, as well as to help make better planning, management, and investment decisions.

LCC on railway tracks includes several key factors to consider such as cost analysis over the life cycle of the railway track which includes construction, operational, and maintenance costs. In addition, it is important to take into account the costs not only during the construction phase but also the costs that arise during the operation and maintenance of the railway track. Many factors affect railway track costs such as the quality of track assets (expected service life and chance of failure) and the maintenance strategies implemented such as maintenance methods, availability of spare parts stock and number of teams [48]. The basic principle of LCC on railways, therefore, involves selecting materials and technologies that can optimize costs over the life cycle. This can be done by considering the lifetime of the materials, energy efficiency, reliability and maintenance costs of the selected materials and technologies. Proper selection of materials and technologies can help reduce long-term operational and maintenance costs.

3.3.1. Planning Phase

At this phase, the initial planning for the construction of the railway track is carried out following the company's business needs. This includes route selection, feasibility study, and initial track design e.g. geometry aspects such as track width and minimum distance between tracks. The selection of a reliable and durable railway track structure is also an important part of the railway track LCC design phase. The initial estimate of construction costs including railway track materials is made in this phase.

The needs and requirements of the railway track project are clearly defined in this phase. Next comes the preliminary design, which involves creating the initial design of the railroad based on the previously identified needs. Then an economic evaluation is conducted, which is an economic analysis to evaluate the total cost of ownership of the railway track throughout its life cycle [49]. This analysis includes construction, operation, maintenance and decommissioning costs. If the results of the economic evaluation indicate the need to make changes to the initial design, then the design revision stage is carried out to make improvements to the railway track design. After the design is revised, the finalization stage is carried out to produce a complete railway design that is ready to be implemented.

3.3.2. Construction *Phase*

This phase involves the physical construction of the railway track. Activities in this phase involve a series of stages such as construction planning, design, execution, and testing of the railway track. Each stage has an important role in determining costs throughout the railway track's lifecycle and ensuring the quality and sustainability of the infrastructure. The costs incurred at this phase are called construction costs.

The construction planning stage involves determining the railroad trajectory, site selection, and environmental, social, and technical studies. At this stage, the railroad right-of-way is mapped, boundaries are drawn, and space for operations is determined. Planning also includes environmental impact analysis, licensing, and budget preparation. Next comes the design phase which involves technical details such as the selection of construction materials, rail structures, rails, and railway facilities [50]. In this phase, detailed technical specifications and construction plans are determined to ensure compliance with railroad safety, reliability and performance standards [51]. The construction execution phase involves the process of constructing the railway by the established planning and design, such as rail laying works, bridge and tunnel construction, rail pavement, earthmoving, and installation of signals and communication equipment. During this stage, strict supervision and oversight are required to ensure the quality and safety of railroad construction. Once construction execution is complete, the testing phase is conducted to verify the performance and safety of the railroad. Testing involves functionality testing, load tests, speed, and

signaling systems [52]. The aim is to ensure that the railway meets the set safety and quality standards before it is put into full operation.

3.3.3. Operation and Mai*ntenance Phase*

The operations and maintenance phase of the railway is the next phase after the railway has been constructed. The operational phase involves a series of activities that include daily operation of the railway track and routine maintenance to maintain the quality, reliability and safety of the track throughout its life cycle. Operating costs included in this phase such as operator fees or salaries, fuel costs, electricity costs and other operating costs associated with operating the railway track.

Maintenance must be carried out to keep the sustainability and performance of the railway track. Routine maintenance includes inspection, and repair of railway track components such as rails, sleepers, bridges, tunnels, and ballast [53]. The aim is to ensure operational safety, travel quality, and reliability of railway tracks. In addition to routine maintenance, emergency maintenance is also required in the event of damage or incidents that affect railroad performance. Emergency maintenance is carried out to repair the damage quickly and restore railway operations as soon as possible [54]. Maintenance is also carried out on railway system support facilities such as train stations, operating facilities, and other supporting systems. This maintenance is important to ensure the supporting facilities function properly and meet safety and comfort standards. With the amount of maintenance that must be done, this phase also includes railway track maintenance costs.

3.3.4. Decommissioning *Phase*

The decommissioning phase is related to the determination of life cycle costs at the stage of decommissioning a facility or equipment. This phase occurs when a facility or equipment reaches the end of its operational life and must be decommissioned [55], [56]. At this stage, it is necessary to discontinue operations and prepare for land acquisition, demolition, or removal of the facility.

The decommissioning phase of a railroad occurs when a railway track is no longer in operation, the railway track reaches a predetermined age or the track is no longer efficient or relevant. This phase is carried out with the termination of operations and dismantling of the railway track. The decommissioning phase begins with the termination of train services on the line. Then, evaluates the railway line to be decommissioned and plans the steps to be taken during this process. One important step in decommissioning is track dismantling. Rails and other components that are no longer in use are lifted and removed from the track. In addition, structures associated with the railroad such as stations, platforms, and other facilities will also be dismantled. After the components and structures of the track are dismantled, the next step is land restoration. This involves environmental cleanup and restoration, or appropriate reuse of the land [57]. The costs associated with replacing the railway track are included in this phase.

3.3.5. LCC Analysis to Support Maintenance

The railway track is an expensive asset with a long service life, so long-term design and maintenance costs must be planned very effectively. Infrastructure quality is measured by various parameters, such as reliability, safety and cost-effectiveness. Infrastructure quality is also susceptible to infrastructure system failures so monitoring the condition of components in the system is essential [58]. Reducing the cost of track maintenance and renewal by assessing the three main track elements such as subgrade, switch and rail repairs and maximizing inspection techniques can improve life cycle costs [59], [60]. Increased track structure requirements in terms of axle load, tonnage, speed, etc. lead to more failures and require more maintenance. This leads to the need for more budget and resources. Therefore, optimization with a systematic analysis approach is required to produce maintenance activities that meet cost-effectiveness reliability and

availability aspects. Replacing components according to their condition and scheduling track renewal work results in effective cost reduction [61].

High operation and maintenance costs can sometimes be a barrier to achieving profitable financial performance for railway track operating companies. It is a challenge for infrastructure managers to optimize the available budget while maintaining reliability and availability without jeopardizing the safety of train travel. This requires an effective maintenance strategy with a data-driven approach to track maintenance and renewals and using advanced technology and data analysis to optimize the defined strategy [62]. Budget constraints can influence decision-making on the maintenance and replacement of railway tracks to minimize LCC and minimize track availability [63]. Based on the study, more investment in maintenance and material replacement can provide higher track availability.

LCC analysis is an engineering economics method that can be used in determining maintenance strategies to minimize life cycle costs. The total life cycle cost of railway infrastructure includes construction costs, maintenance and renewal costs, and end-of-life costs. Maintenance costs are particularly important for railroad infrastructure because they are a significant part of the rail system life cycle [64]. Decision-makers can use LCC analysis to optimize investments in planning and building new construction as well as optimizing maintenance and renewal of track components over the long term. LCC analysis can help decision-makers in the railway industry to make informed decisions on investment, maintenance, and operation [65]. Later the maintenance strategy with the lowest LCC can be selected as a cost-efficient solution and feasible to implement in railway infrastructure maintenance.

4. Conclusion

This research has comprehensively explored the application of Life Cycle Cost (LCC) analysis as a strategic approach to optimizing railway track maintenance. By integrating estimated degradation models, the study effectively guides the selection of materials and maintenance strategies that align with the economic and operational demands of railway infrastructure. The findings underscore the importance of considering long-term investment values rather than just initial costs in the selection of railway track components. This approach not only enhances the durability and functionality of the components but also ensures cost-efficiency over their lifecycle.

The study advocates for a tailored maintenance strategy where corrective maintenance is deemed suitable for less critical components with lower cost implications, while condition-based preventive maintenance is recommended for high-value assets to preempt failures and mitigate expensive restoration costs. Furthermore, the utilization of technology and historical maintenance data plays a crucial role in enabling proactive maintenance practices, significantly reducing the Life Cycle Cost.

A critical insight from this research is the importance of understanding the interdependencies between different cost phases in the LCC framework. By conducting a holistic LCC analysis that considers these interrelationships, stakeholders can make more informed decisions regarding asset management and investment, ultimately leading to more sustainable financial and operational outcomes.

In conclusion, the application of LCC analysis in this study presents a robust framework for enhancing the efficiency and effectiveness of railway track maintenance. This approach not only promises substantial economic benefits for Indonesian railways but also ensures the reliability and safety of railway operations, thereby delivering greater value to consumers, operators, regulators, and business stakeholders in the railway industry. This strategic focus on optimizing the total Life Cycle Cost through informed material selection and maintenance planning is poised to significantly influence future investment and development decisions in the railway sector.

Acknowledgments

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