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Railway Infrastructure Asset Management Optimization: Comparative Analysis of RAMS, LCC, and their Integration Approaches on Track Asset

Angga Tri Maulana[1*], Leonardo Gunawan[1],
Fakultas Teknik Mesin dan Dirgantara, Institut Teknologi Bandung, Jl. Ganesa No.10, Lb. Siliwangi, Kecamatan Coblong, Kota Bandung, Jawa Barat 40132, Indonesia[1]
*) corresponding author: Angga Tri Maulana / 23122037@mahasiswa.itb.ac.id

ABSTRAK

Manajemen aset infrastruktur perkeretaapian penting untuk mencapai keseimbangan antara biaya pemeliharaan dan operasi, meningkatkan efisiensi dan produktivitas sistem perkeretaapian, serta menghindari biaya yang tidak perlu selama siklus hidup aset. Dalam hal ini, pendekatan Reliability, Availability, Maintainability, dan Safety *(RAMS) dan* Life Cycle Cost *(LCC) digunakan secara optimal untuk mengelola aset infrastruktur perkeretaapian.* Review paper *ini melakukan perbandingan efektivitas antara pendekatan RAMS, LCC, dan integrasi keduanya di aset jalur kereta api, yang menunjukkan manfaat integrasi konsep RAMS dan LCC dalam perencanaan desain, operasi, dan pemeliharaan untuk pengambilan keputusan yang lebih baik. Metode analisis komparatif yang mendasarkan pada beberapa penelitian digunakan dengan mempertimbangkan faktor teknis, biaya, dan tujuan strategis jangka panjang untuk menentukan konsep terbaik antara RAMS, LCC, ataupun integrasi keduanya. Oleh karena itu, penting untuk mempertimbangkan aspek teknis dan ekonomi dalam mengoptimalkan kinerja aset dan meminimalkan biaya. RAMS memberikan kelebihan dalam meningkatkan kinerja sistem namun memiliki kekurangan karena tidak mempertimbangkan biaya keseluruhan sistem, sementara LCC memberikan kelebihan dalam evaluasi biaya keseluruhan sistem namun memiliki kekurangan dalam hal perhitungan kinerja sistem. Integrasi RAMS dan LCC membantu dalam pemilihan, perencanaan, evaluasi, dan pengelolaan aset dengan cara yang efektif dan efisien. Dengan mengintegrasikan kedua pendekatan tersebut, akan tercapai manajemen aset yang lebih baik baik dari segi teknis maupun biaya. Sebagai contoh, penelitian yang dilakukan* review *pada studi ini membandingkan jalur kereta api dengan atau tanpa balas dalam konteks desain dan pemeliharaan. Hasilnya menunjukkan solusi yang disesuaikan dengan kebutuhan jangka pendek dan jangka panjang. Di masa depan, studi optimasi aset pada seluruh sistem perkeretaapian dan digitalisasi data aset akan menjadi langkah penting untuk kemajuan selanjutnya.*
Kata Kunci: RAMS, LCC, aset jalur kereta api, Optimasi.

ABSTRACT

Railway infrastructure asset management is essential to balance maintenance and operation costs, improve the efficiency and productivity of the railway system, and avoid unnecessary costs during the asset life cycle. In this case, Reliability, Availability, Maintainability, and Safety (RAMS) and Life Cycle Cost (LCC) approaches are optimally used to manage railway infrastructure assets. This review paper compares the effectiveness of RAMS, LCC, and their integration in railway track asset. It demonstrates the benefits of integrating RAMS and LCC concepts in design, operation, and maintenance planning for better decision-making. A comparative analysis method based on several studies is used by considering technical factors, costs, and long-term strategic objectives to determine the best concept between RAMS, LCC, or their integration. Therefore, it is essential to consider technical and economic aspects to optimize asset performance and minimize costs. RAMS has the advantage of improving system performance but has the disadvantage of not considering the overall cost of the system. In contrast, LCC has the advantage of evaluating the overall cost of the system but has the disadvantage of calculating system performance. The integration of RAMS and LCC helps select, plan, evaluate, and manage assets effectively and efficiently. By integrating the two approaches, better asset management will be achieved from a technical and cost perspective. For example, the research reviewed in this study compared railways with or without ballast in the context of design and maintenance. The results showed solutions tailored to both short-term and long-term needs. In the future, asset optimization studies on the entire railway system and digitization of asset data will be essential steps for further progress.
Keywords: *RAMS, LCC, Railway Track Asset, Optimization.*

1 INTRODUCTION

Railway infrastructure assets include railway lines, railway stations, and railway operating facilities to be operated [1]. Optimal asset management will help improve the efficiency and productivity of the railway system as a whole and also help prevent unnecessary costs in the asset lifecycle. Railway infrastructure assets must have good reliability, availability, maintainability, and security to ensure the continuity of the railway transportation system in providing good services to transportation users, maximizing the benefits generated from railway infrastructure assets, and helping to drive the country's economy.

The challenge in managing railway infrastructure assets is an in-depth understanding of the complexity of railway infrastructure network components, interactions between components, and the impact on network performance. The railway system must also provide maximum performance for all stakeholders, and the management of these assets must be managed with strict financial planning where there is a balance between maintenance costs and operating costs as needed so that the performance and safety of the railway infrastructure system can be optimized. Railway transportation safety must be the highest priority, with all system safety procedures referring to applicable safety regulations [2]. Care and maintenance of the railway network infrastructure, which is a highly complex system, must be carried out continuously because the infrastructure consists of many different components in terms of material and technical life and has different failure modes. Maintenance time must also be considered not to disrupt railway operations. In addition, with the increase in rail traffic needs, additional infrastructure assets are needed to support railway operations that must be managed properly. New asset construction and maintenance activities should be organized when traffic loads are low so that the highest priority is to keep traffic flow in optimal conditions [3]. Asset management is necessary for quality control of railway operations as measured by time reliability.

Asset management that can be done includes the concepts of Reliability, Availability, Maintainability, Safety (RAMS), and Life Cycle Cost (LCC). RAMS is an asset management approach used to assess the performance of high-complexity systems such as railway infrastructure systems. The RAMS approach works by considering the system's reliability, the availability of components/systems to be used, the ease of maintenance of components/systems, and the safety of its users. Considering these four factors, RAMS can help identify and improve the performance of railway infrastructure components/systems [4]. In recent years, RAMS has become a rapidly growing method because it can meet the needs of rail traffic services in a timely, safe, and cost-effective manner. RAMS can improve the competitiveness of railways against other modes of transportation [5]. In addition, RAMS is an engineering combination of concepts, methods, and tools used to ensure the long-term operation of railway systems. The process starts from the design planning stage until the operation stage. RAMS requirements have been decided since design planning for all stages of the system, i.e., concept selection and development, construction execution planning, to operation and maintenance [6]. The implementation of RAMS can be adapted to existing standards and specific requirements. Such standards can be applied systematically to promote cooperation between railway stakeholders in achieving the optimal combination of RAMS and costs for railway applications [7], [8]. LCC is an analytical technique used to evaluate the overall cost of a system or asset over its entire life cycle. This analysis considers all costs associated with the system, including acquisition, operation, maintenance, and disposal costs. The objective of LCC is to perform cost optimization to obtain a certain output [9]. By considering all costs incurred during the life cycle, LCC provides a comprehensive analysis for the calculation of economic feasibility with several design choice methods at different planning and construction phases [10].

By definition, RAMS and LCC are two management approaches used to evaluate the performance and cost-effectiveness of railways [11]. RAMS ensures the rail system is reliable, available, easy to maintain, and safe for passengers and workers. On the other hand, LCC evaluates the total cost of a railway throughout its lifecycle, considering costs associated with construction, inspection, maintenance, renewal, and use, as well as environmental costs. The integration of RAMS and LCC can optimize the performance of railway infrastructure assets and create overall cost efficiency in the life cycle. This integration has attracted much attention in the railway sector, which is devoted to developing and deploying asset systems [12]. This integration is very flexible in life cycle phases, which can be done starting from the design phase and starting at the operation and maintenance phase [11]. Integrating RAMS and

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LCC in the design process makes it possible to make trade-offs between performance and cost and select the most cost-effective design alternative [13]. In the operation and maintenance phase, the RAMS and LCC approach has been demonstrated on a railway and signaling maintenance case study where RAMS analysis provides input parameters for LCC analysis, such as maintenance cost, downtime cost, and safety cost [14]. A detailed report can be used to select the best alternative according to the needs and goals of asset optimization. However, performance and cost analysis can be better performed at the concept design stage, where design options, such as between bridges or tunnels, can be determined. This process can quantify the entire system based on performance [13].

This article discusses the optimization of railway infrastructure assets carried out by several researchers who implemented the integration of RAMS and LCC concepts in design planning and the operation and maintenance phases. In the design phase, the selection of asset types of railway structures ballasted and ballastless track obtained different results between long-term and short-term use. In the short term, the ballasted track has better performance which can be seen from the lower Present Value (PV) value, but in the long term, the ballastless track is preferred due to lower maintenance costs over time and higher RAMS aspects [4]. In the operation and maintenance phase, the Life Cycle Cost with the RAMS parameter approach can calculate the total cost of maintaining the railway over its remaining life based on predicted failure and damage rates [15].

2 LITERATURE STUDY

2.1 Railway Infrastructure Asset Management

Railway infrastructure assets is the foundation of the railway system and has an important role in ensuring trains' safe and efficient operation [16]. The hierarchy of railway infrastructure assets is described into three major parts: the railway, all civil science structures, and systems/parts that ensure smooth traffic flow, as shown in Figure 1. The three major parts are composed of smaller parts. For example, a railway asset consists of components that transfer static and dynamic traffic loads and consists of two main parts: superstructure and substructure [17].

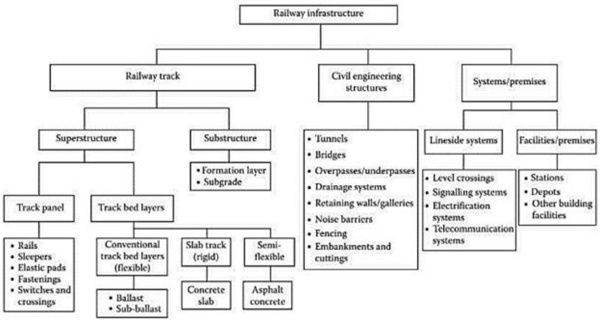


Figure 1. Hierarchy of railway Infrastructure Assets [17]

Large railway infrastructure assets require lifecycle management to make asset management more effective and efficient, as all phases of the asset lifecycle are integrated and considered as a whole. Such asset management can consider that when the cost of manufacturing and constructing an asset is cheap, the maintenance cost is likely to be expensive, or if buying a new asset at a low price but with low reliability, the cost of replacing the asset will also be expensive [18]. In addition, to maintain and improve its quality, railway infrastructure asset management is required through various investment efforts such as construction, inspection, maintenance, repair, and infrastructure rejuvenation [19].

2.2 The importance of rail infrastructure asset optimization

Optimizing railway infrastructure assets will help improve operational efficiency and reduce maintenance and upkeep costs. It can be achieved by maximizing asset utilization, reducing downtime for maintenance, and reducing the risk of failures and accidents. In addition, asset optimization can also help improve service quality and customer satisfaction, as well as significant financial benefits. Optimizing asset maintenance and repair costs can be reduced, thereby increasing expenditure efficiency and reducing long-term operating costs. Maintenance and renewal of railway infrastructure are essential to ensure the railway system's reliability, availability, maintainability, and safety [16]. Asset optimization in railway infrastructure has a positive effect on reliability, availability, maintainability, safety, and cost compared to no optimization, as summarized in Table 1.

Table 1. Asset Optimization Comparison (continue)

Source	With optimization	Without optimization
RAMS analysis of railway network: model development and a case study in China [20]	Can identify high-risk sections and stations and determine the investments needed to improve the safety and resilience of rail network operations	It can provide a big picture of the safety level of the entire network but cannot identify critical safety paths at sections and stations.
Integrated RAMS, LCC, and Risk Assesment for Maintenance Planning for Railway [21]	Help ensure that available resources are optimally utilized to achieve high reliability, availability, maintainability, and security of railway infrastructure at minimum cost.	Regular maintenance and infrastructure improvements can ensure reliability, availability, maintainability, and safety. However, this approach can be expensive and may need to be more efficient regarding resource utilization.
Life Cycle Cost Analysis for Managing Rail Infrastructure [22]	Railway infrastructure reliability can be improved, resulting in fewer delays and less downtime. Railway infrastructure availability can be improved, resulting in more uptime and less downtime. Railway infrastructure maintainability can be improved, resulting in faster and more efficient maintenance and repairs. Railway infrastructure costs can be reduced, resulting in more efficient use of resources and lower costs.	Assets are defined as how often trains are delayed or how often a section of track needs to be closed for maintenance, how often a section of track is open to trains, how long it takes to repair a rail section, or how often maintenance is required, and the cost of building a new rail section or maintaining an existing section.

2.3 Challenges in railway infrastructure asset optimization

The challenges of optimizing railway infrastructure assets have been described by several researchers, including the complexity of railway networks requires management and an in-depth understanding of components, interactions, and their impact on performance [2]. A top priority is the security of the railway network, which must comply with strict safety regulations. The performance of the railway network must always be optimal for all stakeholders, including passengers, freight operators, and the government. Another challenge is balancing increasing traffic volumes with network maintenance needs. High utilization can lead to the degradation of the railway infrastructure, which requires additional and potentially costly maintenance [3]. There is also the unpredictability of maintenance costs, identification of critical components, and the balance between performance, cost, and technical longevity of the complex railway network infrastructure. In addition, the fact that these systems are prone to various types of failures requires well-defined exploitation and maintenance planning to control unforeseen costs [23]. Methods and solutions to overcome these challenges by integrating RAMS parameters in LCC analysis so that it is possible to obtain reliable predictions of system maintenance costs can be used to optimize maintenance activities by reducing life cycle costs while improving safety and reducing travel time.

2.4 RAMS

The RAMS concept in the railway system makes service quality the main indicator of railway RAMS and other attributes [24]. The basic elements of railway RAMS, namely Reliability, Availability, Maintainability, and Safety, form the basis of the RAMS approach in analyzing the performance of railway systems to improve performance in a safe, efficient, and cost-effective manner throughout its life cycle [7] [11]. In the product life cycle, these four factors must be considered for the product to function properly without harming the user or the environment. Details about the RAMS concept can be seen in Figure 2.

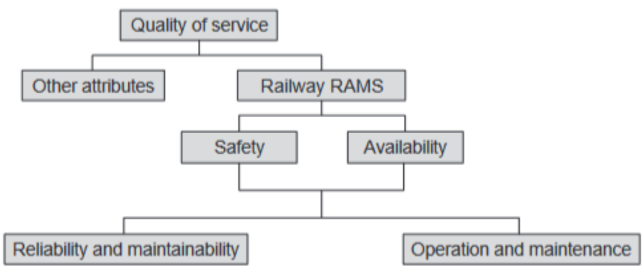


Figure 2. RAMS concepts [24]

2.4.1 Reliability

Reliability is the probability that an item can perform its required function under specified conditions for a specified time interval [4]. In determining reliability, supporting parameters are needed Failure Rate (λ (t)), Mean Up Time (MUT), Mean Operating Time to Failure (MTTF), Mean Operating Time Between Failure (MTBF), Failure Probability (F(t)), and Reliability (R(t)) [7]. Reliability is derived from failure rates, which are obtained using statistical methods. For this to happen, failures must be recorded as historical data, mostly in current databases, past failure datasets, or component or system background data [25]. The entire process is summarized in Figure 3.

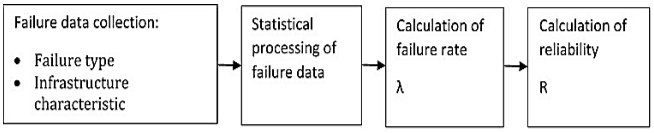


Figure 3. Failure rate and reliability forecasting procedure [25]

The reliability value function with an exponential distribution is as follows

- Probability Density Function
  $f(t) = \lambda e^{(-\lambda t)}$ (1)
- Cumulative Distribution Function
  $F(t) = 1 - e^{(-\lambda t)}$ (2)
- Reliability Function
  $R(t) = e^{(-\lambda t)}$ (3)
- Failure rate function
  $\lambda(t) = \frac{n}{T} = \lambda$ (4)
- Mean Time Between Failure (MTBF) for repairable items
  $MTBF = \frac{1}{\lambda}$ (5)
- Mean Time To Failure (MTTF) for non-repairable items
  $MTTF = \frac{1}{\lambda}$ (6)

Where f is probability density function, λ is Failure Rate (1/time. 1/distance, 1/cycle), and t is time (cycle).

2.4.2 Availability

In the context of the railway industry, availability is an important factor in ensuring railways and other railway assets are operational and ready for use to minimize delays and disruptions to the transportation system. It measures the percentage of time a system or product is available for use, considering downtime due to maintenance, repair, or other factors [26]. Availability consists of an uptime function (An where n=1, 2, ..., n), the time the system works, and a downtime function (Bm where m=1, 2, ..., m), which is the time when the system is not working. The availability graph and the preparation factor of the uptime and downtime functions can be seen in Figure 4 and 5.

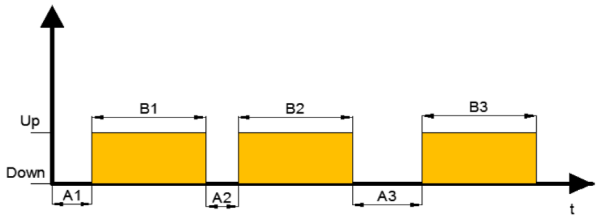


Figure 4. Availability time calculation method [25]

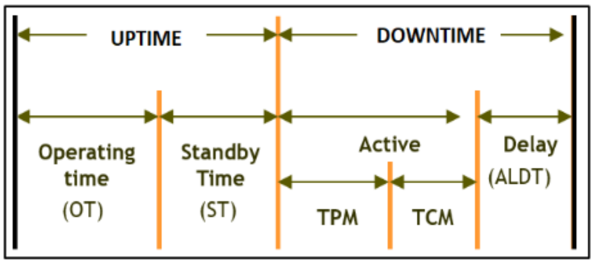


Figure 5. Factors that make up uptime and downtime [27]

Availability parameters are used to ensure that the rail network provides a high level of performance for customers while adhering to safety limits [28]. Availability can be expressed as expressed as

- Availability
  $A = \frac{Uptime}{(Uptime+Downtime)}$ (7)

2.4.3 Maintainability

In the context of the railway industry, maintainability is an important factor in ensuring that railways and other railway assets can be maintained and repaired quickly and efficiently to minimize downtime and ensure the safe and reliable operation of the transport system [26]. It is a measure of the ease and speed with which maintenance and repair tasks can be carried out, taking into account factors such as accessibility, modularity, and availability of parts and equipment usually measured by Mean Time To Repair (MTTR), which includes access time and repair/replacement time [11]. The maintainability parameter, MTTR, is used to provide an overview of the effectiveness of maintenance activities. Maintenance system calculations with MTTR, namely

- Probability that the component is repaired in time
  $M(t) = 1 - e^{-\mu t} = 1 - e^{\frac{-t}{MTTR}}$ (8)

Where μ is restore (repair) rate ($\mu = \frac{1}{MTTR}$)

The main benefit of maintainability analysis is dedicating how long it will take to complete various maintenance tasks. Hierarchically, maintenance is seen as a combination of all technical and administrative actions, including supervisory actions intended to maintain or restore a component or system to a state where it can perform what is required according to its primary function [29]. In Figure 6, we can see the maintenance hierarchy into two broad categories: preventive maintenance, where maintenance operations occur before failure, and corrective maintenance, where maintenance operations occur after failure.

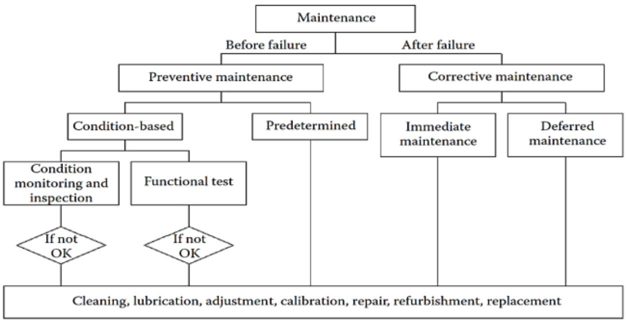


Figure 6. Maintenance Hierarchy [29]

2.4.4 Safety

Safety is one of the components of RAMS, which refers to the ability of a system or product to operate without causing harm or injury to people, property, or the environment. It measures the level of risk associated with operating a system or product, considering factors such as design, construction, operation, and maintenance. In the context of the railway industry, safety is important in ensuring that trains and other railway assets operate without endangering passengers, employees, or the public and that appropriate measures are taken to mitigate potential risks or hazards [26]. Typical safety parameters that have been used for railways are Mean Time Between Hazardous Failure (MTBHF), Mean Time Between Safety System Failure (MTBSF), and Hazard level H(t) [11].

In the safety analysis process, several activities are carried out, namely compiling the potential hazards that occur and conducting a risk analysis of the entire system to find out how much risk and effect may occur and the steps taken to eliminate these risks using the most common method, namely Failure Mode and Effect Analysis (FMEA) or Failure Mode and Effect Critically Analysis (FMECA) [30]. Risk assessment is used for safety planning in the early phase of the RAMS life cycle, where the process can be seen in Figure 7.

2.4.5 RAMS Implementation Phase

The RAMS process helps identify potential risks and hazards in the system, which can be addressed before they become problems [6]. To achieve a reliable system, factors that can affect the RAMS of the system must be identified, their effects must be measured, and the causes of these effects must be addressed throughout the system's life cycle through the application of appropriate controls to optimize system performance [8]. The system life cycle phases in order can be seen in Figure 8.

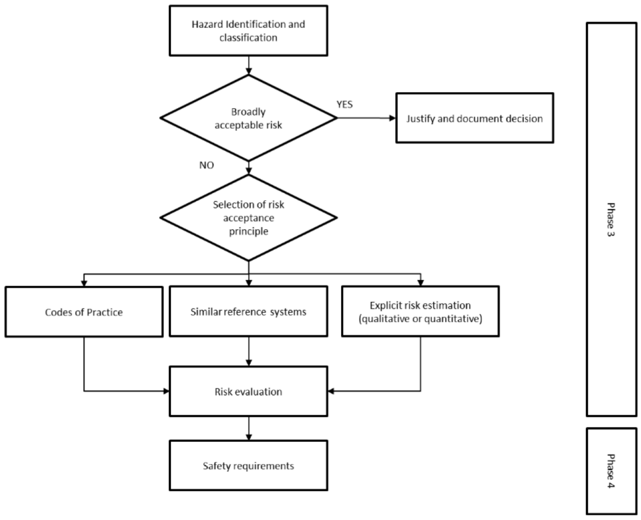


Figure 7. Risk Assesment Process [7]

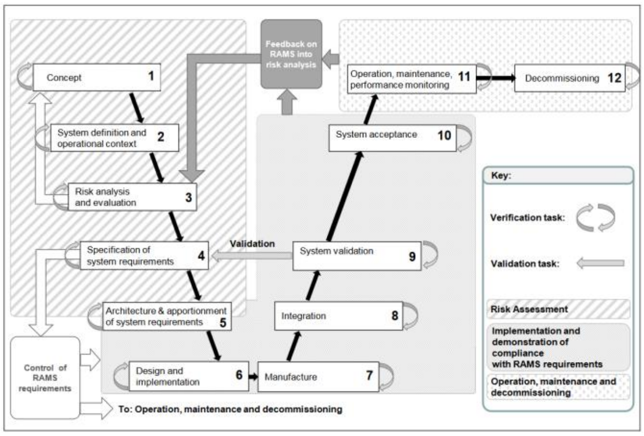


Figure 8. RAMS Cycle Process [7]

2.5 Life Cycle Cost

LCC is a very important tool to assist in deciding which investment alternatives (that meet specified performance requirements) can provide the best long-term price/financing [30]. Figure 9 compares the life cycle cost phases and overall costs. The acquisition phase, which includes building analysis and design decisions, typically "locks in" about 80% of the total lifecycle cost. In comparison, the costs incurred during the acquisition phase are only about 20% of the total lifecycle costs. Therefore, the design phase becomes a key factor in generating efficient and economic life cycle costs where LCC as a tool in Value Engineering is used for the evaluation of several alternatives to obtain an optimal total cost value, with a target of 5-10 per cent reduction in operating costs [31].

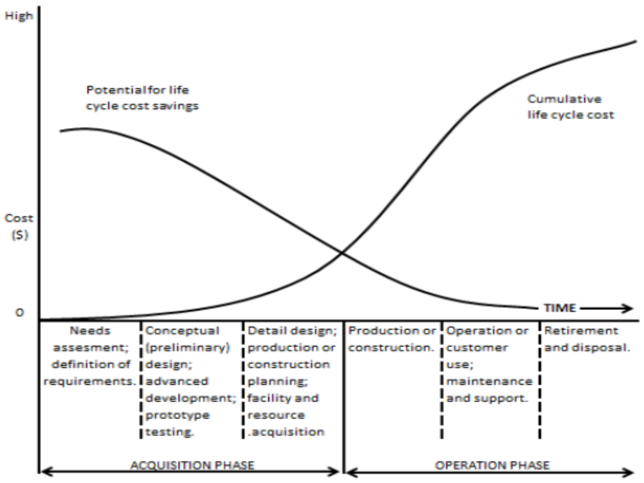


Figure 9. Cost comparison between life cycle phases [31]

The costs calculated at LCC include all costs from the beginning of the purchase or procurement to the end of the service life or the selection of the best option consisting of two major phases, namely the acquisition and operational phases. All of the above costs must be calculated and summed up to get the total cost over the operational life or life of the asset.

All of the above costs must be calculated and summed up to obtain the total cost over the operational life or life of the asset. By knowing the total cost, decision-makers can choose the most efficient option from a financial point of view, for example, by using Present Value, Future Value, Annuity Worth, or Internal Rate Return calculations [31]. The LCC calculation is

- Life Cycle Cost

$$LCC = C + M + O + R - S \quad (9)$$

- Present Worth to Annual Worth Convertion

$$A = P\frac{i\,(1+i)^N}{(1+i)^N - 1} \quad (10)$$

- Future Cost to Annual Cost Convertion

$$A = F\frac{1}{(1+i)^N - 1} \quad (11)$$

- Annual Present Cost with another future cost calculation

$$P = F\frac{1}{(1+i)^N - 1} \quad (12)$$

Where C is initial cost, M is Maintenance cost, O is operational cost, R is Replacement cost and function changes, S is Residual value, A is annual cost, P is present cost, F is future cost, N is Period, and i is % interest per annum.

Cost calculation criteria and variables in LCC are essential to accurately evaluate the system's total cost over its life cycle. The discount rate adjusts future cash flows to their present value, considering the expected rate of return or investment risk. The higher the discount rate, the less value is given to future cash flows because the future value of money is considered less valuable than the present value of money [30]. Net Present Value (NPV) considers the time value of money by calculating the present value of future cash flows and discounting them to the present time using a discount rate. Using NPV, it is possible to compare the costs and benefits of different design alternatives throughout the project lifecycle, thus providing a more accurate estimate of the total cost of ownership of the system [13]. In contrast, Annuities are used to calculate fixed payments over a while. Considering these criteria, decision-makers can identify the most cost-effective solution for a particular system [32].

2.5.1 Life Cycle Cost Implementation Phase

All costs associated with a product or system throughout its life cycle are identified and converted to a specific point using NPV method. The NPV formula is then used to calculate the difference between the present value of cash inflows and cash outflows over a while [33]. Figure 10 shows the stages of the LCC Analysis process.

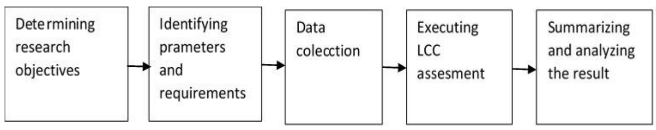


Figure 10. LCC Analyse Process [33]

2.6 RAMS and LCC Integration

The integration of RAMS-LCC helps select, plan, evaluate, and manage assets systematically, effectively, and efficiently as shown in Table 2. The combination of asset performance and total cost of ownership helps make the right decisions to maximize the optimal use of assets over its life cycle.

Table 2. RAMS and LCC Integration (Continue)

Describe	RAMS	LCC	RAMS and LCC
Asset Selection	Identify potential reliability, availability, maintainability, and security issues that may arise during the asset lifecycle.	Identify costs associated with the asset lifecycle, including acquisition, operation, maintenance, and disposal costs.	Identify assets that meet the required performance, security, and cost criteria while minimizing their lifecycle costs.
Design Stages	Identify potential reliability, availability, maintainability, and security issues that may arise during the system lifecycle.	Identify costs associated with the system lifecycle, including design, development, production, operation, and maintenance.	Ensure the system is designed to meet the required performance, security, and cost criteria to optimize system performance with minimal life cycle costs.
Performance Evaluation	RAMS can help evaluate asset performance systematically and continuously, thereby detecting problems and improving asset performance.	LCC can help evaluate asset performance from a cost perspective, thereby detecting inefficient costs and improving cost efficiency.	Systematically and continuously evaluate performance to improve asset efficiency and effectiveness from a technical as well as detection from a cost perspective.
Risk Management	RAMS can help identify and manage the risk of asset failure, thereby minimizing the impact of risk and improving security.	LCC can help identify and manage asset-related financial risks, thereby minimizing costs and improving financial management.	Minimize the impact of technical and financial risks.

Source: [34]

3 METHOD

In carrying out research related to the review of RAMS and LCC for railway infrastructure asset optimization, the method, as shown in Figure 11, was carried out.

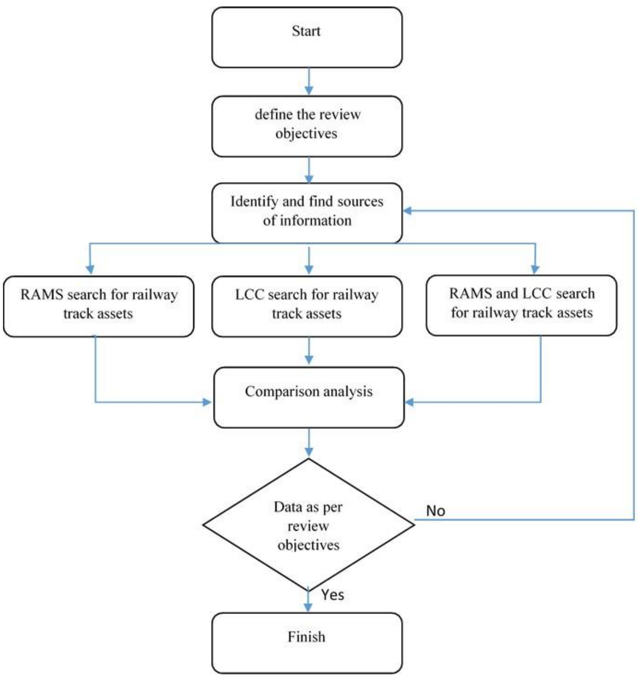


Figure 11. Research method for railway track asset optimization review

4 RESULT AND DISCUSSION

4.1 Case Study of RAMS Implementation

In the RAMS implementation based on research conducted in China, the railway network is analyzed to identify the high-risk sections and stations [20]. The proposed RAMS analysis method considers the probability of station and section failures and the expected loss of network availability due to station and section failures, helping to provide a more comprehensive perspective on rail network safety. Figure 12(a) shows the expected loss of network efficiency (reduction in the speed and frequency of trains that the railway network can operate) due to section and station failures. In contrast, Figure 12(b) shows the expected loss of network capacity (reduction in the maximum number of trains the railway network can accommodate) due to section and station failures. In other words, capacity reduction affects the maximum number of trains that can be operated, while efficiency reduction affects the speed and frequency of trains that can be operated.

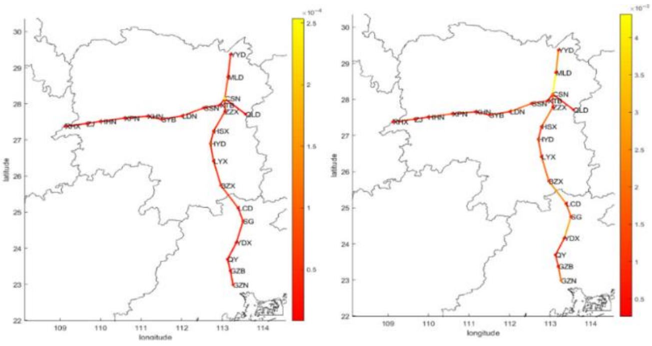


Figure 12. (a) An estimated loss of network efficiency due to failures at stations and sections of the route (b) Estimated loss of network capacity due to failures at stations and sections of the route [20]

In another implementation, research in Uzbekistan demonstrated the potential benefits of RAMS analysis in railway maintenance on the network between Tashkent and Sirdaryo stations [16]. Tables 3 and 4 illustrate the successful implementation of RAMS in high-speed rail infrastructure management in the region. Analyses were conducted for the track geometry and each type of rail component to achieve a reliable, available, and maintainable infrastructure and rail system success analysis with IL (Immediate Limit) and IAL (Immediate Action Limit) limits for head-loss and gauge surface wear on the railway.

Table 3. Reliability of Uzbekistan Railways Infrastucture

	Infrastructure parameters								
RAM Parameter	Gauge	Alignment	Twist	Cant	Levelling	Rails	Sleepers	Ballast	Total
Reliability (IL)	0.86	0.73	0.89	0.76	0.73	0.87	0.62	0.78	0.13
Reliability (IAL)	0.94	0.97	0.94	0.94	0.97	0.94	0.97	0.96	0.68

Source: [16]

Table 4. Availability and Maintainability of Uzbekistan Railways Infrastucture

	Subsections							
RAM parameters	1	2	3	4	5	6	7	Overall
Availability	0.9226	0.9375	0.9451	0.9425	0.9275	0.9477	0.9502	0.64
Maintainability	0.9312	0.9364	0.9364	0.9415	0.9312	0.9467	0.9519	0.65

Source: [16]

The RAMS analysis results show that the reliability for rail components is at 62% - 97% with IL and IAL limits. However, the system reliability value is only 13% - 68%. Meanwhile, the availability of components is at 92% - 95% with a system availability of only 64%, and for maintainability, the components are at 93% - 95% with a system availability of only 65%.

Based on the implementation of RAMS that has been carried out in previous studies, asset optimization with the RAMS method focuses on the technical system in the form of reliability, availability, maintainability, and security. It does not focus on the cost aspect of the asset.

4.2 Case Study of LCC Implementation

The Russian study compared the life cycle costs of three upper railway track structures (URTS) on a double track. Line 1 has high freight load acceptance intensity and short service life, so two options were made for line 1, namely option 1, with a service life of 6 years and routine maintenance, and option 2, with rail replacement and rail geometry improvement to extend the service life to 12 years, while line 2 has low load acceptance intensity with a service life of 20 years [35]. The calculations in Table 5 show that line 2 has the lowest annual life cycle cost of 1,563 thousand rubles over a 20-year life cycle.

Table 5. LCC calculation result

Track	Without consideration of the discount		With consideration of the discount	
	LCC, thousand rubles	$\overline{LCC}$ (LCC), thousand rubles	LCC, thousand rubles	$\overline{LCC}$ (LCC), thousand rubles
1 (option 1)	37,947	6,325	34,884	5,814
1 (option 2)	62,169	5181	46,693	3,891
2	39,650	1,983	31,254	1,563

Source: [35]

The Italian study analyzed five different scenarios for the construction and maintenance of railway infrastructure on excavated and embanked areas with varying materials (virgin or RAP) and construction methods (e.g., lime stabilization) as well as superstructure maintenance planning where maintenance A is performed every five years and maintenance B every ten years [10]. Scenario 1 uses virgin materials and conventional construction methods, Scenario 2 uses lime stabilization in the embankment body, Scenario 3 uses lime stabilization and highly compacted soil, Scenario 4 uses RAP materials in the sub-ballast, and Scenario 5 uses RAP materials, lime stabilization and highly compacted soil. Table 6 shows that Scenario 5 is the most economical option for the embankment and excavation sections and all maintenance options.

Table 6. Total Cost Railway Infrastructure

		Net Present Value [€]				
Section	Maint. Plan	1	2	3	4	5
Embank.	A	3,244,012.53€	3,141,938.70€	3,076,981.96€	3,242,179.96€	3,075,150.70€
	B	3,179,341.37€	3,077,267.53€	3,010,675.39€	3,177,510.10€	3,008,844.12€
Cut	A	3,732,961.79€	3,620,736.54€	3,604,204.95€	3,731,123.63€	3,602,366.80€
	B	3,668,288.16€	3,556,062.91€	3,539,531.33€	3,666,450.01€	3,537,693.17€

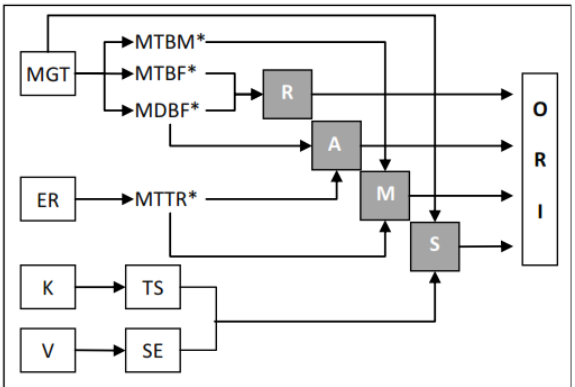
Source: [10]

The entire implementation of Life Cycle Cost Analysis research results above shows asset optimization focusing on economic aspects where technical aspects related to reliability, availability, maintainability, and safety still need to be considered.

4.3 Case Study of Implementation Stage RAMS-LCC since The Design Phase

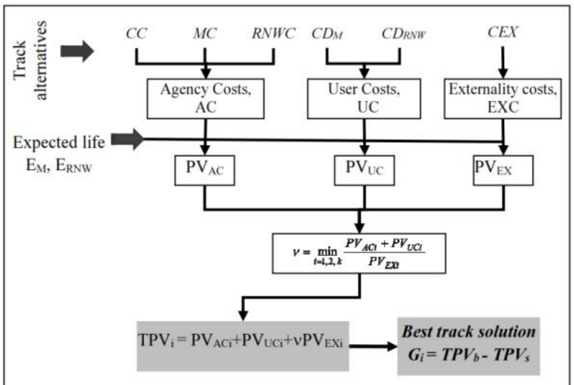
Research at the design stage proposed a blended decision-support approach for rail design and maintenance strategies with two alternative high-speed rail double-track designs: ballasted track and ballastless track (slab) [11] . The proposed approach involves developing a Decision support system based on LCC analysis that balances short-term and long-term costs and considers a comprehensive analysis based on agency and user costs and environmental costs with RAMS performance. Figure 13 shows the overall RAMS indicator (ORI) workflow, where RAMS modelling involves measurements based on Mean Distance Between Failures (MDBF) and Mean Time to Repair (MTTR) after a failure. Figure 14 shows the LCC modelling of agency, user, and externality costs, which involves assessing the costs associated with construction, inspection, maintenance, and renewal of the line, as well as the costs associated with its use, such as costs associated with delays. The results shown in Figure 15 indicate that the RAMS of the ballastless track (slab) is generally higher than that of ballasted track. However, a ballastless track (slab) has higher construction and maintenance costs due to the need for specialized equipment and materials, resulting in a lower Total Present Value (TPV). The break-even point between the two solutions is depicted at point B.

In another study, RAMS and LCC analyses were conducted to determine future trends in railway tunnel design in hard rock and cold weather in Norway [36]. The three main issues considered necessary in selecting tunnel lining technical solutions for railway tunnels are safety, minimum break time, and total cost-effectiveness.



Symbols. MTBM*: *Mean Time Between Maintenance; MTBF* Mean Time Between Failure;* MDBF*: *Mean Distance Between Failure,* MTTR*: *Mean Time To Repair;* MGT: *Millions of Gross Tonnes;* ER: *External Resources;* K: *Factor;* TS: *Track Safety;* V: *Speed;* SE: *Speed Effect;* R: *Reliability;* A: *Availability;* M: *Maintainability;* S:*Safety;* ORI: *Overall RAMS Indicator.*

Figure 13 Overall RAMS Indicator (ORI) Diagram [11]



Symbols. CC: construction cost; MC: maintenance cost; RNWC: renewal cost; CD_M: delay-related costs for maintenance; D_{RNW}: delay-related costs for renewal; EX_{kj}: externality cost which refers to the k-th activity/processes and j-th indicators: CO2e, SOx, NOx, CO, VOC, PM; E_M, E_{RNW}: expected lives which refer to maintenance (M) or renewal (RNW); PV: present values, TPV: total present value; b: ballasted track, s: slab track; G = gains.

Figure 14. LCC Model Assesment [11]

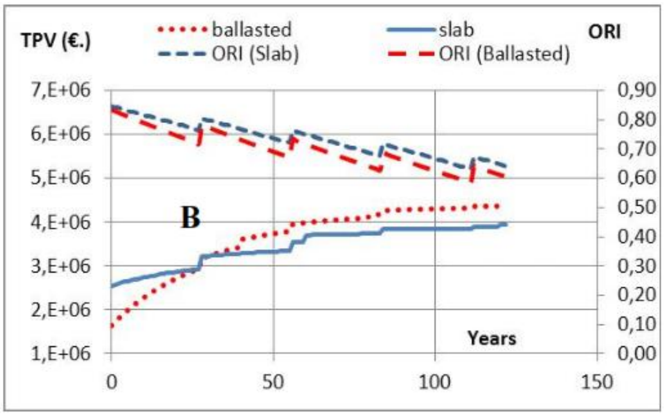


Figure 15. PV and ORI Analysis Results for MGT per year = 6 and 200 km/h facility speed [11]

Modern analysis tools RAMS and LCC are suggested to achieve cost-effective technical solutions for tunnel lining by modern functional requirements with the methodology for implementing RAMS and LCC analysis involving steps, as shown in Figure 16.

1. Collecting input data: The first step is to collect input data on the system or structure being analyzed, including design specifications, operational data, and maintenance records.
2. Conducting a RAMS analysis: The RAMS analysis evaluates the reliability, availability, maintainability, and safety of the system or structure. This analysis helps identify potential problems and risks associated with the system or structure and develop strategies to mitigate those risks.
3. Conduct an LCC analysis: LCC analysis evaluates the total cost of a system or structure over its entire life cycle, including initial investment costs, maintenance costs, and operating costs. This analysis helps identify the most cost-effective technical solution for the tunnel lining.

4. Combining RAMS and LCC analysis: The RAMS and LCC analyses are combined to provide a detailed decision basis for cost-effective technical solutions for tunnel linings that meet modern functional requirements.
5. Implementing the selected technical solution: Once the most cost-effective technology solution for tunnel lining has been identified, it can be implemented in the design and construction of the tunnel lining.

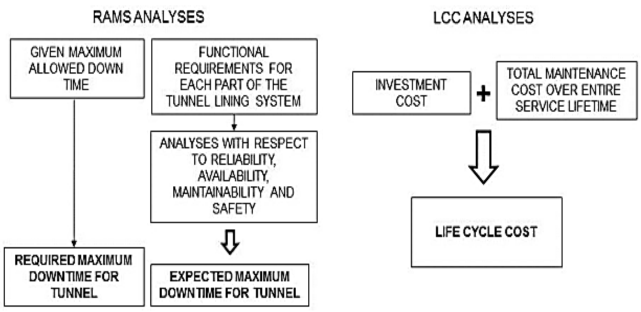


Figure 16. Methodology of RAMS and LCC implementation on future trend of railway tunnel design [36]

By using RAMS and LCC analysis, a cost-effective technical solution for tunnel lining can be achieved, which can improve performance and reduce maintenance costs over the life cycle of the tunnel.

4.4 Case Study of Implementation Stage RAMS-LCC that starts in the operational and maintenance phase

Research on RAMS and LCC analysis for linear transportation emphasizes the focus on processes in the maintenance phase. It provides probabilistic information relevant to conditional planning, maintenance risk, and long-term investment decisions [3]. The proposed methodology integrates RAMS parameters in LCC analysis to predict system maintenance costs and the dependency of costs on certain factors, such as switches and crossings (S&C) maintenance, through sensitivity analysis. Figure 17 shows the workflow of RAMS and LCC involving the following steps:

1. Collected data on system reliability, maintainability, availability, and safety (RAMS) parameters through registered maintenance activities.
2. Used the collected data to develop a probabilistic model for the system RAMS parameters.
3. Integrating the probabilistic RAMS model into the LCC analysis to obtain reliable predictions of system maintenance costs.
4. Conducted sensitivity analysis to identify the dependency of maintenance costs on specific cost drivers.
5. Using RAMS & LCC analysis results for condition and risk-based maintenance activity planning and decision support in long-term strategic investment planning.

This approach can reduce maintenance costs, improve safety, and enhance asset performance. The analysis results show that the cost of maintenance interventions for S&C is highly dependent on the type of intervention, the age of the asset, and the traffic volume, so it can be concluded that the proposed methodology can be used to obtain reliable predictions.

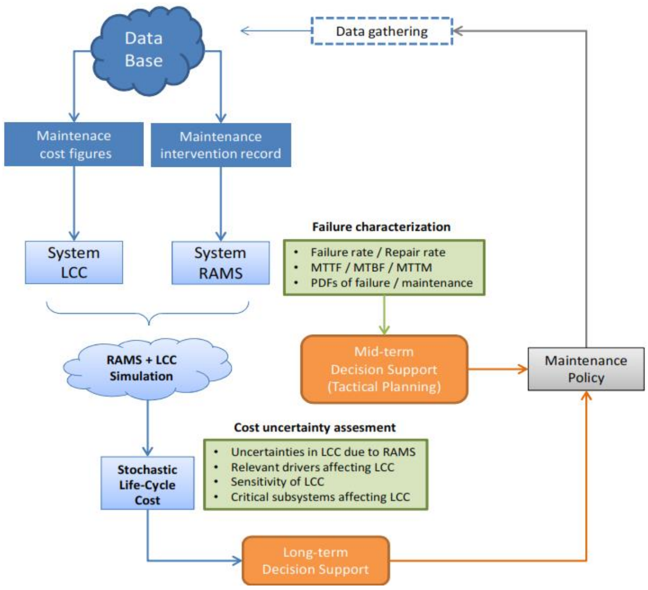


Figure 17. Flow chart of RAMS and LCC for railway infrastructure asset maintenance optimization [3]

Another research that focuses on railway maintenance is the analysis of maintenance optimization calculations conducted in Indonesia, where RAMS is an indicator to determine the railway's performance in a period by predicting failures on the railway every period of the life of the railway can predict the number of failures. LCC provides the total cost required during the remaining phase of the railway asset life by calculating construction, maintenance, and delay costs [37]. Figure 18 shows the flow chart of the relationship between RAMS and LCC. The first thing to do is obtain data on the damage incurred and downtime caused by railway damage and then perform statistical analysis to determine the distribution parameters. The reliability value and damage rate will be obtained from the data, where the damage rate value is used as a failure prediction parameter.

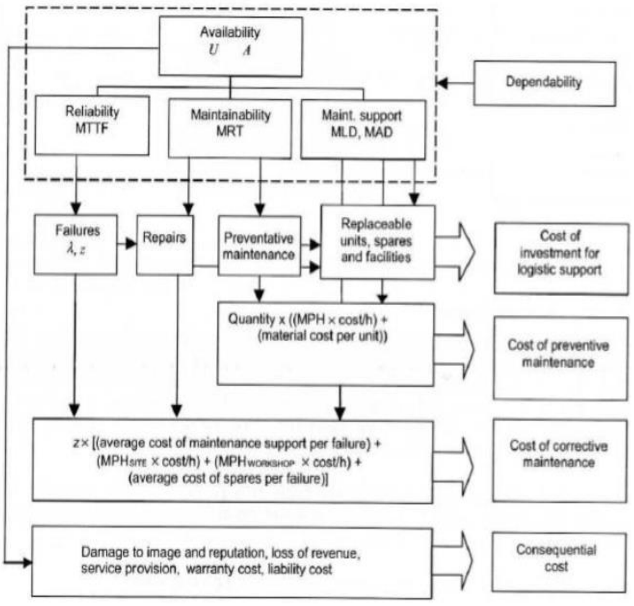


Figure 18. Flow chart of RAMS and LCC relationships [37]

The results show that RAMS and LCC can be used to obtain reliable predictions of system maintenance costs. The LCC value of the remaining technical life is obtained by summing up the Construction Cost or Consequential Cost (CC), Cost of Preventive Maintenance or Recurring Repair Cost (RC), Cost of Corrective Maintenance or Unexpected Maintenance Costs (MC), and Cost of Investment for Logistic Support or Delay Cost (DC). One of the results obtained is the availability of the railway system, which can be seen in Figure 29. Availability decreases year by year over the remaining technical life due to the cost of delay, which causes downtime to increase due to the increasing deterioration of railway components. Figure 20 shows the annual LCC increasing year by year. It is because most of the constituent cost components increase each year. The increase affects the damage cost components that increase yearly, such as annual unplanned maintenance and delay costs.

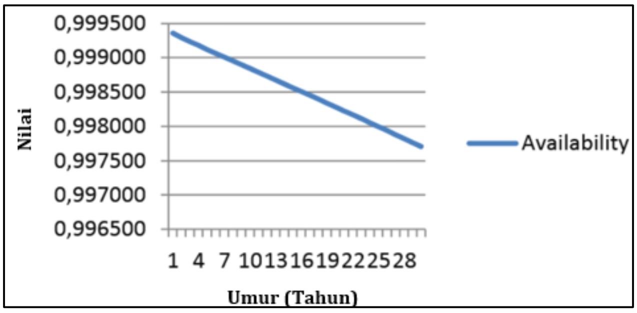


Figure 19. Railway component Availability. [37]

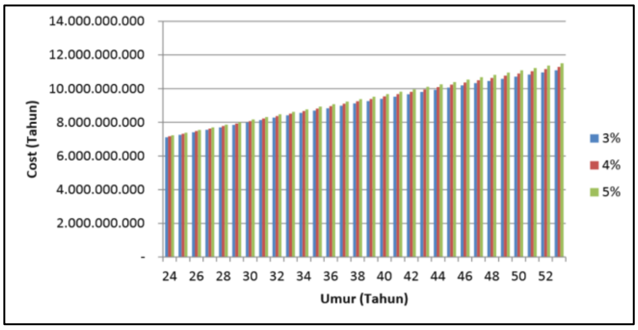


Figure 20. Results of annual LCC analysis of the remaining railway life with three delay cost schemes (3%, 4%, 5%) [37]

The RAMS and LCC approaches have been demonstrated on railway maintenance and signaling case studies where RAMS analysis provides input parameters for LCC analysis, such as maintenance cost, downtime cost, and safety cost [14].

4.5 Discussion on implementation benefits and future challenges

An important overview of how asset management can be done effectively to improve the efficiency and productivity of rail systems and reduce unnecessary costs has been presented in the discussion of this article. RAMS and LCC are two concepts that are related to asset optimization. The integration of RAMS and LCC has successfully optimized rail infrastructure assets and provide better value. This article also highlights the importance of considering the entire asset lifecycle, from design to operation and maintenance. The implementation of RAMS and LCC should be done during the design phase so that the technical and cost capabilities of the asset can be optimized. A great deal of effort is required to use this concept because it requires a large amount of historical asset data. With the development of technology, asset data can be digitized using a computerized system, and sensors to monitor asset conditions will be used as lesson-learned data in the future.

In addition to requiring quite a lot of data, another challenge is to obtain accurate and complete data on the condition of these assets. It is important because RAMS and LCC assessments require detailed and valid data on asset conditions, which can influence decisions on asset replacement, maintenance, or repair, as well as the challenge of determining appropriate performance attributes and formulating mathematical models that can account for interactions between different infrastructure components.

In addition, the implementation of RAMS and LCC concepts also requires strong support from skilled and trained management and human resources. In many cases, railway companies may need more human resources or the right management systems to implement the concepts successfully. Another challenge is to ensure that the RAMS and LCC concepts are not just guidelines or recommendations but also properly implemented in practice. It requires a strong commitment from management to change the existing organizational culture and ensure that railway companies are focused on financial outputs, effective and sustainable asset management, and collaboration between railway companies and other relevant parties, such as governments, service users, and technology providers.

In the future, the challenges of RAMS and LCC implementation in asset management will include adopting new technologies and infrastructure development. Implementing RAMS and LCC will be increasingly complex and require stakeholder collaboration to achieve optimal performance, cost efficiency, and safety. To address these challenges, adopting digital technologies in asset management, such as artificial intelligence, big data, and the Internet of Things (IoT), can help improve RAMS and LCC implementation by providing real-time data and analytics to support decision-making. Collaborating with stakeholders, including governments, operators, and service providers, is crucial to ensure the successful implementation of RAMS and LCC in asset management.

By addressing these challenges, RAMS and LCC can be effective tools in improving the efficiency and productivity of the rail system.

5 CONCLUSION

Railway infrastructure asset management is very important in improving the efficiency and productivity of the railway system as a whole. It can be done with Reliability, Availability, Maintainability, Safety (RAMS), and Life Cycle Cost (LCC). Integration between RAMS and LCC concepts can be done in all phases of the railway life cycle, from design planning to operation and maintenance phases. In the design phase, asset optimization is done better considering technical and economic aspects.

Several studies have shown that integrating RAMS and LCC concepts can lead to better strategic decisions in railway design and maintenance planning. In addition, this integration can also be used to calculate the total cost of railway maintenance over the remaining life based on the predicted failure and damage rates and used for long-term strategic investment planning.

The research on asset selection between ballasted and ballastless railways found that using ballasted track and ballastless track has different short-term and short-term results. In the short term, ballasted track perform better, as seen from the lower Present Value (PV) value, but in the long term, ballastless track are preferred due to lower maintenance costs over time and higher RAMS aspects.

The integration of RAMS and LCC can also be used to analyze future trends in rail tunnel design in hard rock and cold weather. The results of RAMS and LCC analysis can lead to cost-effective technical solutions for tunnel linings that can improve performance and reduce maintenance costs over the life cycle of the tunnel.

In the future, it is necessary to study asset optimization on the entire railway system, from facilities to infrastructure, to see the optimization results of these two concepts. Digitization can be carried out related to RAMS and LCC requirements with the asset system so that when there are additional assets or maintenance/renewal of assets, there is already a lot of comparative data.

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