***Overview Of RAMS Analysis and ITS Implementation in Railway Vehicles***

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**Abstract**

Reliability, availability, maintainability, and safety (RAMS) analysis, as a tool to ensure performance, safety, and cost-effectiveness throughout the system’s life cycle, has been widely applied in various industries, including the railway industry, specifically railway vehicles. This article provides an overview of various studies exploring the implementation of RAMS analysis in railway vehicles. This literature review consists of an introduction, method, RAMS analysis, results and discussion, and conclusion. Several studies on the implementation of RAMS analysis in railway vehicles are presented and explained, and key points from each study are discussed to provide a comprehensive overview of the implementation of RAMS analysis in railway vehicles. In general, the benefits of the implementation of RAMS analysis are enhanced performance (reliability, availability, and maintainability), safety, and cost-effectiveness of railway vehicles throughout their life cycle. However, many studies only focus on one or a few aspects of performance, safety, or cost-effectiveness without comprehensive discussions of all these aspects. Additionally, many studies only concentrate on the operational phase, including maintenance and repair, without a complete discussion of the entire life cycle from concept to disposal stage.

**Keywords:**  RAMS Analysis, Railway Vehicles, Performance, Safety, Cost-Effectiveness.

**INTRODUCTION**

RAMS analysis has advanced significantly over the past few decades, particularly in ensuring product quality [1]. This analytical process was highly complex, encompassing a comprehensive evaluation of the system's lifecycle and the performance of its subsystems and components [2]. The successful implementation of RAMS analysis was achieved by identifying potential failures and their impacts to attain the desired performance level, estimating system performance, and optimizing design and maintenance strategies.

Several studies were conducted on the implementation of RAMS analysis across various industrial sectors. For instance, Cano et al. [3] proposed a Bayesian framework for RAM analysis of hardware systems involving multiple states by offering short-term and long-term performance studies based on the posterior distribution of its parameter values. Hameed & Vatn [4] presented a methodology and framework for RAMS analysis in the wind turbine sector to develop more reliable and efficient wind turbines. Adhikary et al. [5] investigated the RAM features of a 210 MW coal thermal power plant (Unit-2) to enhance the availability of electricity supply. In the paper industry, Garg et al. [6] proposed an Artificial bee colony-based lambda-tau (ABCBLT) method for calculating RAM parameters. In the electric power transmission system, Khalil et al. [7] used RAM evaluation to analyze the severity of power outages and the reliability of overhead transmission lines (OHTLs) in Italy, while Nugraha et al. [8] proposed a maintenance decision model based on RAMS analysis to determine the appropriate maintenance schedule for power transmission systems in Indonesia. In the transportation sector, Soltanali et al. [9] provided a framework for optimizing RAM in evaluation and maintenance to improve the performance of car assembly line systems, while Graboń-Chałupczak & Sitarz [10] proposed a component-based road vehicle maintenance evaluation method in RAMS analysis to enhance the performance and maintenance of transportation systems.

The railway system was acknowledged as a key driver of the global economy and an environmentally friendly and safe mode of transportation [11]. The railway system was a complex system comprising numerous subsystems and components. Broadly, it consisted of two major asset groups: railway infrastructure assets such as tracks, bridges, signaling, and stations, and rolling stock assets such as locomotives, passenger cars, and freight cars [12]. The complexity of the railway system necessitated a comprehensive evaluation methodology like RAMS analysis to ensure that the performance and reliability of each component contributed to the overall effectiveness of the system.

The implementation of RAMS analysis in the railway system was the subject of several studies. Calle-Cordón et al. [13] proposed a combined methodology of RAMS and LCC (life cycle cost) for railway and highway system infrastructure that could provide relevant probabilistic data for condition-based and risk-based maintenance planning and support decisions in long-term strategic investment planning. An enhanced RAMS architecture was presented by Litherland et al. [14], which enabled railway asset managers to assess asset performance and make crucial choices about the development of the railway network. Lu et al. [15] proposed a model to evaluate the RAMS of Global Navigation Satellite Systems (GNSS) for train localization and control. Nguyen et al. [16] proposed a predictive RAMS analysis procedure for localization units using a combination of GNSS and ECS (eddy current sensor) for train control applications like "braking loop control" to ensure compliance with railway safety standards. Szkoda & Kaczor [17] investigated the application of RAMS analysis using the EN 50126 standard to evaluate the reliability of railway vehicles throughout their life cycle. In their discussion on using RAMS analysis to create maintenance strategies for the 6Dg diesel locomotive, Szkoda et al. [18] demonstrated how it enabled accurate hazard classification, estimation of hazard frequency, and the use of appropriate criteria for risk assessment. To conduct a reliability study of air brake systems, Cai et al. [19] introduced the GO-Bayes technique, which integrates GO (goal-oriented) engineering structural modeling with probabilistic inference from the Bayesian method. The implementation of RAMS analysis in the railway system was based on regulations such as IEC 62278 [2] and EN 50126 [20 - [21]. The primary objectives of RAMS analysis in the railway system were to enhance system performance and safety, reduce maintenance costs, and ensure customer satisfaction.

The national standardization agency in Indonesia issued regulations regarding RAMS for railway system applications in 2019 [22], adopting identically the IEC 62278 standard. In the context of implementing RAMS analysis in Indonesia, a review of implementation studies conducted in various countries is necessary. This article aims to provide a comprehensive overview of the implementation of RAMS analysis in railway systems, especially railway vehicles which are crucial assets in the system. The discussion includes applications, parameters, required data, proposed methods, outcomes, as well as benefits and limitations. The contribution of this article is to synthesize research, highlight best practices, provide methodological insights, and identify areas for future research and improvement, serving as a reference for implementing RAMS analysis in railway systems in Indonesia.

**METHOD**

The method used in writing this article was qualitative with content analysis. The initial step involved determining the theme to be discussed, which in this case pertained to RAMS analysis in railway vehicles. Once the theme was established, sources were searched for writing materials from various databases such as Scopus, Science Direct, IEEE, Springer, Google Scholar, and other relevant databases. The search for writing materials was limited to the use of the English language and open access to ensure the availability of required writing materials. The keywords used in the search included 'RAMS', 'Reliability, Availability, Maintainability, and Safety', 'Railway RAMS', 'RAMS Analysis', 'RAMS Analysis in Rollingstock', and 'RAMS Analysis in Railway Vehicles'.

After the writing materials were gathered, the next step involved screening titles and abstracts based on their relevance to the theme to identify writing materials that were suitable for the research focus. Subsequently, a content filter was applied to the writing materials by considering the alignment of themes and overall content, to determine the writing materials that would be reviewed in-depth. From the selected writing materials, a comprehensive content analysis was then conducted regarding applications, parameters, required data, proposed methods, outcomes, as well as benefits and limitations. This analysis was elaborated in the results and discussion section to provide a comprehensive understanding of the implementation of RAMS analysis in railway vehicles. To facilitate an explanation of the writing method, Figure 1 provides an illustration that visually explains the flowchart of processes conducted in this research.



Figure 1.Flowchart of writing method

**RAMS ANALYSIS**

RAMS is a term used to describe the reliability, availability, maintainability, and safety of a system or product. Reliability refers to the likelihood that a part or system will function as intended for a predetermined period when used under specified operating conditions [23]. Availability refers to the ability of an item to be in a functional state and perform its required function, either at a specific time or over a defined period, under certain conditions, provided that the necessary external resources are available [20]. Maintainability refers to the likelihood that specific maintenance tasks for a product can be completed within a designated timeframe under specific conditions, using particular procedures and resources [24]. Safety means being free from risks considered unacceptable [20].

RAMS analysis was conducted throughout the life cycle of the system, starting from the conceptual phase, manufacturing, operation and maintenance, to disposal. Figure 2 illustrates the modified scheme of RAMS analysis implementation from Mańka & Wachnik [25]. This scheme also incorporates Life Cycle Cost (LCC) analysis as a justification for the cost-effectiveness of RAMS analysis implementation. The input process, which includes the plans and objectives set for RAMS analysis, as well as the analysis of current operational data or results from previous implementations, is on the left side. On the right side, it shows the actions taken as a result of evaluation or feedback on RAMS implementation, comparing planned and target outcomes with the results obtained at each stage of the system's life cycle to achieve RAMS analysis goals.



Figure 2.RAMS analysis implementation scheme (modified and redrawn)

Source: (Mańka and Wachnik [25], 2010)

In the context of RAMS analysis, several trends and challenges emerged. The availability and completeness of data from the concept phase, manufacturing, operations, and maintenance, up to decommissioning, were key factors that determined the success of RAMS analysis implementation. Collaboration from various stakeholders was required to address data availability issues. This collaboration involved manufacturers, suppliers, and operators to establish RAMS targets for a product and evaluate these targets at each phase. The implementation of RAMS analysis was a cyclical process for continuous improvement that required feedback from previous deployments. Besides data availability and completeness, adjustments to regulations and standards were also determining factors in the successful implementation of RAMS analysis. Regulators needed to involve manufacturers, suppliers, and operators in the creation of regulations and standards to ensure they aligned with the conditions faced by each party and could be implemented effectively.

Several regulations and standards serve as references in RAMS analysis, especially for railway applications, including the European Norm EN 50126 prepared by the Technical Commission CENELEC in 1999 and IEC 62278 [2] issued by the International Electrotechnical Commission in 2002 based on EN 50126 TC 9X: electrical and electronic applications for railways. CENELEC is the European Committee for Electrotechnical Standardization, while IEC is a global organization for standardization comprising all national electrotechnical committees aimed at promoting international cooperation on all questions concerning standardization in the electrical and electronic fields. The process established in IEC 62278 assumes that railway authorities and railway support industries have business-level policies addressing quality, performance, and safety. Additionally, the approach defined is consistent with the application of quality management requirements contained within the international ISO 9000 standards. In 2017, EN 50126 underwent a significant revision followed by the issuance of BS EN 50126 specifically for UK implementation in the same year. BS EN 50126 comprises two parts, where Part 1 [20] explains the Generic RAMS Process, while Part 2 [21] elaborates on the Systems Approach to Safety. Indonesia, through its national standardization agency, adopted IEC 62278 identically and established SNI RAMS [22] in 2019. These regulations and standards serve as references in the development of the RAMS analysis framework involving various stakeholders.

The selection of parameters also plays a crucial role in the successful implementation of RAMS analysis. Based on existing standards, several parameters in determining the value of RAMS components can be seen in Table 1.

Table 1. RAMS parameters

| **Parameter** | **Symbol** | **Dimension** |
| --- | --- | --- |
| **Reliability Parameters** |
| Failure Rate | λ(t), Z(t) | 1/time, 1/distance, 1/cycle |
| Mean Up Time | MUT | time (distance, cycle) |
| Mean Operating Time/Distance To Failure(for non-repairable items) | MTTF, MDTF | time (distance, cycle) |
| Mean Operating Time/Distance Between Failure (for repairable items) | MTBF, MDBF | time (distance, cycle) |
| Failure Probability | F(t) | dimensionless |
| Reliability (Success Probability) | R(t) | dimensionless |
| **Maintainability Parameters** |
| Mean Down Time | MDT | time (distance, cycle) |
| Mean Operating Time/Distance Between Maintenance | MTBM, MDBM | time (distance, cycles) |
| MTBM/MDBM (corrective or preventive) | MTBM/MDBM (c), MTBM/MDBM (p) | time (distance, cycles) |
| Mean Time To Maintain | MTTM | time |
| MTTM (corrective or preventive) | MTTM (c), MTTM (p) | time |
| Mean Time To Restore | MTTR | time |
| Mean Repair Time | MRT | time |
| False Alarm Rate | FAR | 1/time |
| Fault Coverage | FC | dimensionless |
| Repair Coverage | RC | dimensionless |
| **Availability Parameters** |
| AvailabilityInherentAchievedOperational | A(t) = MUT/(MUT+MDT)AiAaAo | dimensionless |
| Fleet Availability | FA = available vehicle/fleet | dimensionless |
| Schedule Adherence | SA | dimensionless or time |
| **Safety Parameters** |
| Mean Time Between Hazardous Failure | MTBF(H) | time (distance, cycle) |
| Mean Time Between "Safety System Failure” | MTBSF | time (distance, cycle) |
| Hazard rate | H(t) | 1/time, 1/distance, 1/cycle |
| Probability of wrong-side failure | PWSF | dimensionless |
| Safety Related Failure Probability | Fs(t) | dimensionless |
| Probability of Safe Functionality | Ss(t) | dimensionless |
| Active time to return to a safe state | - | time |

The digital transformation and advancements in data analytics also influenced the trends and challenges faced in the implementation process of RAMS analysis. This led to the evolution of RAMS analysis methods from conventional to more sophisticated methods in line with technological advancements. Mahboob & Zio [26] classified methods in RAMS analysis into two categories, namely basic methods and advanced methods, as shown in Figure 3. Those methods could be used individually or in combination with several methods. Some commonly used methods included FMEA/FMECA, RBD, FTA, Markov Model, and Monte Carlo Simulation.



Figure 3.Classification of methods or tools used in RAMS analysis based on Mahboob and Zio

Several examples of using FMEA/FMECA in RAMS analysis include the study from Szkoda & Satora [27], which focused on using FMEA to analyze modification risks in railway vehicle maintenance systems, particularly the 6Dg locomotive. Their study used FMEA to identify potential hazards, quantify risk components, and determine preventive safety measures, ultimately proving that modifying the maintenance schedule for the 6Dg locomotive was feasible without compromising safety. Catelani et al. [28] presented FMECA for HVAC systems in trains, aiming to precisely identify critical HVAC components and enhance their reliability and availability. They also proposed an innovative finite differences-based risk threshold analysis to differentiate between negligible failure modes and critical failure modes. Petritoli et al. [29] analyzed RAMS to expand a 'Smart Street' pilot site, combining reliability analysis with FMECA to optimize an Industry 4.0 case study without sacrificing safety. Rechena et al. [30] reported FMECA for the front element of Collective Thomson Scattering (CTS) diagnostics in the International Thermonuclear Experimental Reactor (ITER). They identified possible failure modes, impacts, consequences, and risk reduction measures using FMECA techniques, revealing no major failure modes that compromise ITER operations, although they require some mitigation measures to lower the risk of CTS diagnostic availability. Li et al. [31] discussed the impact of failures on Automatic Traffic Control (ATC) system evaluations crucial for air traffic safety. Their study developed a reliability theory-based methodology, including reliability logic diagrams and FMECA, to assess the consequences of subsystem or component failures across the entire ATC system. The research also included methods for calculating reliability, availability, maintainability, and other assessment indicators, along with quantitative evaluations of failure consequences in ATC system operations.

Jagtap et al. [32] combined RBD with FTA and the probabilistic Markov birth-death approach, evaluating the Water Circulation System (WCS) performance in coal-fired power plants using the RAM framework. This study enables decision-makers to allocate resources and manage maintenance tasks based on subsystem criticality levels due to the recommended RAM architecture. Distefano & Puliafito [33] compared two different notations used in system reliability modeling, DFT (dynamic fault trees), and DRBD (dynamic reliability block diagrams), which are developments from conventional FTA and RBD, allowing failure modeling based on system dynamics and time dependencies. They provided DFT elements to map onto the DRBD domain and investigated the potential reversal of this translation. Marquez et al. [34] proposed a methodology for identifying critical components in wind turbines based on FTA to optimize reliability, availability, maintainability, and safety. Their study used Binary Decision Diagram (BDD) methods to reduce computational costs and applied heuristic methods to identify crucial events. Quantitatively, this technique allows for unique maintenance planning. Marugán et al. [35] provided maintenance management optimization for offshore wind farms by reducing computational costs, using FTA with BDD to determine defect probabilities. They used dynamic failure probability data and key metrics to create planned maintenance that enhances decision-making and reduces maintenance costs. Hofig et al. [36] discussed the benefits of using component failure trees for safety analysis in complex software systems. They presented two case studies, Situation Display, and Crosslink Redundancy, to demonstrate the effectiveness of this approach, comparing it with traditional failure trees and listing the advantages and disadvantages of each modeling approach.

For examples of using advanced methods in RAMS analysis, Cortes et al. [37] introduced a new technique for computing error probabilities in digital circuits using Monte Carlo Sampling (MCS). Their proposed approach is more cost-efficient in terms of computation compared to existing methods. However, further analysis and comparisons with other methods are still necessary. Wang et al. [38] reported on a fault-tolerant computer system built as a 2-out-of-2 dual redundant component architecture. The RAMS of this design was quantitatively and probabilistically evaluated using Markov modeling techniques. The 2-out-of-2 dual redundant system exhibited the highest reliability and met Safety Integrity Level (SIL) 4 requirements, making it suitable for critical safety systems such as high-speed train systems.

Some methods in RAMS analysis have their own advantages and limitations. Table 2 provides explanations regarding each method commonly used in the implementation process of RAMS analysis, especially in their applicability, strengths, and weaknesses [26].

Table 2. The applicability, strengths, and weaknesses of commonly used methods in RAMS analysis

| **Method** | **Applicability** | **Strengths** | **Weaknesses** |
| --- | --- | --- | --- |
| **FMEA (Failure Mode and Effects Analysis)** | Commonly used to analyze potential failure modes, their likelihood of occurrence, and their effects on item performance. | - Can be widely applied to human operators, equipment, and system failure modes, as well as hardware, software, and processes, employing a systematic approach to identify component failure modes, their causes, and their effects on the system, and presenting them in an easily readable format.- Helps avoid the need for costly equipment modifications in service by identifying problems early in the design process. | - Generally can only be used to identify single failure modes, not combinations of failure modes.- The analysis can become time-consuming and costly without proper planning and focus, especially for complex systems. |
| **FMECA (Failure Mode, Effects, and Criticality Analysis)** | Step further from FMEA by incorporating criticality measures that combine parameters such as severity, likelihood, and detectability to prioritize failure modes. | - Provides deeper insights than FMEA into the risks and priorities of failures within the system, thereby minimizing significant failure risks.- Generates more detailed analysis results and enables more effective planning of corrective actions than FMEA. | - More complex than FMEA as it involves critical assessment and deeper analysis.- Requires more resources and time to conduct thorough and detailed analysis, especially for complex systems. |
| **RBD (Reliability Block Diagram)** | Utilized as an effective visual and quantitative tool to evaluate a system's performance regarding functionality and failure, aiding in determining potential system configuration improvements. | - Ability to describe most system configurations in a concise, easily understandable diagram derived from functional diagrams.- Provide both qualitative and quantitative assessments, along with certain importance measures. | - Not suitable for describing systems that require consideration of the order of failures or complex repair strategies where repaired blocks are not independent of each other. |
| **FTA (Fault Tree Analysis)** | The well-established methodology used for system reliability, availability, and safety analysis, provides a rational framework to model potential scenarios leading to specified undesired events within a technical system. | - Its systematic and deductive approach, which can address various failure causes, including human interactions, makes it particularly beneficial for analyzing complex systems with multiple interfaces and combinations leading to system failure.- The graphical representation of FTA makes it easy to understand the system's behavior and the factors involved. | - Does not address the sequences of event occurrences and deals only with binary states.- Traditional FTA considers only one Top Event (TE) or failure mode at a time. |
| **Markov Model (MM)** | Utilized in reliability and safety analyses to quantitatively describe the time evolution of a system based on discrete states and transitions, particularly beneficial for systems with redundancy and complex operation and maintenance strategies. | - Its capability to describe complex redundancies and dynamic multistate systems.- Provides various transient or stationary measures as results, and the supporting state-transition diagrams offer a simple and intuitive means for visualizing and communicating the model's structure. | - Numerical evaluation requires more effort.- For complex systems, the number of states in the model may expand significantly, limiting its applicability. |
| **Monte Carlo Simulation (MCS)** | Generates multiple outcomes of a model by repeatedly solving it with randomly chosen values for input variables and events, which are then statistically analyzed to calculate system quantities of interest, taking into account uncertainty effects without directly solving the underlying model, and well-suited for complex systems that pose challenges in analytical modeling. | - Its flexibility to accommodate any input variable distributions and to offer solutions for complex systems that are not easily solved analytically, all while providing a measure of result accuracy. | - The accuracy of solutions is contingent upon the number of simulations conducted, with convergence rates typically slow.- Caution must be exercised when simulating extreme events. |

**RESULT AND DISCUSSION**

Railway vehicles are critical assets in railway systems, functioning to transport both passengers and goods in their operations. As assets along the tracks carry varying loads of passengers and goods, their performance and safety aspects are a primary concern for railway operator companies. Therefore, implementing RAMS analysis in railway vehicles becomes a management strategy to ensure safe, secure, and user-expectation-meeting train journeys.

There were several studies on the implementation of RAMS analysis on railway vehicles based on standards such as IEC 62278 [2] and EN 50126 [20 - [21]. The implementation of RAMS analysis on general railway vehicles was provided by Selech et al. [39], who proposed ISM (Monitoring Information System), a technical system capable of collecting, processing, and evaluating reliability and cost-related data from a railway vehicle. This system supports sophisticated analysis with RAMS concepts that comply with the International Railway Industry Standard (IRIS) and LCC concepts. The ISM system provides a multidimensional analysis of accumulated historical data related to vehicle operations and disturbance data monitoring (in RAMS index, life cycle costs, and component cost identification).

In the context of locomotive vehicles, Szkoda & Kaczor [17] examined the use of RAMS analysis in the life cycle of railway vehicles. Basic concepts and indicators were used to assess the widely recognized reliability of railway vehicles based on the EN 50126 standard. A study evaluating the effectiveness of modernizing railway vehicles to reduce operating and maintenance costs was conducted by Tułecki & Szkoda [40]. A decision-making model based on LCC and RAMS features was created, and an example of this methodology was used to modernize a 6D 588 kW diesel locomotive. The results indicated that modernization was a justified technique to improve efficiency and provide significant total cost reduction. Szkoda et al. [18] also presented the application of RAMS analysis in the safety domain during the creation (or revision) of railway vehicle maintenance plans. This research used a case study of 75 6Dg locomotives running for 15 months. The study's findings showed that this analysis allows for accurate hazard categorization, estimation of hazard event frequencies, and the application of suitable criteria for risk assessment from the developed approach. Subsequently, Leite et al. [41] proposed a Discrete Event Simulation (DES) model to evaluate the reliability and availability of locomotive bogie subsystems. This model takes into account correlation patterns and stochastic behavior related to failure events. To assess the prediction resilience of the model in facing uncertainty, this research provided five alternative scenarios. The findings indicated that the suggested DES model was sufficient to capture critical elements of locomotive bogie subsystems and could assist in developing efficient maintenance strategies.

In passenger coach vehicles, Kim et al. [42] proposed a new LCC model to assess the effectiveness of RAMS requirements. This new model considered three LCC aspects influenced by RAMS standards, namely acquisition costs, maintenance costs, and hazard costs. Han et al. [43] offered an algorithm to determine the target RAM values of components in railway vehicle systems that meet system performance size requirements while considering estimated life cycle costs and system availability as optimization factors. This program considered financial and technological constraints based on meta-heuristics through simulation. Numeric examples in the research showed how model parameters influenced the likelihood of achieving optimal results. Additionally, the study highlighted relevant research on reliability design issues and simulation tools to evaluate system RAM values. The development of a framework integrating RAMS and simulation in IoT-based CBM (condition-based monitoring) for rolling stock was proposed by Park et al. [44]. This study utilized the Internet of Things (IoT) for real-time condition monitoring and continuous technical support services, as well as reliability-centered maintenance (RCM) based on failure data from KTX (Korea Tran eXpress) motor unit failures. The study indicated that criteria for prediction, resolution, and benefits typically aided RAMS management assessments in daily operations. Cai et al. [19] presented the GO-Bayes method, which combines the structural modeling of the GO method with the probabilistic reasoning of the Bayes method to analyze the reliability of air brake systems in rail transit. This method provided comprehensive safety evaluations based on system structure and accumulated data and guided system maintenance strategies to reduce life cycle costs. Data event analysis techniques to identify statistical failure distributions related to door subsystems or critical component failure modes were presented by Hoh et al. [45]. To calculate time to failure or time to event for reliability analysis, this study focused on the Kawasaki Heavy Industries (KHI) C151 metro train in Singapore and used maintenance and operation information. The study helped improve train doors' performance by providing insights into their functioning. Appoh et al. [46] proposed a hybrid model combining reliability, risk, and maintenance strategies. This model consisted of an upstream segment analyzing failures using risk and reliability methodologies, and a downstream segment allocating maintenance strategies and selecting repair options using decision-making grids (DMGs) and group decision-making analysis. This approach was demonstrated using a case study of a railway operator in the UK replacing faulty pneumatic brake units (PBUs). The findings showed that with this approach, an installed PBU subsystem could meet the reliability, risk, and maintenance needs of the railway operator.

In freight wagon vehicles, Sitarz et al. [47] presented the application of the FMEA method to evaluate operational risks in railway transportation and the implementation of RAMS standards for monitoring freight rail vehicles. The FMEA methodology was adopted as a standard for evaluating operational risks for operators and infrastructure managers on Polish railway lines. RAMS standards were implemented in several entities that developed maintenance management systems for freight cars. This study highlighted the benefits of using FMEA methodology and RAMS standards, such as the ability to compare different parameters between operated car types and analyze specific failure types. Factor analysis, which is a statistical analysis to identify the most relevant RAMS indicators that describe a system and reduce the number of RAMS indicators, was proposed by Sitarz et al. [24]. Reducing the number of indicators in RAMS analysis can reduce the amount of required data, thereby increasing efficiency in terms of time and cost without sacrificing the effectiveness of railway vehicle system monitoring.

**The Application, Parameters Used, and Required Data Sources**

The explanation above provides an overview of the implementation of RAMS analysis in railway vehicles. To facilitate discussion, Table 3 provides a systematic overview and comparison from the perspective of the application types of vehicles, the parameters used, and the data sources required from the 13 studies that have been explained.

Table 3. The application, the parameters used, and the required data sources in each study

| **Study** | **Application** | **Parameters** | **Source of Data** |
| --- | --- | --- | --- |
| Selech et al. [39] | General Railway Vehicles | - RAMS parameters: Meantime & Mean distances in available and unavailable conditions (repair or maintenance)- LCC parameters: Cost of repair & maintenance | Historical data on railway vehicle operational |
| Szkoda & Kaczor [17] | Locomotives | RAMS parameters based on EN 50126 standard | - corrective maintenance logbooks- preventive downtime and maintenance logbooks- traction vehicle logbooks |
| Tułecki & Szkoda [40] | Locomotives | - LCC parameters: costs of investments, maintenance, unavailability, fuel consumption, engine oil consumptions, and environmental charge- RAMS parameters: Mean time between failure (MTBF), Operational availability, and Mean time to repair (MTTR) | - Operational data for 134 non-modernized locomotives over a period of 3 years- Modernized locomotive data based on expert and reference methods |
| Szkoda et al. [18] | Locomotives | Probability of failure (FH(t)), Mean time to hazardous failure (MTTHF), Mean time between hazardous failures (MTBHF), Frequency of occurrence of a hazardous failure (H) | The operational data of a selected sample of 75 6Dg locomotives over a period of 15 months |
| Leite et al. [41] | Locomotives | Failure rate, mean time between failure (MTBF), mean time to restore (MTTR) | The failure data and some repair data obtained from references from previous studies |
| Kim et al. [42] | Passenger Coaches | - Acquisition Cost- Maintenance Costs, and- Hazard Cost  | The report didn't specifically state where the data came from |
| Han et al. [43] | Passenger Coaches | MTBF, MTTR, Repair costs, development costs, and investment costs | System structure and RAM of components a rolling stock system with 17 components |
| Park et al. [44] | Passenger Coaches | MTBF, MTTR, Maintenance costs, Failure frequency | The failure data from the KTX (Korea Tran eXpress) motor reduction unit for three years from references |
| Cai et al. [19] | Passenger Coaches | The failure rate of the air braking system | The operating data of the braking system which is transmitted to the ground equipment |
| Hoh et al. [45] | Passenger Coaches | Shape parameter and scale parameter of Weibull statistical distribution | Maintenance and operational records data of the Kawasaki Heavy Industries (KHI) C151 metro trains |
| Appoh et al. [46] | Passenger Coaches | Risk priority number (RPN), failure rate, failure frequency, delay minutes | Historical operational data of the dual-voltage EMUs obtained from the maintenance management system (MMS) over a period of 3 years |
| Sitarz et al. [47] | Freight Wagons | - Probability of appearance, detection of hazard, and effect of threat occurrence for risk assessment- RAMS parameters: number of failures, operational availability, MTTR, MTBHF | Historical data of wagon operational |
| Sitarz et al. [24] | Freight Wagons | Correlation value, eigenvalue, and variance in statistical analysis | Historical data of wagon operations from a prior study |

From the perspective of railway vehicle types, there is 1 study that discusses railway vehicles in general without specifying their type, 4 studies that focus on locomotives as the driving units, 6 studies that cover passenger cars, both conventional without their own propulsion and with propulsion, and 2 studies dealing with freight cars. Compared to passenger cars and freight cars, locomotives have the most complex systems, thus their operational failure risk is also the highest. Additionally, locomotives are used in non-driving passenger train sets and freight cars, requiring them to perform well. Considering these factors, the number of RAMS analysis implementation studies on locomotives should be higher than those on passenger cars and freight cars given their complexity and wide range of applications.

The parameters used in the studies refer to relevant RAMS standards for railway vehicles as described in the previous chapter, where the selection of parameters is adjusted to the research objectives. For performance assessment, the parameters used focus on the time when railway vehicles can be operated and when they cannot be operated (due to repairs or maintenance). For safety assessment, the parameters used focus on railway vehicle failures, including their probability, consequences, and detectability, to determine the safest and least safe components. For cost-effectiveness assessment, the parameters used focus on costs, including purchase costs and operational and maintenance costs of railway vehicles.

The data sources used in the researches consist of operational data (including maintenance and failures), obtained directly from the research object, assumption data, and reference data obtained from similar studies. This indicates that these studies only focus on the operational and maintenance phases and do not cover the entire phase.

**The Proposed Method and Outcomes**

The proposed method and outcomes are crucial parts of this discussion. Table 4 illustrates the proposed methods and the outcomes of each study.

Table 4. The proposed method and outcomes of each study

| **Study** | **Proposed Method** | **Outcomes** |
| --- | --- | --- |
| Selech et al. [39] | The development of a monitoring system known as ISM (Monitoring Information System) | The creation of a monitoring system made it possible to carry out complex research in line with the LCC and RAMS idea |
| Szkoda & Kaczor [17] | The framework for determining the RAMS properties of railway vehicles | The suggested approach, which was based on PN-EN 50126, guided figuring out the RAMS characteristics of railway vehicle |
| Tułecki & Szkoda [40] | The development of a decision-making model based on LCC and RAMS characteristics | The development model was a viable strategy for updating locomotives that increased productivity and resulted in significant overall cost reductions |
| Szkoda et al. [18] | The developed framework of RAMS analysis in the safety domain during the creation (or revision) of the railway vehicle maintenance plan | The devised method made it possible to categorize risks accurately, determine how frequently they occur, and adopt appropriate criteria for risk assessment |
| Leite et al. [41] | The development of a Discrete Event Simulation (DES) model as a numerical method | The suggested model located crucial variables and elements that affected the system's reliability and availability |
| Kim et al. [42] | A new LCC model that considered acquisition cost, maintenance cost, and hazard cost in a mathematical equation | A novel model was employed to evaluate the cost efficiency of the RAMS requirements |
| Han et al. [43] | Genetic algorithm with a heuristic approach | The suggested method identified the components' RAM target values for a rolling stock system |
| Park et al. [44] | The development of a framework that integrated RAMS and simulation on IoT-based CBM (condition-based monitoring) for railway vehicles | The proposed framework offered clear instructions for selecting a failure management approach, boosting the maintainability, sustainability, and cost-effectiveness of railway maintenance systems |
| Cai et al. [19] | The GO-Bayes method combined the structural modeling of the GO method with the probabilistic reasoning of Bayes methods and Monte Carlo simulation | The method could be employed to track down, maintain, and enhance system parts, and finally guarantee the system's safe functioning as a whole |
| Hoh et al. [45] | A technique of life and recurrent event data analysis as a statistical method | The proposed method discovered statistical failure distributions about the door subsystem or its critical component failure modes |
| Appoh et al. [46] | A hybrid model that integrated reliability, risk, and maintenance techniques | The suggested approach successfully assessed and located a new PBU component that satisfied the operator's reliability, risk, and maintenance needs |
| Sitarz et al. [47] | The FMEA (Failure Mode and Effects Analysis) methodology and implementation of RAMS standards | The proposed model examined certain forms of failures and compared various factors between various operating wagon types |
| Sitarz et al. [24] | Factor analysis as a statistical method | The suggested technique assisted in finding the most pertinent RAMS indicators that best represented a system |

From Table 4, we can see that the proposed methods in each study can be categorized into framework development and decision-making model, monitoring systems, mathematical equations, numerical methods, statistical methods, and hybrid or integrated methods. Framework development and decision-making model were conducted by Szkoda & Kaczor [17], Szkoda et al. [18], Tułecki & Szkoda [40], and Sitarz et al. [47]. Monitoring systems were proposed by Selech et al. [39]. Mathematical equations were worked on by Kim et al. [42], numerical methods by Leite et al. [41] and Han et al. [43], statistical methods by Hoh et al. [45] and Sitarz et al. [24], and hybrid or integrated methods by Park et al. [44], Cai et al. [19], and Appoh et al. [46].

The outcomes of each study indicate the effectiveness of the proposed methods. These outcomes also depend on the focus of each study regarding performance improvement, safety, and cost efficiency of the railway vehicle life cycle. Studies focusing solely on performance improvement were conducted by Leite et al. [41] and Han et al. [43], while studies focusing solely on safety enhancement were implemented by Szkoda et al. [18] and Hoh et al. [45], and studies focusing solely on cost efficiency were carried out by Kim et al. [42]. On the other hand, studies concentrating on both performance and safety improvement were conducted by Szkoda & Kaczor [17], Cai et al. [19], Appoh et al. [46], Sitarz et al. [47], and Sitarz et al. [24], whereas studies focusing on performance and cost efficiency improvement were done by Tułecki & Szkoda [40], and studies addressing all three aspects, including performance enhancement, safety, and cost efficiency, were undertaken by Selech et al. [39] and Park et al. [44].

**The Benefits and Limitations**

To complete this chapter, the discussion will focus on discussing the benefits and limitations of each study. Table 5 presents the benefits and limitations of each study.

Table 5. The benefits and limitations of each study

| **Study** | **Benefit(s)** | **Limitation(s)** |
| --- | --- | --- |
| Selech et al. [39] | - The research provided a technological approach for tracking and examining data on a railway vehicle's cost and reliability- The technology may help manufacturers of railroad cars keep track of data about malfunctions and do a multidimensional analysis of historical information on the operation of railway vehicles | - The data analysis process and its formulas were not explained in detail, there was a greater focus on discussing the dashboard presentation of the ISM system- The ISM system was created as part of a research project, thus its suitability for use in different contexts may need to be assessed |
| Szkoda & Kaczor [17] | The study provided the guidelines for determining the RAMS properties of railway vehicles which included the stages of concept development and definition, design, manufacture, and operation | The study did not provide any empirical results or case studies |
| Tułecki & Szkoda [40] | The research suggested a decision-making model based on LCC and RAMS features that Poland's largest rail carrier may utilize as a decision-making foundation | - The analysis was based on a single locomotive model, and the results may not have been generalizable to other locomotive models- The analysis assumed that the modernized locomotive would operate under the same conditions as the non-modernized locomotive, which may not have always been the case |
| Szkoda et al. [18] | - The proposed method assisted in assuring the vehicles' reliability, availability, maintainability, and safety- The study offered a quantitative method for examining the frequency of failures that endangered locomotive sub-assemblies, which could be used to spot possible risks and adopt suitable risk assessment criteria | - Because only 75 6Dg locomotives were used in the study, the findings may not apply to other kinds of locomotives or railway vehicles- The study was conducted over a 15-month period, which might not have been sufficient to cover all potential failure modes and scenarios that could arise during a locomotive's operation |
| Leite et al. [41] | The suggested model was appropriate for capturing the essential elements of the locomotive bogie subsystem and contributed to the creation of efficient maintenance procedures | - The proposed model was based on several assumptions and simplifications, which may not have fully captured the complexity of the system- The failure data used in the study were obtained from previous studies and maintenance experiences, which may not have been representative of the current state of the locomotive bogie subsystem |
| Kim et al. [42] | The study provided a new LCC model that took into account acquisition cost, maintenance cost, and risk cost which might help determine the RAMS required numbers | - The effectiveness of the suggested model was not supported by any empirical findings or case studies in the study- Given that various railway systems might have varied RAMS needs and cost structures, the suggested model could not apply to all types of railway vehicles- The research did not present a comprehensive framework for decision-making regarding RAMS requirements and LCC optimization |
| Han et al. [43] | The study proposed an approach based on meta-heuristics and simulation to identify the RAM target values of components in a rolling stock system that matched the requirements of system performance metrics | - The suggested algorithm was based on simulation, which could not have correctly represented the rolling stock system's performance in practice- The numerical examples presented in the research were limited in scope and might not have been representative of all possible scenarios |
| Park et al. [44] | The suggested approach provided strong guidelines for choosing a failure management strategy, increasing the cost-effectiveness, viability, and maintainability of railway maintenance systems | - Instead of using real data, the information was obtained via references- There were no thorough explanations of IoT applications for railway rolling stock- How the proposed reliability-centered maintenance enhanced RAMS indicators was not explained in great depth |
| Cai et al. [19] | - The suggested technique led the system maintenance plan and offered a thorough safety evaluation based on system structure and accumulated data- The big data platform was also anticipated to speed up data collecting and increase analytical accuracy | - The proposed method had limited applicability to other systems- A large amount of data was needed to achieve accurate results- A certain level of expertise in both GO modeling and Bayes theory was required |
| Hoh et al. [45] | The study helped train doors to work better by offering insights into their performances | - The study may not be generalizable to other types of trains or metro systems as it only examined the dependability of train doors in Singapore's Kawasaki Heavy Industries (KHI) C151 metro trains- The study relied on maintenance and operational records, which may not have captured all relevant information about train door failures |
| Appoh et al. [46] | - By assisting train operators in making informed choices about the upkeep and replacement of rolling stock subsystems, the proposed model increased the reliability and safety of railway transportation networks- The model aided in lowering maintenance expenses and downtime and enhancing asset management decision-making | The proposed model could not be generalized to other railway transport systems with different characteristics and operating conditions and need to be tested and validated |
| Sitarz et al. [47] | - The proposed technique facilitated the identification and assessment of common threats among the participants and averted or decreased the effects of potential rail disasters- Following the development of appropriate solutions in partnership with manufacturers, new constructions' functionality and safety were improved | - The study did not thoroughly examine the effectiveness of the FMEA approach and RAMS standards in enhancing railway safety management- The report did not address the difficulties and constraints of putting these ideas into practice |
| Sitarz et al. [24] | - The suggested method determined which RAMS indicators best represented a system and were most pertinent- The research decreased the amount of information needed to calculate RAMS indicators without reducing the advantages of the railway vehicle monitoring system | - The number of indicators was reduced based on a previous wagon data case, which might not have been suitable for other vehicles and was also out of date- It is necessary to demonstrate how well the strategy explains the system's situation in terms of performance, safety, and cost-effectiveness |

From Table 5, we can see that each study proposes various approaches, whether in the form of frameworks, decision-making models, calculation formulas, or monitoring and data testing systems. This is done to provide benefits in improving performance, safety, and cost efficiency of the railway vehicles, which will play a crucial role in supporting the railway system as a whole.

Most researchers focus on the operational and maintenance phases, with very few discussing the entire life cycle of railway vehicles. While Szkoda & Kaczor [17] have proposed guidelines for determining RAMS properties of railway vehicles from the development and concept definition stage, design, and manufacturing, to operation, no case studies or empirical results are provided. Data availability remains a major challenge faced by most researchers, with some still relying on reference data rather than real data. Selech et al. [39] proposed a monitoring system for data monitoring and testing, but the data analysis process and formulas are not explained. Sitarz et al. [24] have explained that factor analysis can help identify the most relevant RAMS indicators that best describe a system and reduce data requirements in calculating RAMS indicators without sacrificing the benefits of railway vehicle monitoring systems. However, the effectiveness of this approach in describing the system's condition in terms of performance, safety, and cost-effectiveness needs to be demonstrated. Life Cycle Cost (LCC) analysis is one of the analyses used to ensure cost efficiency. Kim et al. [42] have proposed a new LCC model that considers acquisition costs, maintenance costs, and risk costs, which would be useful for establishing RAMS requirements. However, there is no comprehensive framework regarding its use, and no case studies or empirical results are provided.

**Future Research**

From the results and discussion chapter, several important notes need to be highlighted. The direction of further research will be focused on implementing RAMS analysis on locomotives as the most complex railway vehicles. Data availability will be accommodated through technology-based systems for collection, monitoring, and validation. Data processing will be conducted using big data technology with a simulation approach to accelerate the process. Frameworks and decision-making models capable of translating general standards and regulations need refinement to be practically applicable to railway vehicle applications, especially locomotives. Lastly, to justify the implementation of RAMS analysis that can result in overall cost efficiency in the locomotive system life cycle, an LCC analysis needs to be conducted.

**CONCLUSION**

A comprehensive review of several studies on the implementation of RAMS analysis in railway vehicles has been conducted and discussed in this article. Overall, the implementation of RAMS analysis can help improve performance (reliability, availability, and maintainability), safety, and cost-effectiveness throughout the life cycle of railway vehicles.

Many researchers tend to focus only on the operational and maintenance phases, while very few discuss the entire life cycle from concept to disposal from the perspectives of performance, safety, and cost-effectiveness. Moving forward, the implementation of RAMS analysis will be focused on refining the framework and decision-making models derived from established standards and regulations. Additionally, improving the real-time data collection, monitoring, validation, and processing systems is crucial in the implementation of RAMS analysis. Data availability should involve various stakeholders from suppliers, operators, and consumers as system users to cover the entire stages from concept to disposal. LCC analysis needs to be added as justification for the cost efficiency resulting from the implementation of RAMS analysis. Conducting case studies on locomotives in Indonesia would be an appropriate initial step to demonstrate the effectiveness of this approach.

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