A Review of RAMS Analysis Application on Railway System

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Abstract

Railway systems play a crucial role in transportation infrastructure, requiring high levels of reliability, availability, maintainability, and safety (RAMS) to ensure efficient and safe operations. This contribution is an attempt to provide an overview of past and current research on the application of RAMS to railway systems which, is broadly summarized into three review groups; (1) review of RAMS applications on railway networks, (2) review of RAMS applications on railway rolling stock, and (3) review of RAMS applications on railway infrastructure. Based on the review results, the use of probabilistic criteria is widely used to calculate reliability, availability is calculated using maintenance parameters of the system, while maintainability is calculated based on reliability parameters and failure rates. For safety, it is obtained based on the characteristics of the research object of each study. In the end, it is expected that methods from previous studies can be used as a reference for the application of RAMS to the railway system in Indonesia.

Keywords: *Availability, Maintainability, Railway System, Reliability, Safety*

1. Introduction

The railway system can be described as a cohesive and integrated system, which encompasses not only the physical infrastructure and rolling stock, but also the human resources and the various norms, criteria, requirements, and procedures that are essential for the successful implementation of railway transportation [1]. This system has existed since the 19th century and continues to develop today. In the railway system, trains can be used for various purposes, such as for the transportation of passengers, and goods, or even for military purposes where rails are used as the path of movement. The railway system has several advantages, including being able to transport many passengers or goods at once, being efficient in fuel use, and reaching a fairly high speed. In addition, it can also reduce congestion on roads and help reduce air pollution. However, as with other transportation systems, the railway system also has some disadvantages, such as high investment costs, intensive maintenance needs, and limited available lines. With these weaknesses, an efficient and effective railway management system is needed to improve the railway system's performance, both from a technical and non-technical perspective.

The implementation of RAMS (Reliability, Availability, Maintainability, and Safety) for railway management systems is crucial. In 1999, the European Union implemented the EN 50126 standard which aimed to restrict railway accidents and promote the security of railway activities for the entirety of the system's life cycle [2]. The concept of RAMS comprehends four principal aspects, specifically those of reliability, availability, maintainability, and system safety. In this regard, the reliability of the railway system ensures that it operates according to expected specifications and performance, the availability of the system ensures that the railway system is always available and can be used to the best of its ability, the maintainability of the system ensures that the railway system is easily repaired and routinely maintained, and the system's safety ensures that the railway system is safe for all users [3].

Many railway organizations have implemented RAMS in their business activities. This is in line with numerous studies and implementations related to the application of RAMS to railway systems, which consist of various types of reviews, ranging from reliability only, reliability and availability, and even those that review the overall aspects of RAMS. All of these are adjusted to the needs of a railway organization, or the occurrence of specific problems related to railway assets that require certain specific studies. For example, from the infrastructure aspect of railway tracks, research has been conducted on the reliability of railway track maintenance operations [4], availability approaches for railway track renewal operations operations [5], and reliability based on availability factors for railway joints and crossings [6]. Regarding reliability, availability, and maintainability (RAM), [2] has undertaken a comprehensive study on the track geometry as well as the various railway track components. Research on signaling aspects are related to signaling safety assessment [7], availability analysis of railway track circuits [8], and how to improve the reliability and availability of track switching [9]. Meanwhile, the safety and availability evaluation of railway signaling systems has been studied by [10]. From the rolling stocks aspect, the reliability and availability of locomotive bogies have been studied by [11], while the reliability of freight car bogies has been studied using the FMECA method by [12]. Then, [13]-[14] studied the reliability, availability, and maintainability of diesel locomotives. Furthermore, from the operational aspect of railway systems, a railway network model has been developed using RAMS analysis to improve the safety and stability of railway network operations [15]. The balance between network availability for railway operations and track construction activities has also been studied by [16]. Analytical models for reliability assessment have also been conducted by [17] to predict the reliability and unreliability of railway subsystems. On the other hand, RAMS development has been conducted by [18] by adding additional parameters that are specifically related to railways. Therefore, if RAMS studies are applied properly to management, they will result in a reliable railway system, effective and efficient maintenance, and optimal asset life cycle cost (LCC).

The relationship between RAMS and LCC is very close because RAMS directly affects the total lifecycle cost (LCC) of a system. The reliability, availability, and maintainability of a system directly influence maintenance costs, component replacement costs, and repair costs, all of which are important factors in calculating the LCC of a system. The integration of RAMS and LCC approaches can help determine the Key Performance Indicators (KPIs) of a system so that the system's performance can be known and used as a consideration in decision-making throughout the system's lifecycle [19].

The purpose of this literature review is to review, summarize, and compile research that has been conducted on RAMS analysis in railway systems. The railway system discussed in this paper relates to infrastructure, rolling stocks, and railway network operations. This review is expected to serve as a guide and reference for further application and development in railway asset management, especially for railways in Indonesia. The systematic review will be presented as follows: (1) RAMS application in railway network operation, (2) RAMS application in railway rolling stock, and (3) RAMS application in railway infrastructure.

2. Methodology

This research was conducted by exploring existing journals as references by comparing the methods and results of each journal. Each journal is analyzed related to the RAMS method, starting from reliability, availability, maintainability, and safety, then compared with the results obtained and the effectiveness of the method used for application in a case study. After getting methods from each aspect of RAMS, then used as a reference in choosing which methods can be applied in the future to be used on railways in Indonesia.

3. RAMS Review on Railway Systems

In this chapter, the author discusses the application of RAMS for each railway system review into sub-chapters, starting from network, rolling stock, and railway infrastructure. Each sub-chapter will be presented into each aspect of RAMS, starting from reliability, availability, maintainability, and safety to facilitate categorization.

3.1. Review RAMS Application in Railway Networks

The railway network is currently endeavoring to tackle the challenges that have arisen due to the increasing demands for capacity, speed, and mobility for the transportation of products and passengers. This complex system comprises various technologies and a diverse range of stakeholders [20]. The railway system is undergoing constant construction and development, resulting in a more vital temporal and spatial dynamic between the network and the organization of rail lines. However, the rapid growth has made operating and maintaining the entire railway network increasingly challenging. Additionally, the trains traveling between stations have created more complex relationships. In the event of a failure at a crucial station, the transportation efficiency of the entire network would be reduced [21]. Therefore, with RAMS analysis of the railway network, it will help railway organizations in determining the appropriate investments required to enhance safety management in each section and station of the railway network [15]. Doing so could increase the safety and resilience of the railway network's operation. In this section, the application of RAMS to the railway network operation that has been done previously by several researchers will be discussed which can be seen in Table 1.

Table 1. Journal Details and Aspects of RAMS Used for Railway Network

No	Study	Title	Year	Reliability	Availability	Maintainability	Safety
1	Jack Litherland et al. [18]	Development of an Extended RAMS Framework for Railway Networks	2019	✓	✓	✓	✓
2	Zhe Zhang et al. [15]	RAMS analysis of railway network: model development and a case study in China	2020	✓	✓	✓	✓

Reference [18] proposed that assessment framework has the potential to be leveraged by railway asset managers in order to allocate resources in a strategic manner to improve the railway network. The augmented RAMS framework encompasses a hierarchical structure consisting of four levels, which includes not only the conventional RAMS parameters but also supplementary parameters such as security, health, environment, economics, and politics (SHEeP). The methodology is being trialed on the TransPennine route, and if successful, it will be rolled out to other parts of the network. In reference [15], the focus was on a RAMS analysis method for operating railway networks, which takes into account the probability of failure for stations and sections, the anticipated loss of network availability resulting from such failures, and a safety index for assessing the safety of railway stations and sections. The proposed method is demonstrated through a real-world case study, revealing its capability to identify high-risk sections and stations and determine appropriate investments in safety management for each of them. Additionally, this study introduces a data-driven approach to examine network reliability, develops a safety index, and suggests potential applications of the proposed model to enhance the safety and resilience of railway network operations.

3.1.1. Reliability of Railway Networks

Reliability analysis by [18] is defined as the reliability of a component that can be calculated mathematically using the failure / hazard rate, $\lambda(t)$. It can be seen that the failure rate is related to reliability according to the following equation:

$$R(t) = e^{-\int_0^t \lambda(\tau)d\tau} \quad (1)$$

Reliability may be determined through the calculation of a constant failure rate as

$$R(t) = e^{-\lambda t} \quad (2)$$

However, if the failure rate is not uniform, it becomes necessary to employ statistical models, such as Weibull, Gamma, or Log-normal, to calculate reliability. In instances where the component can be repaired, the Mean time between failure (MTBF) is utilized and expressed in the following manner.

$$MTBF = \frac{Total\,Time - Total\,Down\,Time}{n} \tag{3}$$

where, n is the failures number. The railway network consists of many components. Therefore reliability analysis needs to be calculated as a system that consists of series and parallel systems. The system reliability for n components in a series can be calculated based on the assumption of component independence as

$$R^{s}_{sys}(t) = \prod_{i=1}^{n} R_i(t) \tag{4}$$

For n components in a parallel system, the system reliability can be expressed as follows:

$$R^{s}_{sys}(t) = 1 - \prod_{i=1}^{n} (1 - R_i(t)) \tag{5}$$

In the study [18], the number of service affecting failures (SAFs) that occur is the basis for calculating the reliability of the rail network, where SAFs are assumed to be: (1) independent, (2) cause complete failure of the system.

Assuming these two premises, the railway system can be represented as a series of interconnected assets without redundancy, and its reliability can be computed through standard methods outlined in (4). Given that the system consists of numerous components arranged in series, attaining a high level of reliability for a railway network is challenging.

Whereas, in [15], the physical network of the railway system can be characterized as G = (N, E), wherein the node $n \in$ N signifies the railway station while the link e ϵ E represents the railway lines that connect these stations. Assuming that the two adjacent railway stations are denoted by *i, j*, the railway line linking stations *i* and *j* can be represented by (*i, j*). The reliability of a rail network represents the probability of accident-free operation. Accident reports allow us to determine the number of accidents. Accidents can occur on both the up and down lines. Let P^{up}_{ij} and P^{down}_{ij} denote the accident probabilities on the up and down lines connecting neighboring stations *i* and *j*, respectively, and can be elucidated as follows.

$$P^{up}_{ij} = \frac{N^{up}_{ij}}{T}, P^{down}_{ij} = \frac{N^{down}_{ij}}{T} \tag{6}$$

where N^{up}_{ij} and N^{down}_{ij} represent the respective counts of accidents on the upward and downward lines, while T denotes the statistical time period.

Hence, the probability of failure for the railway segment (*i, j*) can be expressed as follows:

$$P_{ij} = P^{up}_{ij} P^{down}_{ij} \tag{7}$$

There are many tracks at the train station for the trains to run on. Let P^{k}_{i} be the accident probability of line *k* at station *i*. As a result, the railway station's failure probability may be expressed as:

$$P_i = \prod_{k=1}^{K} P^{k}_{i} \tag{8}$$

The railway network *G*'s reliability can be expressed as:

$$R_G = \prod_{i,j \in N} (1 - P_{ij}) \prod_{i \in N} \left(1 - P_i\right) \tag{9}$$

3.1.2. Availability of Railway Networks

Reference [18] has explained that the calculation of maintainability has not been accounted for in the study. This implies that the use of MTTF and MTTR is not feasible. However, an alternative approach to determine the availability is to consider the percentage of time that the network is unable to run full service. Hence, the calculation of availability can be derived by aggregating the downtime for all assets.

Whereas, reference [15] explained that from the viewpoint of a complex network, it is possible to examine the accessibility of railway network *G*. The availability of the railway network *G* is represented in this study by the network efficiency *E* and capacity *C*. Given the volume of traffic between stations, the G's railway network efficiency may be summarized as follows

$$E = \sum_{mn} \frac{u_{mn}}{d_{mn}} \tag{10}$$

where u_{mn} represents the number of trains commuting from station m to station n and d_{mn} signifies the least distance between station *m* and station *n, E'* may be utilized to denote the efficiency of the network in the event of a station or section malfunction. The deterioration of network efficiency can be explicated as follows:

$$\Delta E = \frac{E-E'}{E} \tag{11}$$

Then, the trains maximum number that may be put into the network is referred to as the network capacity. Because it can assess both directional and unidirectional networks, the I-O approach is utilized to gauge the railway network's capacity. Let x_{ij} represent the trains number between the nearby railway stations of i and j. Let X_j stand for the number of trains arriving at station j from other stations. The following is a description of the I-O matrix:

$$F_j^i = \frac{x_j^i}{X_j} \tag{12}$$

The trains number arriving at station j as follows:

$$X_j = \sum_{i=1}^{N-1} F_j^i X_i + \sum_{s=1}^{S} x_j^s = \sum_{i=1}^{N-1} F_j^i X_i + U_j \tag{13}$$

where x_j^s is utilized to represent the count of trains that originate from stations situated outside of the railway network and terminate at station j. (13) can be defined into matrix form as follows:

$$X = F^{(-i)}X + U \tag{14}$$

where the trains' total number departing from network stations is represented by U, whereas the trains' total number arriving at all network stations is represented by X. The network capacity can be defined as follows:

$$X = (1 - F^{(-n)})^{-1} U \tag{15}$$

If the train service along the stretch connecting stations u and v becomes inoperable, it would result in a modification of the network's capacity as:

$$X^{-(u,v)} = (1 - F^{(-i-(u,v))})^{-1} U \tag{16}$$

Therefore, network capacity loss ΔC can be expressed as follows:

$$\Delta C = \frac{\sum X - \sum X^{-(u,v)}}{\sum X} \tag{17}$$

3.1.3. Maintainability of Railway Networks

How quickly a system can be fixed after a failure and how much downtime ensues from the breakdown are measured by maintainability. The less complicated the system is to repair, the quicker the repairs may be completed and the shorter the downtime will be. On the railway network system, [18] proposed a method to calculate maintainability with the following equation:

$$M(t) = 1 - e^{\frac{-t}{MTTR}} \tag{18}$$

where $M(t)$ represents the probability that the specific component shall be rectified within the designated time frame t, $MTTR$ is the mean time to repair. The maintainability in this study will be calculated as the number of the hours spent on each of the planned and unplanned maintenance activities in Figure 1.

Furthermore, reference [15] explained that the accident reports have the recuperation time noted. Let ts and te stand for the accident's beginning and ending times. Maintenance M is defined as the ratio of the normal operation time to the total operation time of the railway network., which is expressed as follows

$$M = 1 - \frac{t_r}{t_0} \tag{19}$$

where $tr = te - ts$ and to represents the duration of operation for each day.

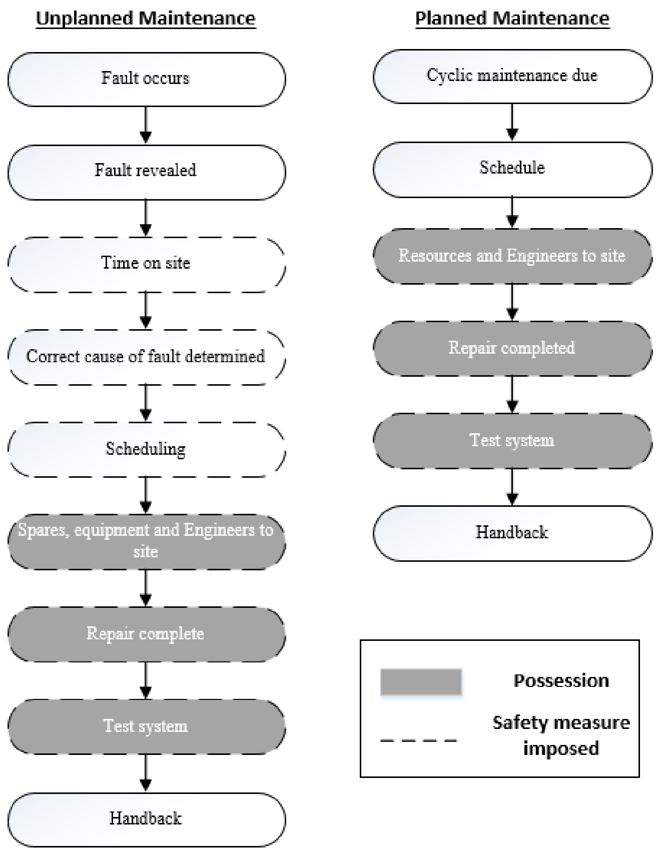

Figure 1. Maintenance Actions During Unplanned and Planned Processes

3.1.4. Safety of Railway Networks

Reference [18] explained that it is challenging to define a measure since there is no accepted concept of safety on the railway. The safety metric has to include a variety of direct and indirect safety components. Fatalities and Weighted Injuries (FWI) are a typical indicator of safety performance on UK railways. The "Safety Risk Model" and "Precursor Indicator Model" were created by NR and the Rail Safety and Standards Board (RSSB) to determine the likelihood of the "Top Event" and the consequent number of injuries and fatalities. In this study, these models will be utilized to evaluate the network's performance in terms of safety.

However, reference [15] explained that the possibility of an accident, the loss of availability, and maintenance (*M*) should all be taken into account when evaluating the safety or risk of the railway network. The accident consequence *S*, which may be used to gauge how safe a railway network is, is as follows:

$$S = (1 - R)\Delta A(1 - M) \tag{20}$$

where, S signifies the outcome of an accident, $(1 - R)$ represents the likelihood of an accident occurring within the railway network, ΔA signifies the magnitude of unavailability that would ensue in the absence of maintenance, (1 – *M*) denotes the impact of maintenance on ensuring operational safety. The network-scale safety, however, cannot account for the significance of each station's or section's safety. Consequently, equation (20) is derived based on the specific categories of section failure and station failure. When section (*i, j*) is disrupted due to operational accidents, the associated risk can be described in the following manner:

$$EL_{ij} = p_{ij}\Delta E(1 - M), CL_{ij} = p_{ij}\Delta C(1 - M) \tag{21}$$

where EL_{ij} denotes the expected loss of network efficiency and CL_{ij} denotes the expected loss of network capacity. If the station i is broken by the operation accidents, the risk can be described as follows:

$$EL_{i} = p_{ij}\Delta E(1 - M), CL_{i} = p_{ij}\Delta C(1 - M) \tag{22}$$

where EL_{i} denotes the expected loss of network efficiency and CL_{i} denotes the expected loss of network capacity.

Evaluating the safety of a section using (21) and (22) can yield varying results. To ensure a comprehensive evaluation, it is necessary to consider the loss of network efficiency and capacity when assessing the level of safety or each section or station grade. To accomplish this, the K-means method was utilized, a clustering method capable of classifying data into distinct groups, to identify critical sections and stations with regard to safety.

3.1.5. Summary of RAMS Application in Railway Networks

The review in this section obtained the following results which can be seen in the Table 2.

Table 2. Assessment Method for RAMS Used for Railway Network in Included Studies

No	Study	Reliability	Availability	Maintainability	Safety
1	Jack Litherland et al. [18]	MTBF, Statistical model	MTTF/(MTTF+MTTR)	MTTR	Fatalities and Weighted Injuries (FWI)
2	Zhe Zhang et al. [15]	Probabilistic Criteria	Network efficiency E, Network capacity C	Proportion of normal operation time	Possibility of an accident, loss of availability and maintenance

The findings indicate that the approaches employed in each examination for every facet of RAMS are not notably identical, given that every utilized technique is best suited for the particular research target of the respective study. In particular, Reference [18] employs a greater number of maintenance parameters to derive reliability, availability, and maintainability values, whereas [15] employs time and accident parameters to derive reliability, maintainability, and safety, and availability utilizes the capacity and efficiency parameters of a network.

3.2. Review RAMS Application in Railway Rolling Stocks

Railway rolling stocks are vehicles that can move on the railway track [1]. It is composed of multiple subsystems, including the car body, bogie, braking system, propulsion, and power supply [22]. A proficient and properly serviced rolling stock system is imperative for achieving the railway system's objective of enhancing performance. Nevertheless, the intricate structures and numerous components of the system pose a challenge to conducting an objective evaluation of its performance [23]. Therefore, applying RAM to railway rolling stock will make maintenance activities effective and optimize life cycle costs. In this section, the application of RAMS to rolling stock will be reviewed, where the references reviewed can be found in Table 3.

Table 3. Journal Details and Aspects of RAMS Used for Railway Rolling Stock

No	Study	Title	Year	Reliability	Availability	Maintainability
1	D. Bose et al. [24]	Measurement and Evaluation of Reliability, Availability and Maintainability of a Diesel Locomotive Engine	2013	✓	✓	✓
2	Maciej SzkodA [25]	Assessment of Reliability Availability and Maintainability of Rail gauge change system	2014	✓	✓	✓
3	Maciej SzkodA [13]	Analysis of reliability, availability and maintainability (RAM) of SM48 diesel locomotive	2014	✓	✓	✓

Reference [24] centers its attention on the reliability and availability facets of a noteworthy constituent within a diesel locomotive engine for railway applications. The application of the Weibull distribution was employed for reliability analysis, and an array of data plots and failure rate information were utilized to attain outcomes that are instrumental in mitigating unforeseen failures while enhancing the engine's reliability and availability. Then, reference [25] centers on conducting a comparative evaluation of the dependability of two distinct rail gauge replacement systems, namely, carriage bogie swapping and the SUW 2000 self-adjusting wheelset. This assessment is achieved by considering dependability as a comprehensive characteristic encompassing reliability, availability, and maintainability. The analysis results show that the SUW 2000 system has a higher failure rate than the bogie wagon exchange system with the average failures number in operation one year (MNF) for the SUW 2000 system more than twice as high as the bogie wagon exchange system. Meanwhile, reference [13] centers on conducting RAM analysis on SM48 diesel locomotives, drawing on operational tests administered on a particular subset of locomotives operated by the Polish railway company PKP CARGO S.A.The outcomes of the RAM analysis serve as a foundation for altering the maintenance cycle of the locomotives, while the reliability ratio established in the analysis can function as a cornerstone for Life Cycle Cost (LCC) analysis.

3.2.1. Reliability of Railway Rolling Stock

In reference [24], the railway diesel locomotive engine is divided into two main subsystems, that are compressor and vehicle and structures. In his study, the prediction of reliability, if the failure rate is constant, is the same as that of reference [18] on the railway network, as well as in calculating MTBF and MTTF.

Because the failure rate of locomotive components is not constant, the Weibull distribution model can be employed. Furthermore, the method of linear regression analysis verifies the appropriateness of utilizing the Weibull distribution for the different constituents of this study. The scrutiny establishes the optimal-fit line in the context of the least square approach. The least square test was conducted to ascertain the increasing/decreasing rate of failures.

The utilization of the Probability equation has facilitated the conduct of a linear regression analysis

$$R(x), f(x) = \frac{\Sigma[xf(x)] - \frac{(\Sigma x)[\Sigma f(x)]}{N}}{\sqrt{[\Sigma(x^2) - \frac{(\Sigma x)^2}{N}][\Sigma f(x^2) - \frac{\Sigma f(x)^2}{N}]}} \tag{23}$$

where, x: The duration of breakdowns, $f(x)$: The cumulative percentage of failures, N: trials number, $R(x), f(x)$: coefficient of correlation that can be seen in Table 4.

Table 4. Correlation Coefficient

Components's name	Coefficient of Correlation
Compressor	0.783
Vehicle and Stuctures	0.741

Weibull distribution can be expressed as follows:

$$f(t) = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (24)$$

where, η: life, β: Values of the shape factor. The shape of the distribution is determined by the beta (β) value.

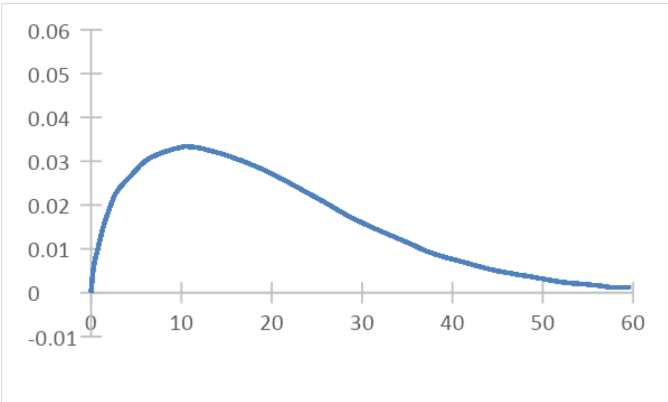

Figure 2. Weibull Distribution

The present examination has condensed its findings to the parameter of Weibull shape. This parameter, which is denoted by β, likewise functions as an indicator of whether the rate of failure is uniform, escalating, or declining. Specifically, when β equals 1.0, β exceeds 1.0, or β falls below 1.0, the corresponding implication is that the rate of failure remains consistent, amplifies, or reduces, respectively.

Reference [25] explained that calculating the reliability of elements, subsystems and systems using relevant reliability ratios. To enable a comparative analysis of the reliability of different systems, the MNF ratio was employed, which represents the average number of failures that occur during a year of operation. This particular ratio is explicitly defined as follows when applied to a singular component:

$$MNF_i = \left(\frac{H_i(t)}{T_i}\right). 8,760.0 \left[\frac{failures}{year}\right] \quad (25)$$

where, MNF_i: refers to the average number of failures experienced by element "i" during a year of operation. The renewal function of element "i" in the maintenance cycle is represented by $H_i(t)$, while T_i: denotes the duration of operation of element "i" in the maintenance cycle, expressed in hours.

For a subsystem, the total failures of failures mean number during a single year of operation is:

$$MNF_s = MNF_1 + MNF_2 + \dots + MNF_n = \left(\frac{H_1(t)}{T_1} + \frac{H_2(t)}{T_2} + \dots + \frac{H_n(t)}{T_n}\right). 8,760 \left[\frac{failures}{year}\right] \quad (26)$$

In the aforementioned formulation, the renewal function denoted as $H(t)$ is utilized. This function, under the assumption that the renewal period is considerably insignificant in comparison to the temporal extent of appropriate functioning of the subject entity, articulates the projected quantity of renewals that is equivalent to the failures number up until time t. Moreover, the renewal function is defined as follows:

$$H(t) = \sum_{n=1}^{\infty} F_n(t) \tag{27}$$

where, $F_n(t)$ is the distribution function characterizing the operation of the object until the n-th failure, which is subject to renewal.

Reference [13] expounds upon the methodology of determining the reliability ratio through the employment of the Weibull distribution. This statistical technique allows for the estimation of the parameters of the probability density function concerning the duration of proper operation before failure. The formula for said calculation is as follows:

$$f(t) = \left(\frac{a}{b}\right)\left(\frac{t}{b}\right)^{a-1} e^{-\left(\frac{t}{b}\right)^{a}} \tag{28}$$

And the function that represents the cumulative distribution of time elapsed until system failure has been derived:

$$F(t) = 1 - exp\left(-\frac{t}{b}\right)^{a} \tag{29}$$

Meanwhile, the mean time to failure is computed using the appropriate operational distribution function, expressed as:

$$MTTF = \int_{0}^{\infty} t.f(t)dt \tag{30}$$

Furthermore, the mean time between failures for the locomotive is determined using the distribution function of the time between failures, formulated as follows:

$$MTBF = \int_{0}^{\infty} t.f_k(t)dt \tag{31}$$

3.2.2. Availability of Railway Rolling Stock

Reference [24] defines availability as the likelihood that the system is functioning appropriately upon request for utilization which can be expressed in three types depending on consideration of the time elements.

(1) Inherent Availability

This concept pertains to the likelihood of a system or equipment functioning adequately when utilized within specified circumstances in an optimal support setting, without factoring in any scheduled or preventative maintenance at any point in time. Its mathematical representation is as follows:

$$A_{IN} = \frac{MTBF}{(MTBF+MTTR)} \tag{32}$$

(2) Achieved Availability

This is a measure of the likelihood that a specific system or equipment will function effectively when utilized in prescribed conditions within an optimal support environment, at any given moment. Such probability can be denoted as:

$$A_a = \frac{MTBM}{(MTBM+MDT)} \tag{33}$$

where, MTBM refers to the average duration of active maintenance downtime that arises from both preventive and corrective maintenance procedures.

(3) Operational Availability

Operational availability is defined as the likelihood of a system or equipment functioning acceptably in accordance with specified conditions and within a real supply context at any given moment. This metric can be articulated as follows:

$$A_{OP} = \frac{MTBF}{(MTBF+MDT)} \tag{34}$$

Furthermore, reference [25] assuming that each and every constituent element functioning within a given system is depicted through probability distribution functions of the same nature, with respect to both the operation duration and restoration, the system availability, denoted as A(t), can be represented by the ensuing function

$$A(t) = 1 - F(t) + \int_0^t [1 - F(t - \tau)]h(\tau)d\tau \tag{35}$$

where, $h(t)$: renewal density function : $h(t) = \frac{H(t)}{dt}$

The aforementioned equation is infrequently utilized in practical applications due to its significant level of computational intricacy. Usually, the technical availability ratio, which represents the average duration when the system in question is operational, is commonly used instead.

$$A(\infty) = A(t) \tag{36}$$

The availability ratio denotes the mean technical availability throughout the maintenance cycle, particularly between successive maintenance (revision) events of the scrutinized entities. The availability ratio of an individual entity is articulated as follows:

$$A_i = \frac{TZ_i}{TZ_i+TN_i+TO_i} \tag{37}$$

where:

TZ_i: average duration of availability for item "i" (in hours).

TN_i: average duration of unavailability for item "i" caused by corrective maintenance (in hours).

TO_i: average duration of unavailability for item "i" resulting from preventive maintenance activities (in hours).

In reference [13], the ratio of operational availability Ao and the ratio of actual availability A_R were used. The operational availability ratio can be expressed as follows:

$$A_o = \frac{TZ}{TZ+TN} \tag{38}$$

Meanwhile, the actual availability ratio was defined as:

$$A_R = \frac{TZ}{TZ+TN+TO} \tag{39}$$

TO denotes the mean duration of locomotive immobilization during scheduled downtimes and upkeep operations amidst consecutive revisions, which can be mathematically represented as follows

$$TO = \sum(PU_i . MTTR_i) \tag{40}$$

where:

PU_i: count of scheduled downtimes or activities of maintenance

$MTTR_i$: average duration of scheduled downtimes or maintenance activities.

3.2.3. Maintainability of Railway Rolling Stock

Reference [24] establishes a correlation between maintainability and maintenance strategies, based on which several novel strategies have been deployed as maintenance strategies aimed at mitigating equipment breakdown-related concerns. A few of the widely used maintenance strategies include:

Table 5. The Strategy of Maintenance

Maintenance Strategy	Maintenance Approach	Signification
Corrective	Fix it when broke	Large maintenance budget.
Preventive	Scheduled Maintenance	Peplacement of periodic component
Predictive	Condition based Monitoring	Maintenance decision based on equipment condition.
Proactive	Failures sources detection	Failure correcting root causes and monitoring

Reference [25] explained the utilization of mean maintenance time (MMT) in a year of operation. This variable encompasses the entirety of time allocated towards corrective and preventive maintenance of a system and is utilized to compare system maintainability. This ratio is defined as follows for one element:

$$MMT_i = \left(\frac{\left(H_i(t).MTTR_{Bi}\right)+\left(NPMA_{Pi}.MTTM_{Pi}\right)+\left(NPMA_{Ni}.MTTM_{Ni}\right)}{T_i}\right).8,760.0\left[\frac{hrs}{year}\right] \quad (41)$$

where:
$H_i(t)$: function of renewing element "i" within the maintenance cycle.
$MTTR_{Bi}$: average duration required to restore element "i" (in hours).
$NPMA_{Pi}$: quantity of scheduled maintenance activities performed on element "i" within the maintenance cycle.
$MTTM_{Pi}$: average duration required to conduct periodic inspections for element "i" (in hours).
$NPMA_{Ni}$: quantity of maintenance activities for revising element "i" within the maintenance cycle.
$MTTM_{Ni}$: average duration required to perform maintenance revisions on element "i" (in hours).
T_i: duration of element "i" being in operation within the maintenance cycle (in hours).
The total average maintenance time for a subsystem during a year of operation is:

$$MMT_s = MMT_1 + MMT_2 + \ldots + MMT_n\left[\frac{hrs}{year}\right] \quad (42)$$

Meanwhile, reference [13] explain that the evaluation of the maintainability of the SM48 locomotive encompasses both planned and preventative maintenance efforts conducted throughout its maintenance regimen. The distribution function G(t) for renewal time, both empirical and theoretical, as well as the average time required for repair (MTTR), has been established about scheduled maintenance. The MTTR encompasses both repair time and the technical delays incurred during diagnostic procedures and the procurement of spare parts. The locomotive renewal time cumulative distribution function as follows:

$$G(t) = 0.5\left(1 + \Phi\left(\frac{Ln(t)-a}{\delta\sqrt{2}}\right)\right).\ for\ t > 0 \quad (43)$$

where:

$$\Phi(z) = \frac{2}{\sqrt{\Pi}}\int_0^z \exp exp\left(-t^2\right)dt \ \square \text{ Gauss distribution function} \quad (44)$$

The renewal time distribution function has been utilized to determine the mean renewal time, as follows:

$$MTTR_B = exp\left(a + \frac{\delta^2}{2}\right) \quad (45)$$

3.2.4. Summary of RAMS application in railway rolling stock

The review in this section obtained the following results which can be seen in the Table 6.

Table 6. Assessment Method for RAMS Used for Railway Rolling Stock in Included Studies

No	Study	Reliability	Availability	Maintainability
1	D. Bose et al. [24]	Statistical model (Weibull)	MTBF, MTTR, MTBM, MDT	Common maintenance strategy
2	Maciej SzkodA [25]	Mean number of failures (MNF)	Probabilistic criteria, $A_i = \frac{TZ_i}{TZ_i + TN_i + TO_i}$	MTTR, MTTM
3	Maciej SzkodA [13]	Statistical model (Weibull)	$A_R = \frac{TZ}{TZ + TN + TO}$	Distribution function, MTTR

The findings indicate that the Weibull distribution is extensively employed for reliability computation owing to the non-constant failure rate of railway systems, necessitating the adoption of an appropriate approach for obtaining the reliability value. Moreover, nearly all maintenance criteria are utilized for achieving availability and maintainability as a consequence of reliability.

3.3. Review RAMS Application in Railway Infrastructure

Railway infrastructure generally consists of railways track, railway stations, and railway operating facilities [1]. In this section, a review of the application of RAMS to railway infrastructure will be discussed from the research that has been conducted. The RAMS journals of railway infrastructure reviewed by the author will be more related to railways track because many previous studies have discussed these topics. Not all the research journals in apply all aspects of RAMS to their analysis. Therefore, the authors have divided each study according to the reviewed aspects and the details of the research journals can be seen in Table 7.

Reference [26] focused on implementation of the EN 50126 standard and the use of RAMS analysis techniques can improve the safety and reliability of railway systems. The investigation carried out on the railway system in Uzbekistan demonstrates that the implementation of RAMS analysis can be effectively employed to discern potential hazards and enhance the efficacy of maintenance and restoration endeavors on railway systems. Reference [19] focused on rail performance assessed by incorporating life cycle cost (LCC) and availability, maintainability, and safety (RAMS) approaches into key performance indicators (KPIs). These KPIs can quantitatively influence decision-making throughout the railway lifecycle (design, maintenance, and renewal). Reference [2] has directed its focus toward the application of Reliability, Availability, and Maintainability (RAM) analysis in the context of railway infrastructure management. The study incorporates a case study of the high-speed ballasted railway line between Tashkent and Sirdaryo railway stations in Uzbekistan. The study's objective is to identify the individual reliability level of infrastructure parameters and system reliability level for IL (Intervention limit), and IAL (Immediate action limit) limits. The study's results indicate that the individual reliability level of infrastructure parameters ranges from 62% to 89% for IL and IAL limits. However, the system reliability level is found to be between 13% and 68% for IL and IAL limits, respectively. This implies that any issue arising with one of the infrastructure parameters necessitates a restriction or closure of railway line operations. This study shows that periodic planned and corrective maintenance methods are preferable for Uzbekistan's railways. Reference [27] conducted a comprehensive analysis of reliability, availability, maintainability, and safety (RAMS) applications in the railway industry. Subsequently, a novel framework referred to as extended RAMS (ExRAMS) was proposed for railway infrastructure, which integrates diverse RAMS analysis approaches employed in the railway sector into a unified approach. The ExRAMS framework comprises ten parameters arranged in a four-level hierarchy for evaluating RAMS performance. The framework facilitates railway asset managers in assessing the attributes and current state of the railway infrastructure, comparing different network components, and evaluating the requirements of various stakeholders.

Table 7. Journal Details and Aspects of RAMS Used for Railway Infrastructure

No	Study	Title	Year	Reliability	Availability	Maintainability	Safety
1	Hidirov and Guler [26]	Railway Infrastructure Reliability, Availability,	2017	✓	✓	✓	

		Maintainability and Safety (RAMS) analysis					
2	Praticò and Giunta [19]	Proposal of a Key Performance Indicator for Railway Track Based on LCC and RAMS Analyses	2018	✓	✓	✓	✓
3	Hidirov and Guler [2]	Reliability, availability, and maintainability analyses for railway infrastructure management	2019	✓	✓	✓	
4	Litherland et al. [27]	An alternative approach to railway asset management value analysis Application to a UK railway corridor	2021	✓	✓	✓	✓

3.3.1. Reliability of Railway Infrastructure

From the findings in this journal review, almost all studies discuss reliability. References [2], [19], [26], and [27] have examined the track system side. The study conducted by [26] on reliability commences with the assessment of the railroad track, wherein each track component is scrutinized based on predetermined threshold values. Subsequently, the evaluation is conducted at the levels of the analysis segment and maintenance segment. The statistical analysis of the data gathered from the measuring instruments is performed, and this includes the determination of the type of reliability function and its coefficients. The approach adopted is akin to the computation of the railway network and rolling stock's reliability probability, as demonstrated in references [18] and [24], which employ the failure rate (λ) as a parameter.

The work of [19] utilizes reliability measures that are expressed through the mean time between failures (MTBF) and mean distance between failures (MDBF), both of which are indicative of failure rates. It has been observed that the values of MTBF and MDBF tend to decrease as the traffic load increases. Concerning MTBF and MDBF, the outcomes indicate:

$$MTBF = 1 - \frac{a_1 - b_1 . e^{-\frac{MGT}{\tau_{1n}}}}{c_1 - d_1 . e^{-\frac{MGT}{\tau_{1d}}}} \tag{46}$$

$$MDBF = 1 - \frac{a_2 - b_2 . e^{-\frac{MGT}{\tau_{2n}}}}{c_2 - d_2 . e^{-\frac{MGT}{\tau_{2d}}}} \tag{47}$$

where MGT = traffic expressed in millions of gross tons, $a_1 = b_1 = c_1$ and $a_2 = b_2 = c_2$, while τ_{in}, τ_{id}, a_i, b_i, c_i, and d_i are the calibration factor coefficients.

$$MGT = MGT_R + MGT_T . \alpha \tag{48}$$

where MGT_R = total traffic accumulated since the last restoration, MGT_T = Total accumulated traffic resulting from the construction, and α = coefficient that accounts for minor effects. From (46) and (47), reliability is defined as

$$R = \sqrt{MTBF . MDBF} \tag{49}$$

For the reliability analysis of the study conducted by [2], several statistical programs were employed to fit the distribution to both track geometry and track data components. The fit test methods, including Chi-square, Kolmogorov-Smirnov, Anderson-Darling, and Shapiro-Wilk, were utilized to derive a distribution function that conforms to the collected data set. Concerning track geometry, it was discovered that the Gumbel Max distribution is exceptionally well-suited to the twisting data set, while the four-parameter Burr (4P) distribution is appropriate for the gauge data set, and the three-parameter Dagum (3P) distribution proves suitable for the alignment, cant, and leveling data sets. The Gumbel Max (Maximum Extreme Value Type 1) probability density function (pdf) is provided as follows:

$$f(x) = \frac{1}{\sigma}\exp exp\,(-\ z\ -\ \exp exp\,(-\ z)\,) \tag{50}$$

where x is independent variable, σ is continuous scale parameter ($\sigma\ >\ 0$) and μ is continuous location parameter. x is between $-\ \infty\ <\ x\ <+\ \infty$ and $z\ =\ \frac{x-\mu}{\sigma}$. The Gumbel Max (Maximum Extreme Value Type 1) cumulative distribution function (*cdf*) is given by

$$F(x) =\ \exp exp\,(-\ \exp exp\,(-\ z)\,) \tag{51}$$

The provided equation represents the probability density function (pdf) of the three-parameter Dagum distribution:

$$f(x) = \frac{\alpha k\left(\frac{x}{\beta}\right)^{\alpha k-1}}{\beta\left(1+\left(\frac{x}{\beta}\right)^{\alpha}\right)^{k+1}} \tag{52}$$

where x is independent variable, k is continuous shape parameter ($k\ >\ 0$), α is continuous shape parameter ($\alpha\ >\ 0$) and β is continuous scale parameter ($\beta\ >\ 0$). The three-parameter Dagum cumulative distribution function (*cdf*) is given by

$$F(x) = \left(1\ +\ \left(\frac{x}{\beta}\right)^{-\alpha}\right)^{-k} \tag{53}$$

The four parameters Burr density function (*pdf*) is given by

$$f(x) = \frac{\alpha k\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1}}{\beta\left(1+\left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right)^{k+1}} \tag{54}$$

where x is independent variable, k is continuous shape parameter ($k\ >\ 0$), α is continuous shape parameter ($\alpha\ >\ 0$) and β is continuous scale parameter ($\beta\ >\ 0$) and γ is continuous location parameter ($\gamma\ =\ 0$ yields the three-parameter Burr distribution). The four-parameters Burr cumulative density function (*cdf*) is given by

$$F(x) =\ 1\ -\left(1\ +\ \left(\frac{x-\gamma}{\beta}\right)^{\alpha}\right)^{-k} \tag{55}$$

Based on the study results, the cumulative density function is a factor considered to determine the reliability of track geometry parameters. The resulting reliability function can be used to calculate the reliability level of each track geometry parameter following the established railway organization limits.

For track components, reference [2] conducted a study of rails, sleepers, and ballast layers. The measurement and damage criteria for track components refer to Uzbekistan Railways regulations, namely for rail damage head-loss and gauge face wear has a maximum limit of 18 mm. The sleepers are defined into three damages: damaged sleepers, cracked sleepers, and broken sleepers, with cracking criteria below 0.2 mm, between 0.2 and 1.0 mm, and above 1.0 mm. As for the ballast layer, the damage criteria are defined as the fouling characteristics and strain-shear modulus of clean and dirty ballast. Such ballast fouling can cause degradation of the ballast layer and ballast elastic modulus.

The three components were evaluated using the Johnson SB distribution method for reliability analysis. The Johnson SB distribution is considered to be a better fit for the damage data obtained compared to other statistical methods. The mathematical definition of the Johnson SB (Maximum Extreme Value Type 1) distribution function for the probability density function (*pdf*) is given by

$$f(x) = \frac{\delta}{\lambda\sqrt{2\pi}z(1-z)}exp\left(-\ \frac{1}{2}\left(\gamma\ +\ \delta\ln ln\left(\frac{z}{1-z}\right)\right)^{2}\right) \tag{56}$$

where x is the variable of independent, γ is continuous shape parameter, δ is continuous shape parameter ($\delta\ >\ 0$), λ is continuous scale parameter ($\lambda\ >\ 0$) and ζ is continuous location parameter. x

is between $\zeta \leq x \leq \zeta +$ and $z = \frac{x-\zeta}{\lambda}$. The Johnson SB (Maximum Extreme Value Type 1) cumulative distribution function (*cdf*) is given by

$$F(x) = \Phi\left(\left(\gamma + \delta \ln ln\left(\frac{z}{1-z}\right)\right)\right) \quad (57)$$

where the Laplace Integral, denoted as Φ, is utilized in determining the cumulative density function, which is a crucial factor in assessing the reliability of track component parameters.

From the reliability of track components and track geometry, the system's overall reliability, either in series or in parallel, is calculated. The overall reliability for a series system is defined as follows:

$$R_i = \prod_j^n r_{ij} \quad (58)$$

The overall reliability for parallel systems is defined as follows:

$$R_i = 1 - \prod_j^n (1 - r_{ij}) \quad (59)$$

where R_i: i^{th} section overall reliability, r_{ij}: j^{th} component reliability at i^{th} section, n: component number.

The mathematical definition of reliability analysis, as presented by [27], is the component or system probability to continue functioning from its initial time to a certain time τ, provided that it was time zero operational. This probability can be determined using formula:

$$R(t) = \int_t^\infty f(x)dx \quad (60)$$

where f (x) is the distribution of failure times of probability density function.

Due to the lack of independence among numerous components, the analytical determination of $f(x)$ is often impractical in railway systems. Moreover, numerous interdependent components are arranged in series and parallel, making it impractical to calculate reliability using conventional methods. As a result, railway asset managers resort to various metrics to describe their system's reliability, none of which adhere to the mathematical definition presented in (60). Reference [27] introduces two metrics that can evaluate the railway system reliability: number of service-affecting failures (SAFs) and mean time between SAFs.

3.3.2. Availability of Railway Infrastructure

The demand for higher availability in railway operations is constantly increasing, and the availability of railway systems and subsystems significantly impacts the overall operational availability [28]. In railway systems, enhancing the availability of infrastructure is a crucial objective, as accidents or incidents often result in substantial losses. Availability refers to a system's capacity to execute a necessary function under specified conditions at a particular moment [29]. The application of RAMS on railways related to availability will be discussed in this section.

Reference [26] formulates availability as the period when a line can be opened or closed for operation. Below is the mathematical representation of the availability analysis:

$$A_i = \frac{T_i}{T_i + t_i} \quad (61)$$

where A_i is the availability, T_i is the total time (365 days), dan t_i is the time the line is closed for operation (days).

Suppose availability is analyzed under sub-headings such as line inspection time (Ao^T), defect detection time (Ao^K), required material supply time (Ao^M), and correction time (Ao^D). In that case, the average availability equation (Ao) is expressed as follows.

$$A_o = Ao^T . Ao^K . Ao^M . Ao^D \qquad (62)$$

The study conducted by [19], indicates that the availability (A) of railway systems is subject to the influence of the mean time between failures (MTBF) and the duration required for repairing a track post a failure occurrence. To assess the reliability, availability, maintainability, and safety (RAMS) components, it is imperative to measure the mean time to repair (MTTR). The MTTR is contingent upon various external maintenance resources, such as competent personnel, advanced tools and technologies, and specialized expertise. A higher number of maintenance personnel and tools, along with their skill levels, translates into a higher availability. Additionally, the availability is also impacted by traffic volume, which results in a decrease as the traffic increases. The proposed model employs the normalization of MTTR through the utilization of a function as follows:

$$MTTR = 1 - \frac{a_3 - b_3 . e^{-\frac{ER}{\tau_{32n}}}}{c_3 - d_3 . e^{-\frac{ER}{\tau_{3d}}}} \qquad (63)$$

where ER = the coefficient which considers the contribution of external resources, $a_3 = b_3 = c_3$, while $\tau_{3n}, \tau_{3d}, c_3, d_3$, are calibrate coefficients. Under certain assumptions, the availability can be expressed as follows:

$$A = \frac{MDBF}{MDBF + MTTR} \qquad (64)$$

Similarly to reference [26], reference [2] calculates availability using the time the line is open and closed for operation. However, when there are multiple reasons (n) for intervention, such as defect detection, material supply, and correction, the overall operational availability (A) is represented by the following equation:

$$A = \prod_{i}^{n} A_i \qquad (65)$$

If the system is defined as a series, then the overall availability is:

$$A_i = \prod_{i}^{n} a_{ij} \qquad (66)$$

For parallel system overall availability is:

$$A_i = 1 - \prod_{j}^{n} (1 - a_{ij}) \qquad (67)$$

where A_i: i^{th} section Overall availability, a_{ij}: j^{th} component availability at i^{th} section, n: component number.

Based on the study by [27], the availability is determined by calculating the mean time to failure (MTTF) based on reliability and the mean time to repair (MTTR) based on maintainability.

$$Availability = \frac{MTTF}{MTTF + MTTR} \qquad (68)$$

This measurement is suitable for systems that exhibit a binary state (operational or failed) and where the comprehensive understanding of component or asset failure impact on the system is considered.

3.3.3. Maintainability of Railway Infrastructure

Maintainability is a term that denotes the ability of an object to be conserved or rejuvenated to a state where it can function as necessitated under particular conditions of operation and upkeep. [30]. Furthermore, it will be discussed related to the study of the application of maintainability in railway infrastructure that has been carried out by previous researchers.

Reference [26] explained that maintenance activities carried out at a certain time are calculated to keep the line at the expected quality. The Poisson distribution is used in obtaining the probability of maintenance activities, which is as follows.

$$P(x) = \frac{(\lambda T_i)^x . e^{-\lambda T_i}}{x!} \tag{69}$$

where, $P(x)$: the probability of the desired amount of maintenance in a given period, λ: the amount of maintenance performed in the selected period, T_i: the desired period (365 days), dan x: the probability of occurrence of the required amount of maintenance.

Reference [19] explained that maintainability of a system is affected by two factors: the amount of traffic it receives (which reduces maintainability as traffic increases) and the time required for repairs, which is linked to the resources available for the task. Maintainability is defined by the following equation:

$$M = \sqrt{MTBM.(1 - MTTR)} \tag{70}$$

Mean time between maintenance (MTBM) is assumed to be a traffic function as follows:

$$MTBM = 1 - \frac{a_4 - b_4 . e^{-\frac{MGT}{\tau_{4n}}}}{c_4 - d_4 . e^{-\frac{MGT}{\tau_{4d}}}} \tag{71}$$

where $a_4 = b_4 = c_4$, while τ_{4n}, τ_{4d}, c_4, d_4, are coefficients to calibrate.

From reference [2], it can be inferred that probability distribution functions hold significant value in the realm of maintenance analysis. The Poisson distribution is a frequently utilized discrete probability distribution, as demonstrated in reference [26], however, in this study it is explained if the system is defined as a series, then the overall maintainability is:

$$M_i = \prod_i^n m_{ij} \tag{72}$$

For parallel system overall maintainability is:

$$M_i = 1 - \prod_j^n (1 - m_{ij}) \tag{73}$$

where M_i: i^{th} section overall maintainability, m_{ij}: j^{th} subsection maintainability in i^{th} section, n: subsections number.

According to a study conducted by [27], the concept of maintenance can be precisely described mathematically as the probability that a component or system will be fully functional within a specified time interval. This approach is analogous to the approach adopted by reference [18] when analyzing the railway network.

3.3.4. Safety of Railway Infrastructure

Safety is the absence of unacceptably high risk [30]. Safety depends on track structure and geometry, train traffic, and speed [19]. It also depends on maintainability. Train accidents are dominated by track defects. Defects can be categorizes into structural failures (rails, fasteners, sleepers, and ballast) and track geometry failures (alignment and gauge). This equation can be used to represent safety:

$$S = \sqrt[4]{1 - \frac{a_5 - b_5 . e^{-\frac{V}{\tau_{5n}}}}{c_4 - d_4 . e^{-\frac{V}{\tau_{5d}}}} . M.TS.SE} \tag{74}$$

where, *M* is maintainability, *TS* is the track safety correlated with the speed effect (*SE*) which is defined as:

$$TS = \frac{K}{100} \tag{75}$$

where K is the coefficient, which, depending on the track's circumstances, can range from 0 to 100. The normalized safety of the track (S) is affected by high K (ideal circumstances, TS close to 1) and low K (unsatisfactory conditions, TS close to 0). The SE looks like this:

$$SE = 1 - \frac{a_5 - b_5.e^{-\frac{V}{\tau_{5n}}}}{c_4 - d_4.e^{-\frac{V}{\tau_{5d}}}} \tag{76}$$

where, V is line speed in km/h, $a_5 = b_5 = c_5$, while τ_{5n}, τ_{5d}, c_5, d_5, are coefficients to calibrate.

The management of a railway infrastructure manager (IM) places utmost importance on safety, as per the findings of reference [27]. To evaluate safety performance, several performance indicators can be utilized, including persons seriously injured and killed, significant accidents, suicides, and attempted suicides, as well as workforce accidents. The hazardous events, identified by the RSSB are considered within the safety parameter. The proposal suggests evaluating the outcome of each hazardous event in relation to the fatalities and weighted injuries (FWI) index. Under the FWI index, a fatality is assigned a score of 1, a major injury is assigned a score of 0.1, and a minor injury is assigned a score of 0.05. Safety is evaluated as the projected number of FWI per year per kilometer.

3.3.5. Summary of RAMS Application in Railway Infrastructure

The review in this section obtained the following results which can be seen in the Table 8.

Table 8. Assessment Method for RAMS Used for Railway Infrastructure in Included Studies

No	Study	Reliability	Availability	Maintainability	Safety
1	Hidirov and Guler [26]	Probabilistic criteria	$A_i = \frac{T_i}{T_i + t_i}$	Probabilistic criteria (Poisson)	
2	Praticò and Giunta [19]	MTBF. MDBF	MDBF, MTTR	MTTR, MTBM	Maintainability, Track Safety (TS), Speed Effect (SE)
3	Hidirov and Guler [2]	Probabilistic criteria	$A_i = \frac{T_i}{T_i + t_i}$	Probabilistic criteria (Poisson)	
4	Litherland et al. [27]	SAFs, mean time between SAFs	MTTF, MTTR	Probabilistic criteria, MTTR	Fatalities and Weighted Injuries (FWI)

The findings indicate that probabilistic standards are commonly employed to derive dependability due to the variability in the frequency of infrastructure failures. Thus, this approach is deemed appropriate for determining the reliability of a system. It is worth noting that infrastructure is tantamount to maintenance undertakings aimed at preserving dependability, and hence, maintenance standards serve as the principal benchmark for determining the availability. Consequently, probabilistic standards are extensively utilized to achieve maintainability since maintenance activities are intricately linked to the possibility of a system breakdown. With respect to the safety facet, the methodology is tailored to suit the object of inquiry, and hence, the approach utilized differs across studies.

4. Results and Discussions

From the review of several papers on the application of RAMS to railway systems, it is found that to calculate reliability if the failure rate is constant, equations (1) and (2) can be used for all systems, in this case, the railway network, rolling stock, or infrastructure. However, if the failure rate is not constant, then a statistical model is more suitable to be applied which will be fitted to get which model is most suitable for a system or component.

Furthermore, in calculating availability, the maintenance parameter is most widely used in calculations, especially in railway rolling stock and infrastructure, this is because maintenance activities make the system or component inoperable so that it is categorized as downtime. As for the railway network, availability is calculated based on the overall downtime of the system, as well as the efficiency and capacity parameters of the network. In this railway network, it is not so related to the physical component, but rather to the arrangement or management of train travel.

Maintenance activities are the main factor in getting the maintainability of the railway system, both preventive and corrective. In the railway network and rolling stock, MTTR is the most widely used parameter because in these systems planned maintenance activities are often applied. Whereas in railway infrastructure, probabilistic criteria are widely used, due to the uncertainty of maintenance activities due to unpredictable material or system failures, so more corrective maintenance is carried out, in addition to preventive maintenance on the system.

For the safety aspect, the application is adjusted to the system under review. There are several different methods for obtaining safety values on the railway system, but it is all inseparable from the reliability, availability, and maintainability of the system.

5. Conclusions

A review of previous and current research on the application of reliability, availability, maintainability, and safety (RAMS) to railway systems is conducted and discussed in this contribution. The methods used in calculating and obtaining RAMS values are presented and discussed in detail.

In railway networks, an assortment of maintenance parameters is employed to derive reliability, availability, and maintainability values. Meanwhile, time and accident parameters are utilized to obtain reliability, maintainability, and safety. Additionally, availability relies on network capacity and efficiency parameters. It is widely known that the Weibull distribution is a popular method used for calculating reliability within the railway industry. This is attributed to the non-constant failure rate of railway systems, which necessitates the application of appropriate approaches to derive reliable values. Moreover, it is worth noting that almost all maintenance criteria are employed to achieve availability and maintainability as a direct result of reliability. The assessment method with probabilistic criteria is the most widely used method for calculating reliability in railway systems, especially infrastructure. This is due to the uncertainty or inconstancy of the failure rate of infrastructure assets such as components and railroad geometry. Asset reliability is closely related to the failure rate so it will affect maintenance and availability activities. Therefore, the method to obtain the maintainability value of an asset is related to its failure rate, and the availability value is obtained from the total operating time and maintenance activities carried out. This safety aspect method is related to the characteristics of the existing railway in a study.

Currently, there is no research related to the application of RAMS in Indonesian railways even though RAMS regulations and standards already exist and apply. Assessment of reliability, availability, ease of maintenance, and safety integrity needs to be carried out on the Indonesian railway system, especially related to infrastructure because currently, infrastructure is the largest contributor to train accidents in Indonesia. Some of the methods used in previous studies may be used and applied in Indonesian railways, where the methods to be used can be validated in advance with the characteristics of the railways and compared with the characteristics of railways in Indonesia. The application of RAMS is expected to improve reliability and safety and optimize the life cycle of Indonesian railway assets.

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