

Application of RCM in the national railways sector: a case study

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Master's Dissertation

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Master's in Mechanical Engineering

June 2024

"Quality is everyone's responsibility."

W. Edwards Deming

Resumo

O *Green Deal* Europeu promoveu o desenvolvimento e a melhoria do setor ferroviário, salientando a necessidade de soluções de transporte sustentáveis e eficientes. Em resposta a este desafio, esta dissertação analisa uma das formas de melhorar o sistema ferroviário com a aplicação de estratégias de Manutenção Centrada na Fiabilidade (MCF) na indústria ferroviária nacional, com especial incidência nos *bogies* para vagões de transporte de mercadorias. O principal objetivo é melhorar a fiabilidade, a segurança e a relação custo-eficácia das operações de manutenção através da aplicação de uma estratégia de manutenção sistemática que cumpra as normas da indústria para permitir a certificação e autorização de comercialização do *bogie*, bem como a interoperabilidade na União Europeia.

O âmbito do estudo inclui uma análise funcional de um *bogie* de vagão de transporte de mercadorias, que serve de base para a subsequente Análise de Modos de Falha, Efeitos e Criticidade, FMECA. Esta análise detalhada identifica os potenciais modos de falha, avalia os seus efeitos no desempenho do sistema e dá prioridade às atividades de manutenção com base na criticidade. Ao implementar esta metodologia, esta investigação pretende fornecer uma visão pragmática para melhorar a fiabilidade e o desempenho dos *bogies* para vagões de mercadorias, reduzindo assim o tempo de inatividade e os custos de manutenção sem comprometer a segurança.

Além da FMECA, é efetuada uma análise do Custo do Ciclo de Vida para avaliar as implicações económicas das diferentes estratégias de manutenção ao longo do ciclo de vida do bem. Esta análise considera vários fatores de custo, incluindo aquisição, operação, manutenção e eliminação, fornecendo uma visão holística da atribuição do custo total. A análise enfatiza os benefícios financeiros da implementação da MCF, demonstrando potenciais poupanças de custos e um maior retorno do investimento. Isto é corroborado por uma análise do Valor Atual Líquido, VAL, ao longo da vida útil do ativo para um dos seus subsistemas.

Em adição, a dissertação analisa as técnicas de sensores e o seu papel na promoção da manutenção baseada na condição. Ao integrar sensores avançados e sistemas de monitorização, a investigação destaca o potencial para a avaliação do estado em tempo real, a deteção precoce de falhas e as suas implicações na manutenção preditiva. Esta abordagem proativa, aliada a desenvolvimentos na produção e recolha de energia para sensorização independente, pretende melhorar a gestão de ativos, reduzir o impacto ambiental e garantir a eficiência operacional.

Em conclusão, esta dissertação demonstra a importância da aplicação da RCM e da FMECA a um *bogie* para um vagão de mercadorias, destacando como estas abordagens melhoram significativamente a fiabilidade, disponibilidade, facilidade de manutenção e segurança do ativo, enquanto permitem o desenvolvimento de planos de manutenção otimizados e rentáveis, adaptados ao sistema em análise. Sublinha o profundo impacto que a implementação da RCM tem na gestão de ativos e manutenção, promovendo novos projetos neste domínio.

Palavras-chave: Gestão de ativos, Fiabilidade, Modos de falha, Custo do ciclo de vida, Manutenção centrada na fiabilidade, Manutenção, Caminho de ferro, *Bogie*, Vagão de mercadorias

Abstract

The European Green Deal has provided a major impetus for railway improvement, highlighting the necessity for sustainable and efficient transportation solutions. In response to this challenge, this dissertation examines the application of Reliability-Centred Maintenance (RCM) strategies in the national railway industry, with a special focus on freight bogies. The main objective is to improve the availability, safety, and cost-effectiveness of railway operations through a systematic maintenance strategy complying with industry standards to allow the certification and market authorization of the bogie, as well as interoperability across the European Union.

The scope of the study includes a functional breakdown of a freight bogie, which serves as the foundation for subsequent Failure Modes, Effects, and Criticality Analysis, FMECA. This detailed analysis identifies potential failure modes, evaluates their effects on system performance, and prioritizes maintenance activities based on criticality. By implementing this methodology, this research aims to provide pragmatic insights into improving the reliability and performance of freight bogies, thus reducing downtime and maintenance costs without compromising safety.

Additionally, a Life Cycle Cost analysis, LCC, is performed to evaluate the economic implications of different maintenance strategies over the lifecycle of the asset. This analysis considers various cost factors, including acquisition, operation, maintenance, and disposal, providing a holistic view of the total cost allocation. The LCC analysis emphasizes the financial benefits of implementing RCM by demonstrating potential cost savings and higher return on investment. This is corroborated by a Net Present Value analysis across the useful life of the asset for one of its subsystems.

Furthermore, the dissertation reviews sensor techniques and their role in promoting condition-based maintenance. By integrating advanced sensors and monitoring systems, the research highlights the potential for real-time condition assessment, early failure detection, and its implications on predictive maintenance. This proactive approach allied with energy harvesting developments intends to enhance asset management, reduce environmental impact, and ensure operational efficiency.

In conclusion, this dissertation demonstrates the importance of applying RCM and FMECA to a freight bogie, highlighting how these approaches significantly enhance the asset's reliability, availability, maintainability, and safety while enabling the development of optimized and cost-effective maintenance plans tailored to the system under analysis. It underscores the deep impact that RCM implementation has on asset and maintenance management, promoting further projects in the area.

Keywords: Asset Management, Reliability, Failure Modes, Life Cycle Cost, Reliability-Centred Maintenance, Maintenance, Railway, Bogie, Freight Wagon

Acknowledgements

I would like to express my deepest gratitude to my esteemed supervisor at FEUP, Professor Luís Andrade Ferreira. His unwavering guidance, support, and insightful instructions have played a significant role in shaping my journey during this semester through the proposal of this challenging project. His mentorship and assistance have been indispensable in the successful completion of projects that would have otherwise been unattainable, laying a robust foundation for the achievement of this dissertation.

I am equally thankful to Eng. Dora Alves, my supervisor at CCF, for her invaluable feedback, warm hospitality and amicability in the institution, and consistent support throughout all the stages of the development of my dissertation.

I would also like to express my gratitude to Eng. Andreia Santos and Eng. Rúben Santos for their additional support, guidance, and willingness to help and clarify any doubts I had pertaining to the work that was developed.

Additionally, I would like to thank Eng. Paulo Alves, Eng. Paulo Oliveira, Eng. João Martins, and Eng. Ângelo Cândido for the guided tour of the Medway “*Oficina de vagões*”. The opportunity to observe the real bogies and their components up close and gain a deeper understanding of their design and functionality was invaluable.

A thank you to my friends who have always been by my side and encouraging me to strive for better. The engaging discussions and leisurely moments spent together have made my academic journey much more meaningful and enriching.

My heartfelt appreciation also to my parents, Maria Teresa Dias and Luís Dias, and brother, Miguel Dias, for always believing in my goals, and for encouraging me to never give up, while also teaching me invaluable lessons throughout my life. I thank them for their patience, understanding, help, and love that they have always been willing to provide.

Thank you all for being part of this profoundly meaningful journey.

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Abbreviations and Symbols

ALARP	A s L ow A s R easonably P racticable
ARPN	A lternative R isk P riority N umber
ATA	A ir T ransport A ssociation of A merica
AUPD	A verage U navailability of the P rotective D evice
BIM	B uilding I nformation M odelling
BS	B ritish S tandard
C_i	Item Criticality
C_m	Modal Criticality
CAPEX	C apital E xpenditure
CBM	C ondition- b ased M aintenance
CCF	<i>Associação Centro de Competências Ferroviário</i>
CE	C arbon E quivalent
CENELEC	<i>Comité Européen de Normalisation Électrotechnique</i>
CM	C ondition M onitoring
CP	<i>Comboios de Portugal</i>
D	Detectability
ECM	E ntity in C harge of M aintenance
EN	E uropean N orm
EU	E uropean U nion
$f(t)$	Probability density function – failure density
$F(t)$	Cumulative distribution function – failure function
FEUP	<i>Faculdade de Engenharia da Universidade do Porto</i>
FFI	F ailure F inding task I nterval
FMEA	F ailure M ode and E ffects A nalysis
FMECA	F ailure M ode, E ffects and C riticality A nalysis
FSI	F unctionally S ignificant I tem
FTA	F ailure T ree A nalysis
HAZ	H eat A ffected Z one
HRA	H azard R isk A ssessment
HRI	H azard R isk I ndex
IAPMEI	<i>Agência para a Competitividade e Inovação</i>
IEC	I nternational E lectrotechnical C ommission
IIoT	I ndustrial I nternet o f T hings
IP	<i>Infraestruturas de Portugal</i>

ISO	International Standards Organization
JIT	Just-In-Time
L_{10}	Bearing life associated with a 90 percent reliability
LCC	Life Cycle Costing
LRU	Line Replaceable Unit
M_{TIVE}	Mean time between failures of the Protection Device
MCF	<i>Manutenção Centrada na Fiabilidade</i>
MSG	Maintenance Steering Group
MTBF	Mean Time Between Failures
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
O	Probability of Occurrence
OEE	Overall Equipment Effectiveness
OPEX	Operational Expenditure
PFP	<i>Plataforma Ferroviária Portuguesa</i>
PFPF	Probability of Failure of the Protected Function
PM	Preventive Maintenance
PMF	Probability of a Multiple Failure
$R(t)$	Reliability function
RAMS	Reliability, Availability, Maintainability and Safety
RBD	Reliability Block Diagram
RCA	Root Cause Analysis
RCM	Reliability-Centred Maintenance
RPN	Risk Priority Number
RTF	Run To Failure
RUL	Remaining Useful Life
S	Severity
TBU	Tapered roller Bearing Unit
TPM	Total Productive Maintenance
TQM	Total Quality Management
TSI	Technical Specification for Interoperability
UIC	<i>Union Internationale des Chemins de fer</i>
UP	<i>Universidade do Porto</i>
VAL	<i>Valor Atual Líquido</i>
WSN	Wireless Sensor Networks
$\lambda(t)$	Failure rate

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1 Introduction

1.1 Motivation

Portugal's commitment to the European Green Deal, seeking to make the European economy competitive, resource-efficient and climate-neutral by 2050, emphasizes the importance of efficient and reliable railway systems as the transformation of the transportation sector is one of the key initiatives to overcome the following goals (European Commission, 2019):

- no net emissions of greenhouse gases by 2050;
- economic growth decoupled from resource use;
- no person and no place left behind.

Rail transportation provides a low-emission and efficient alternative to road and air transportation, making it essential for the increased demand for sustainable mobility. The European Green Deal emphasizes the importance of improving railway systems to achieve environmental goals and increase railway connectivity across the continent. By focusing on Reliability-Centred Maintenance, this project hopes to raise awareness about railways' vital role in sustainable transportation, adding to the existing body of knowledge on the theme and promoting more investigation in this critical sector. Increased awareness and understanding of the complex and unique characteristics of the theme at hand can lead to better-informed decisions and investments in railway systems, which are consistent with national and European sustainability objectives as stated above.

1.2 Contextualization of the Receiving Institution

The Railway Competence Centre Association, *Associação Centro de Competências Ferroviário* (CCF), was created following the Council of Ministers Resolution 110/2019, which discussed a set of measures aimed at safeguarding a quality public railway service. In line with these strategic measures, the Ministry of Economy and the Portuguese Rail Platform cluster signed a sector pact that defines a set of strategic measures and actions to promote the competitiveness of the rail sector and revitalise the rail passenger transport service, with emphasis on the creation of a national technology centre (Diário da República, 2023).

CCF is a railway skills centre, located in *Guifões*, with the mission to lead the national railway system and promote its advancement in technological, industrial, and business capacities. It encompasses the conception and cultivation of innovative ideas and projects, the testing and validation of proofs of concept, the acceleration of business projects to the market, the emergence of new opportunities and skill development, as well as the integration of technologies into new products and systems, culminating in their operational deployment. To satisfy its objectives, CCF promotes training activities for both human capital and national companies, and research into emerging technologies and products. This exhaustive effort aims to position Portugal as a benchmark in the railway industry and leverage the attractiveness of

the railway sector, emphasizing its importance for the pursuit of the European Green Deal objectives. It currently works with the following public organisations: *Comboios de Portugal* (CP), *Infraestruturas de Portugal* (IP), *Metropolitano de Lisboa*, *Metro do Porto*, *Fundação Universidade do Porto* (UP), *Agência para a Competitividade e Inovação* (IAPMEI) and *Plataforma Ferroviária Portuguesa* (PFP).

With its solid foundation in Research, Development, and Innovation, it has been rapidly developing and boosting its influence, engaging in a multitude of projects for innovation, including the following (CCF, 2024):

- **AM Ferrovia:** production of railway rolling stock in Portugal;
- **Smart Wagons:** development of production capacity in Portugal for intelligent freight wagons;
- **DIGITALbuilt:** digital innovation hub for the built environment and application of BIM (Building Information Modelling) to railway infrastructures.

While CCF has been working on innovative projects and helping in academic dissertations related to the fabrication of a rail bogie, it is not the entity that will be responsible for the actual production of the rail bogie. A private enterprise with the appropriate industrial conditions and machinery will be responsible for accomplishing it.

1.3 Scope and Goals of the Project

This dissertation's objectives focus on applying the RCM methodology to systems and analysing its impacts on the assets under management of a railway rolling stock undertaking, consequently leading to increased knowledge and interaction with management, logistics, operation, and maintenance. It also involves the development and improvement of failure management plans and preventive maintenance plans aimed at enhancing reliability and availability throughout the life cycle of the asset with the prioritisation of an effective cost-based approach. Additionally, there are some specific objectives this project aims to address, such as:

- Development of skills in the area of maintenance and quality;
- Improvement of maintenance processes and planning of a railway company, including raising awareness of the priority actions to be carried out;
- Retainment of dispersed knowledge by documenting information on maintenance processes and instructions for carrying out continuous improvement actions.

To successfully satisfy and understand the scope of the project, the following steps of an FMECA must be considered:

- Analyse and understand the operation of the systems to be studied;
- Identify and characterize failure modes, their effects and consequences;
- Prioritize the most critical failure modes;
- Identify the root causes that lead to these failure modes;
- Create a risk matrix;
- Implement new and optimized maintenance methods and plans.

1.4 Methodology

The methodology employed in this dissertation spans a comprehensive approach aimed at investigating and addressing the research of the planned objectives within the designated timeframe of 4.5 months. Beginning with a thorough literature review to establish the fundamental theoretical background, this approach ensures a holistic understanding of the

research problem and enables the formulation of robust conclusions and a critical analysis of the available data, as well as highlighting the potential for future works for further improvement that could not be addressed due to time or data constraints. It is imperative to delineate the sequential tasks and milestones to be achieved throughout the dissertation to allow for better project management and ensure timely progress towards the desired outcomes.

- Integration and contextualisation of the student in the organisation;
- Review of the state-of-the-art (bibliographical review of the application of maintenance methodologies to the railway sector);
- Study and recording of the various existing "as is" processes;
- Identification of system functions, failures and effects of failures for the FMECA;
- Definition of the RCM workflow;
- Proposition of alternative "to be" processes and evaluation of strategic action tasks;
- Writing the dissertation.

1.5 Structure of the Dissertation

This dissertation is organised into six major chapters, structured as follows:

Chapter 1 - Introduction introduces the motivation for the research, provides a brief literature review, and outlines the structure and objectives of the work.

Chapter 2 – State-of-the-Art presents the fundamental terminology and methodologies of asset management, maintenance, and reliability. The section provides a comprehensive overview of asset management and maintenance, tracing the evolution of maintenance concepts and techniques, and examining various types and methodologies of maintenance, including corrective, preventive, and condition-based approaches. Additionally, it introduces key concepts of reliability, failure, and maintainability, with a specific focus on the degradation curve and its implications for maintenance strategies.

Chapter 3 – RCM Implementation covers the implementation of Reliability-Centred Maintenance (RCM), discussing asset functions and availability, and detailing various maintenance tasks and actions, including proactive tasks and default actions. It also explores critical methodologies such as Failure Modes and Effects Analysis (FMEA) and Failure Modes, Effects, and Criticality Analysis (FMECA), alongside risk management, RAMS (Reliability, Availability, Maintainability, and Safety), life cycle costing, and circular economy principles. Finally, it addresses the planning and documentation of an RCM program, reviews potential barriers to RCM, and compares RCM II and RCM III frameworks.

Chapter 4 – Case Study – Y25 Bogie Frame focuses on the project description and outputs, specifically the freight wagon and the bogie. An FMECA analysis is applied to the case study, and due to a lack of extensive data and information on the bogie, the calculation of the RPN index is mostly achieved through assumptions and other considerations to be explained in detail in this section. Based on the RPN values, failure modes can be ordered in terms of criticality to define a certain prioritisation in terms of maintenance actions that need to be performed.

Chapter 5 – LCC Analysis delves into a practical application of Life Cycle Cost (LCC) analysis with the intent of assessing the impact of the proposed maintenance actions on the overall costs across the useful life of the components. All the necessary assumptions are stated, and the formulas are presented to streamline the calculation to all components of the system. It is further complemented by an example of NPV calculation.

Chapter 6 – Conclusions and Future Works for Improvement presents the conclusions drawn from this research and suggests future lines of development, particularly identifying projects that could not have been concluded in time for the dissertation due to lack of time or readily available high-quality data.

2 State-of-the-Art

2.1 Asset Management and Maintenance

Asset management involves overseeing a group of assets throughout their entire lifecycle, to ensure optimal performance, returns, and adherence to predefined service and security standards. This discipline plays a pivotal role in identifying and evaluating decisions critical for achieving long-term economic viability and maximizing profitability. However, it is inevitably confronted with several challenges, including the alignment of strategic objectives and operational activities with stakeholder values and objectives, the balancing act between reliability, safety, and financial considerations, and the effective utilization of performance-based incentives amidst the presence of output-based penalty regimes (Schneider et al., 2006).

The international standard ISO 55000:2014 defines asset management as the “coordinated activity of an organization to realize value from assets”, meaning that assets and their value must be described in detail. Particularly, the standard states that “the value (which can be tangible or intangible, financial or nonfinancial) will be determined by the organization and its stakeholders, per the organizational objectives”, according to the following criteria:

- value generation (benefits from use or simply ownership of assets);
- value determination (such as valuation of assets or the organization, for example, the sale price of the asset or organization, if it is sold);
- values (principles that guide an organization’s internal and external conduct).

When defining value, it is important to recognize that perceptions are highly subjective and thus will differ even within an organization, depending on its stakeholders. This divergence arises because, for some stakeholders, an organization's value hinges on factors like risk exposure and return on investment. Customers, who are integral stakeholders, assess value in terms of price-to-benefit ratio, along with the quality of their relationship with the organization. Finally, other stakeholders such as regulators, interest groups, or the broader community, may evaluate value based on yet another distinct criterion altogether, such as health and safety assurance, or environmental friendliness (Pais et al., 2023).

In practice, asset management coordinates the strategic oversight of assets, aligning closely with maintenance efforts aimed at sustaining functionality, minimizing downtime, managing costs, and mitigating risks effectively. Therefore, asset management and maintenance are tightly intertwined. Maintenance is perceived as a fundamental concept encompassing the systematic actions taken to preserve, repair, and sustain the functionality and integrity of equipment, systems, or infrastructure as a whole. According to the standard EN 13306:2017 it can be defined as the “combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function”.

This European Standard aims to establish universal terminology applicable to all forms of maintenance and maintenance management, regardless of the nature of the item under consideration. It is important to note that this standard does not cover software maintenance. However, it does encompass maintenance activities pertaining to items and systems that incorporate software components. It is the responsibility of any maintenance management to formulate its maintenance strategy according to the following primary objectives (EN 13306: 2017):

- Ensuring the availability of the item to perform as required, while optimizing costs;
- Addressing safety concerns, safeguarding individuals, the environment, and any applicable regulatory requirements associated with the item;
- Assessing environmental impact considerations;
- Preserving the longevity of the item and/or maintaining the quality of the product or service provided, while managing costs.

Standard EN 16646:2014 clarifies the interrelationship between asset management and maintenance and states that “the management of a maintenance process is based [...] on the physical asset management solutions and asset management policies, strategies and plans which reflect the business objectives and requirements of the organization in question”. Additionally, it introduces physical asset management as a framework for maintenance activities, namely by defining the role and the importance of maintenance within asset management for the whole life cycle of a given asset. Figure 1 further illustrates the link between asset management and maintenance, justifying the need to present both concepts.

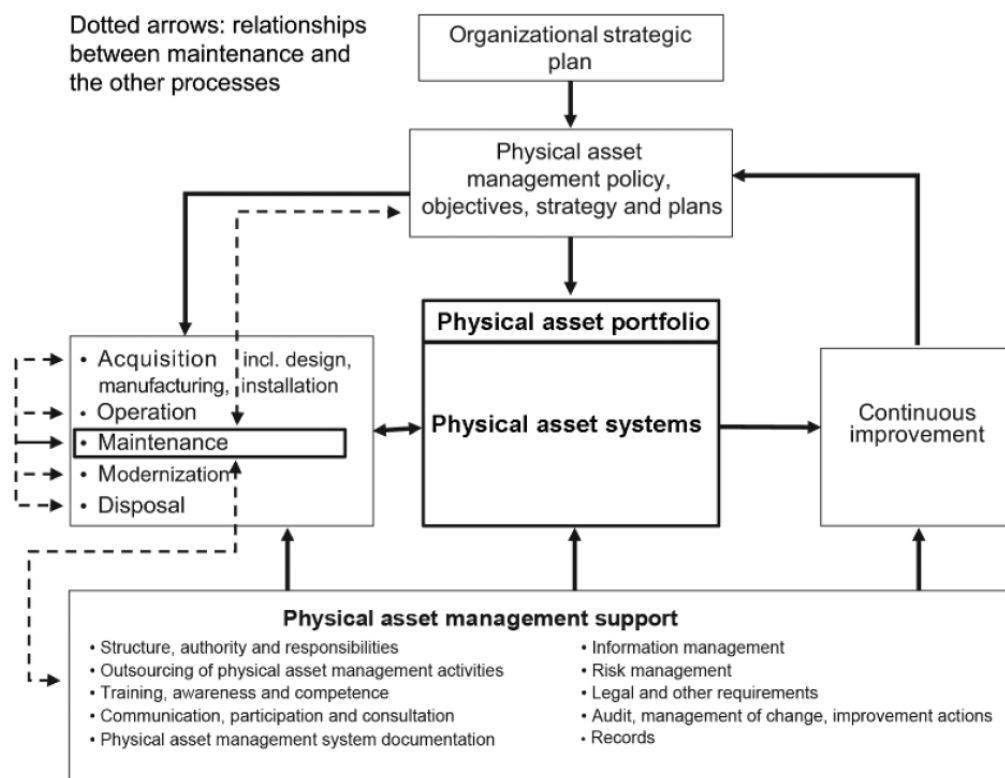


Figure 1 - Interrelationships between asset management processes and maintenance processes (EN 16646:2014).

2.1.1 Evolution of the Concept of Maintenance and Maintenance Techniques

The concept of maintenance has evolved significantly over time, reflecting advancements in technology, changes in industrial practices, and shifting paradigms in reliability management. Understanding this evolution provides valuable insights into the development of maintenance techniques and the strategies employed to ensure the optimal performance of assets that take into account the increasingly more complex demands and expectations expressed by organisations and users of the assets (Cabral, 2013).

From its origins until today, four dominant stages can be identified, as can be seen in Figure 2.

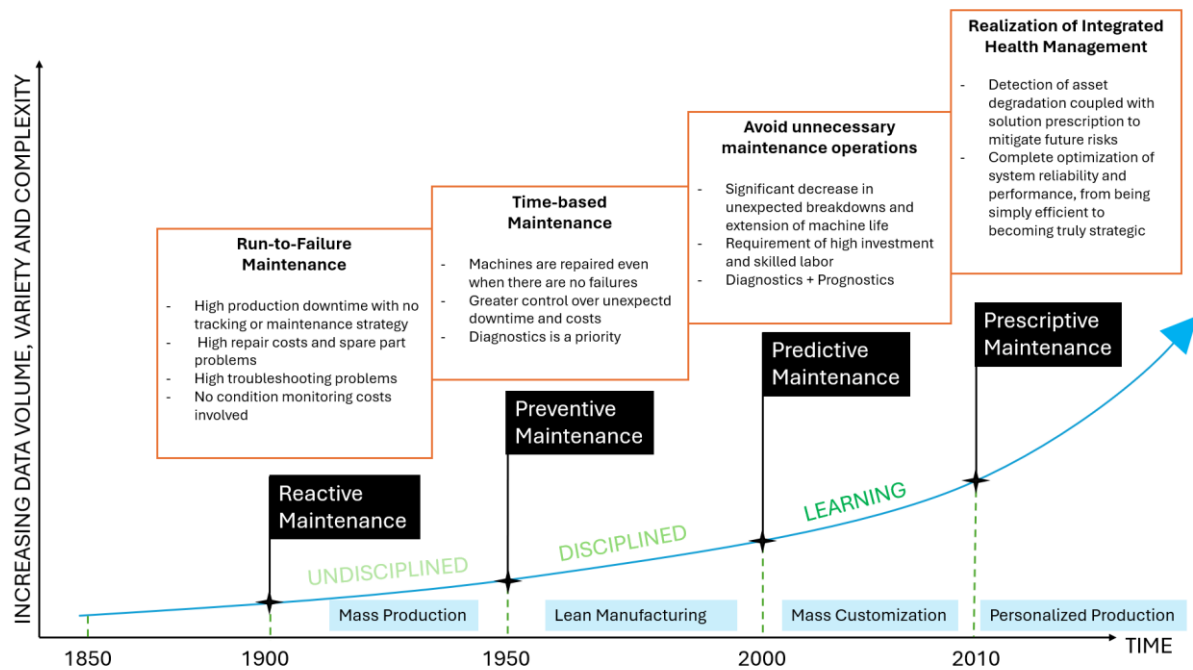


Figure 2 - Evolution of maintenance types. Adapted from (Lee et al., 2020).

The first stage refers to a reactive approach focused on repairing failures only after they occur (Run-To-Failure). At the time, systems were simple and oversized, with little mechanization, low automation, and no need for high and demanding availability and maintenance practices were purely corrective. This period was referred to as Classical Manufacturing (Lee et al., 2020).

The second stage, concurrent with the Second World War, led to an increase in the need for goods and growing automation of the industry, leading to a greater dependence on industrial production capacity and the emergence, for the first time, of preventive maintenance.

The third period is characterised by increased automation, production growth, export expansion, and a significant improvement in product and service quality (Moubray, 1997).

Finally, the fourth and last stage of maintenance so far, known as the Fourth Industrial Revolution, distinguishes itself from all the past periods. It is a major paradigm shift as it not only changes "what we do" but also "how we do it", employing innovations that emerge combined with increasing quality demands to drive this evolution. While this paradigm may disrupt many traditional job roles, with fundamentally new training and education, it is expected to also create more specialized positions and job opportunities, in the areas of Industrial Internet of Things (IIoT), artificial intelligence, machine learning and Big Data. Now is the era of Smart Manufacturing (Lee et al., 2020; Sahal et al., 2020).

Simultaneously, the concept of maintenance has been facing challenges that must be addressed through new and tailored innovations and methodologies, accompanying the evolution of the industrial world (Moubray, 1997).

In essence, the challenges facing modern maintenance managers include:

- dealing with each type of possible failure process;
- selecting the most appropriate and cost-effective techniques;
- fulfilling all the ever-increasingly competitive and demanding expectations of the owners of the assets, its users and of society as a whole.

In specific, the new developments encompass:

- decision support tools, such as failure modes and effects analyses and hazard studies;
- new maintenance technologies (example of condition monitoring);
- major shift in organisational philosophies enforcing teamwork and involvement;
- equipment designed with an increasing emphasis on reliability and maintainability.

Understanding the ongoing evolution of maintenance strategies is of paramount importance to contextualise the current maintenance paradigms in railways. For instance, the traditional approach to planning maintenance and renewal work for railway tracks relies on heuristics and basic scheduling techniques. However, with the advent of the most recent sensor technologies, the railway industry is now able to gather extensive data on the condition of various track components. Since the late 20th century, data-driven models have been increasingly utilized for predictive maintenance of railway tracks, alongside the shift in management paradigms (Xie et al., 2020).

Predictive maintenance is favoured because it reduces rolling stock failure rates and lowers maintenance costs by prolonging the lifespan of components and enabling operators to schedule maintenance tasks proactively. The effectiveness of maintenance strategies in the railway sector hinges on the information obtained from monitoring equipment and methods such as walking patrols, mechanized track patrols, and wayside detectors. This way, the railway industry now has access to an abundance of data (Big Data), characterized by its large volume, multi-source, as well as high noise which will only be further improved upon as better algorithms are developed (Moubray, 1997; Xie et al., 2020).

2.2 Types of Maintenance

Maintenance strategies are fundamental in ensuring the reliability, efficiency, and longevity of various systems across industries. They encompass a spectrum of approaches, ranging from meticulously planned interventions to reactive responses to unexpected failures.

Figure 3 illustrates a simple scheme of the different types of maintenance activities.

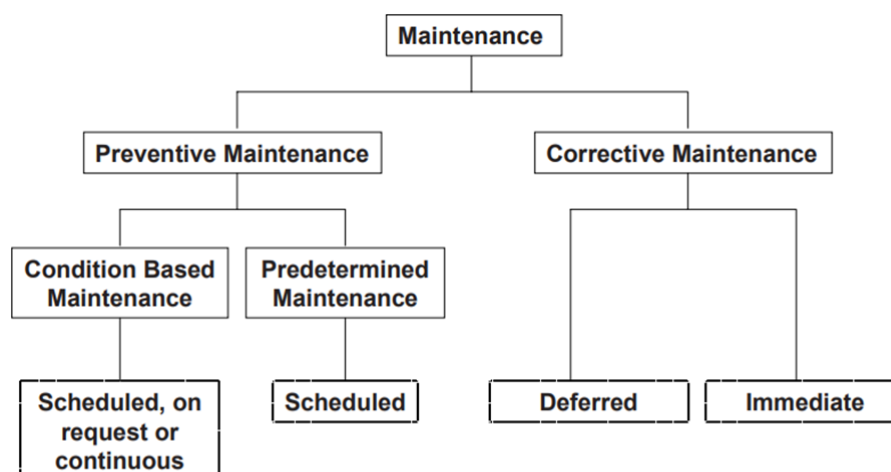


Figure 3 - Types of maintenance activities (EN 13306:2017).

2.2.1 Corrective Maintenance (Run-to-Failure)

Run-to-Failure maintenance, RTF, is “carried out after fault recognition and is intended to put an item into a state in which it can perform a required function” (EN 13306:2017). RTF

involves carrying out maintenance tasks only after the failure of the asset, to identify, isolate, and rectify a fault state and restore it to an operational state so that it can perform its necessary functions. The restoration process can be immediate or delayed (depending on maintenance criteria) and is mainly applicable to low-value assets, assets for which failures do not result in catastrophic consequences, or assets subject to predominantly random failures that make it hard to estimate the remaining useful life (RUL). This approach ensures the full utilisation of parts, avoiding waste of component lifespans (Moubray, 1997).

Although relatively easy to implement, as it does not require significant organisation and planning efforts, resulting in a reduction of indirect costs associated with maintenance management and planning, corrective maintenance has a multitude of disadvantages, such as an increase in repair costs, production losses, and potentially increasing the number of defects due to unplanned downtime, or even compromising user safety by increasing the risk of accidents (Moubray, 1997).

2.2.2 Preventive Systematic Maintenance (Time-based)

It refers to the “maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item” (EN 13306:2017). Commonly, preventive maintenance plans are enforced by the legislation.

This approach involves scheduling maintenance actions for an asset according to a predetermined periodicity between consecutive interventions to reduce the likelihood of failure or degradation, thus it is commonly known as calendar-based, clock-based, or time-based maintenance. It is primarily employed for critical assets to proactively prevent failures or for routine inspections conducted regularly to assess the condition of safety equipment. The optimal frequency is determined based on factors such as the reliability of the asset and the comparative costs of preventive maintenance versus corrective maintenance (Cabral, 2013).

It is assumed that there is a relationship between loss of reliability and operating time, with constant failure patterns (no recourse to monitoring or analysing the current state of equipment and its components) and that the maintenance actions carried out restore the reliability (Moubray, 1997).

2.2.3 Condition-based Maintenance, CBM

Preventive CBM

In this case, preventive maintenance actions are determined by the condition of the component being maintained. Asset condition is monitored over time through statistical process control techniques and regular inspections and testing of railway equipment performance and the preventive maintenance tasks are carried out when the related indicators exceed a certain threshold. Therefore, preventive condition-based maintenance is suitable for equipment whose failure can be predicted by a degradation curve of characteristics that can be detected. Nowadays, this information can be provided by the equipment's self-diagnosis system, which monitors its operating status and indicates when something is wrong by signalling (Moubray, 1997).

Unnecessary actions can be avoided while necessary actions can be executed. This strategy is however dependent on the possibility to measure the state of the required function at hand. Obtaining direct measurements of the variable of interest is often challenging so related variables are used instead to estimate the variable of interest (Moubray, 1997).

Furthermore, this strategy usually leads to an increase in indirect maintenance costs since the selected timing for intervention may not be ideal from an operational standpoint and

may underutilize the component's lifespan. Nevertheless, it is a very useful type of maintenance as it usually increases asset availability and reduces the inherent consequences of failure.

Predictive CBM

According to the EN 13306:2017 standard, predictive maintenance is "based on the condition of the equipment and is carried out according to the forecast obtained by repetitive analysis and evaluation of operating parameters or other known characteristics of the equipment". It is essentially an extension and evolution of (preventive) CBM in a way that the state of the asset is forecasted to predict the failure time and allow for the development of proactive appropriate maintenance tasks. It is sometimes referred to as adaptive maintenance as the maintenance schedule is continuously adapted according to the updated actual degradation level of the asset and its forecasting (Paolanti et al., 2018).

By increasing the lifespan of components (compared to preventive maintenance) and reducing unscheduled maintenance and labour costs (compared to corrective maintenance), it provides companies with competitive advantages. This can only be achieved when accurate predictions of the asset's future functional states and properties are made (Schmidt et al., 2017).

Predictive maintenance should utilise various types of information to accurately estimate an asset's health and degradation status, such as (Schmidt et al., 2017):

- equipment-related data, including machine type, location, and composition.
- work orders, detailing maintenance actions performed on the equipment, descriptions of faults or failures, lists of replacement parts used, identification of their causes, and methods employed to address them;
- monitoring of equipment operating parameters (temperature, pressure, vibrations, geometric measurements, among others).

2.3 Methodologies of Maintenance

2.3.1 Total Productive Maintenance

Total Productive Maintenance (TPM) is a methodology employed to optimize equipment efficiency throughout its operational lifespan with the core principle being to uphold equipment in prime condition, while avoiding unforeseen breakdowns, minimizing speed losses, and mitigating quality defects stemming from process activities (Nakajima, 1988).

Traditional TPM was developed by Seiichi Nakajima in the late 1960s and early 1970s for the Japanese car industry and harmoniously linked autonomous management, continuous improvement, and preventive maintenance to reshape the industrial view of asset management and maintenance. Its emergence was an integral component of the Toyota Production System as it filled a crucial gap in achieving not just top-tier equipment performance to bolster Total Quality Management, TQM, and Just-In-Time, JIT, but also served as a potent tool for enhancing overall company performance. Hence, after the early 1990s it began to proliferate rapidly throughout Western countries, enhancing the operational efficiency of manufacturing, processing, and mining companies (Agustiady and Cudney, 2018).

As a side note, TQM consists of organization-wide initiatives aimed at fostering a continuous improvement culture wherein employees enhance their capabilities to deliver products and services that resonate with customers. It is a holistic approach to quality that does not provide specific guidance on how to implement quality management. The term "Total" implies the involvement of all departments (production, sales, marketing, accounting, finance, engineering, and design), in refining their processes. Meanwhile, the term "Management" underscores the responsibility of executives to actively oversee quality through investment,

training, staffing, and goal setting. The emergence of TQM is mainly attributed to William Edwards Deming, Joseph Juran, and Kaoru Ishikawa (Hoyle, 2007).

TPM emphasizes the importance of metrics such as Overall Equipment Effectiveness (OEE), productivity, quality level, cost, delivery, safety, and morale, to aid organizations in working towards zero breakdowns, zero defects, zero rework, zero machine stoppages, and zero accidents. The term “Total” refers to total effectiveness, total maintenance system, and total participation of all employees. The OEE parameter can be calculated based on Equation (2.1) (Nakajima, 1988).

$$OEE = Availability \times Performance\ rate \times Quality\ level \quad (2.1)$$

A comprehensive application of TPM includes five key elements:

- maximization of overall equipment effectiveness;
- establishment of carefully crafted PM plans for the entire life span of the asset;
- implementation across varying departments, from engineering to operations and maintenance;
- involvement of every single employee, from top management to shop-floor workers;
- motivational management.

As presented, the TPM philosophy advocates for total employee involvement, empowering operators to engage in autonomous maintenance tasks to enhance equipment reliability and productivity, while fostering a culture of continuous improvement, known as Kaizen. In practical terms, it extends the responsibility of production employees beyond machine operation to include detecting machine failures, conducting basic maintenance, and maintaining clean and orderly work environments (Nakajima, 1998; Swanson, 2001).

TPM employs a multitude of techniques, such as Pareto analysis, Statistical Process Control (control charts), problem-solving techniques (brainstorming, cause–effect diagrams and 5M approach), team-based problem solving, autonomous maintenance, continuous improvement, 5S, setup time reduction, waste minimisation, bottleneck analysis, recognition and reward programmes, and simulation as tools to analyse and effectively solve problems (Sharma et al., 2006).

2.3.2 Reliability-Centred Maintenance

Reliability-Centred Maintenance (RCM) stands as the basis for the evolution of maintenance strategies based on risk analysis. Its emergence can be traced back to the aviation industry in the 1960s and Maintenance Steering Group (MSG), with the pioneering work of Stanley Nowlan and Howard Heap at United Airlines. Nowlan and Heap’s work addressed the limitations of routine-based maintenance policies through a transformative analysis of equipment reliability and failure modes. These authors coined the name RCM, expanding MSG to other industry sectors (Nowlan and Heap, 1978).

It is important to contextualise the emergence of MSG and understand the background that led to the development and adaptation of this maintenance logic.

In 1968, MSG was initially established to devise a decision-making framework for developing scheduled maintenance requirements for new aircraft. During this period, members of the steering group formulated "MSG-1 - Maintenance Evaluation and Program Development," which employed a decision-logic diagram tailored to the Boeing 747 aircraft.

By 1970, MSG-1 evolved into MSG-2 to extend its applicability to subsequent generations of aircraft and introduce a third primary maintenance approach known as Condition Monitoring. Under Condition Monitoring, no predetermined services or inspections are scheduled to ascertain integrity or serviceability and instead, mechanical performance is

continuously monitored and analysed. It is not categorized as a preventive maintenance process since it permits failures to occur, with the failure modes of condition-monitored items deemed not to directly compromise operational safety (Ackert, 2010).

The Air Transport Association of America (ATA) task force collaborated to create a groundbreaking task-centric maintenance protocol called MSG-3, building upon the foundation of MSG-2. This approach utilized a decision tree methodology with two main objectives: distinguishing safety-critical components from those with economic considerations and defining appropriate strategies for managing hidden functional failures. Within this innovative framework, evaluations were conducted at the system level rather than the component level. Essentially, if it could be determined that the functional breakdown of a specific system had no impact on operational safety, or that the financial implications were minimal, routine maintenance activities were deemed unnecessary (ATA MSG-3, 2007).

Extending beyond the aviation industry, John Moubray further refined the methodology in his book "RCM II: Reliability-Centred Maintenance" published in 1997 providing guidance into implementing RCM across diverse industrial sectors to enhance safety and reliability at controlled costs. Moubray's work introduced a few changes, such as the addition of environmental consequences to the decision tree and the definition of seven questions that guide the implementation of the methodology. It also adopts the usage of new terms, particularly "technically applicable" and "worth doing". Finally, more precise selection criteria were developed to determine the optimum frequency of inspections and maintenance strategies, with the inclusion of risk analysis. Later, the introduction of on-condition inspection and the philosophy of CBM was a major development that took place in the aviation industry through the MSG-3 concept, which implicitly incorporated the key principles of RCM for a more efficient maintenance decision logic programme. Nowadays, the MSG-3 and RCM II approaches are fundamentally the same so the terms can be used interchangeably (ATA MSG-3, 2007).

Figure 4 provides a graphical representation of the major stages in the history of RCM, highlighting the breakthroughs that shaped the way organizations view maintenance management. The horizontal axis represents time, spanning from 1960 to 2010.

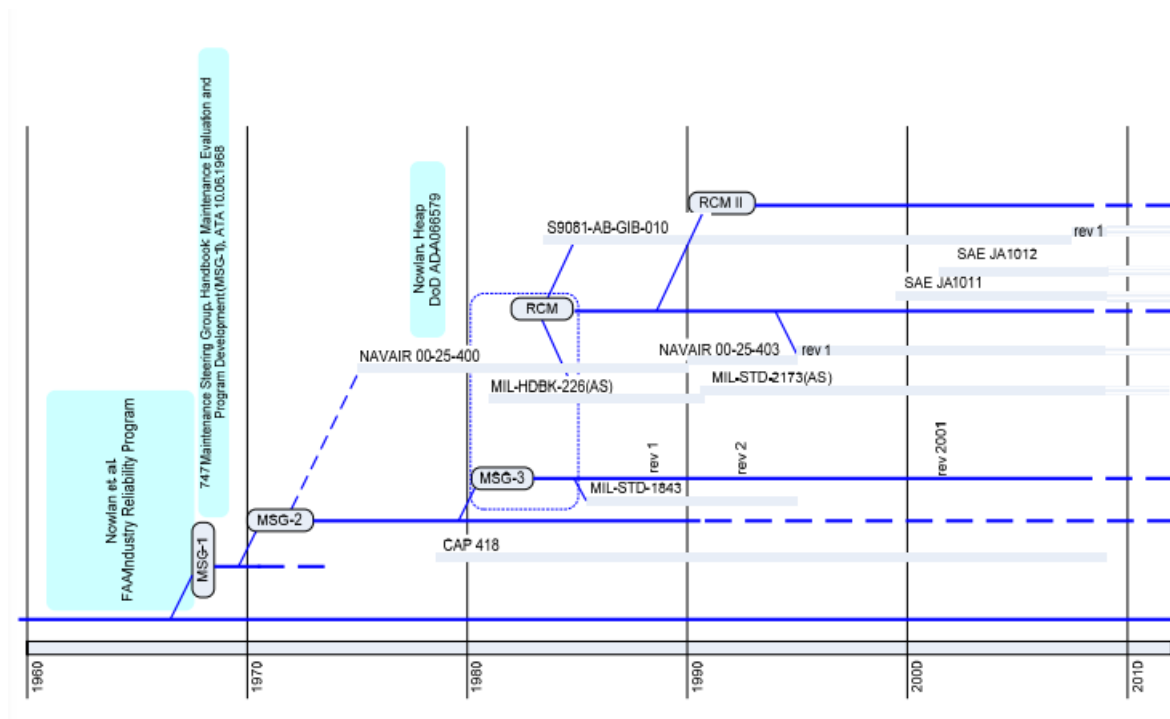


Figure 4 - History of MSG and RCM. Adapted from (Pelrokorpi, 2009).

The timeline illustrates the continuous development and refinement of maintenance strategies. Key organisations and documentation have contributed significantly to these advancements, resulting in the current comprehensive set of guidelines and standards.

RCM is an analytical process used to determine preventive maintenance (PM) requirements and identify the need to take other actions that are warranted to ensure safe and cost-effective operations of a system with a focus on system functions (NAVAIR, 2005). It is “an approach that employs reactive, preventive, and proactive maintenance practices and strategies in an integrated manner to increase the probability that a machine or component will function in the required manner over its design lifecycle with minimum maintenance” (SKF Reliability Systems, 2008).

RCM can be seen as complementary or as an alternative to the TPM and TQM approaches, with its advantages and disadvantages based on the context of the system under analysis. In fact, a TPM project can precede a full-blown RCM analysis to ensure that basic equipment conditions are established and that the operators are qualified for the tasks they perform. In addition, comparing RCM and TQM, TQM focuses on quality management at an organizational or process level, not at an engineering or product development level. Nevertheless, the core idea of TQM, quality management as a continuous process, is very well incorporated in RCM, as stated by Moubray: “This emphasis on what the asset does rather than what it is provides a whole new way of defining the objectives of maintenance for any asset [...] the most important single feature of the RCM process and is why many people regard RCM as TQM applied to physical assets” (Moubray, 1997).

Complementing Moubray’s definition of RCM, Richard B. Jones added that “RCM employs a system perspective in its analyses of system functions, failures of the functions, and prevention of these failures”, which further reinforces the importance of RCM and proper maintenance of system functions in the industrial world (Jones, 1995).

The methodology is characterized by the following four features (Mokashi et al., 2002):

- preservation of system functions;
- identification of the underlying failure modes that can compromise the functions;
- prioritisation of the function needs (via the failure modes);
- selection of applicable and effective maintenance tasks.

RCM intends to provide organisations with better resource allocation to the tasks that promote system reliability the most, promoting the most effective maintenance strategy for each case. This is defined through a set of seven basic questions to evaluate the processes and contextualise the operational context of the asset (Moubray, 1997):

- What are the functions and associated desired standards of performance of the asset in its present operating context (functions)?
- In what ways can it fail to fulfil its functions (functional failures)?
- What causes each functional failure (failure modes)?
- What happens when each failure occurs (failure effects)?
- In what way does each failure matter (failure consequences)?
- What should be done to predict or prevent each failure (proactive tasks and tasks interval)?
- What should be done if a suitable proactive task cannot be found (default actions)?

One major aspect of the analysis is the creation of a Failure Modes, Effects, and Criticality Analysis (FMECA), which helps determine which failure consequences should be prioritized. It is important to note that not all failure modes can or should be corrected, as it may not be feasible or not lead to significant performance improvements, therefore the key challenge lies in finding the balance between technical feasibility and economic viability.

Nonetheless, it offers several benefits when correctly implemented, including improved performance, more effective cost control through maintenance, enhanced safety, and increased environmental protection, and all is achieved through a dynamic approach that allows for continuous improvement and adaptation as the system evolves. It is recommended to carry out this analysis during the system's useful life, ideally at an early stage, to establish a comprehensive understanding of the system and develop an optimal maintenance strategy, thereby avoiding costly errors throughout its lifecycle (Bertling et al., 2005).

The fundamental steps in the RCM procedure are represented in Figure 5.

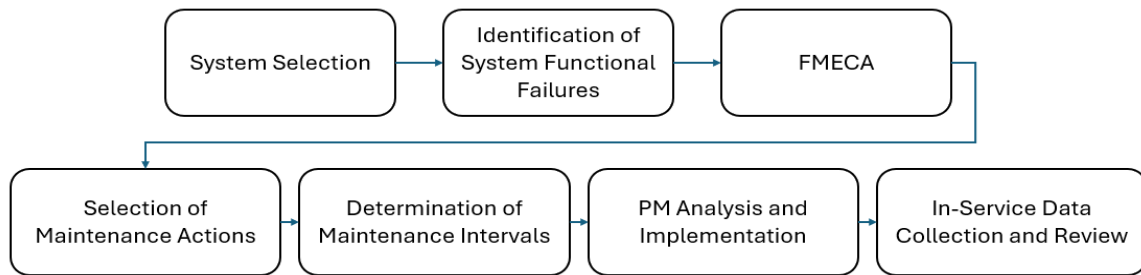


Figure 5 - Fundamental steps in RCM implementation Adapted from (Selvik and Aven, 2011).

The expected outcomes from the implementation of RCM can be summarised as reduction of maintenance activities, optimisation of maintenance planning, increased productivity, increased human and environmental safety, reduction of unnecessary maintenance interventions, material and operating costs and mitigation of risks (Moubray, 1997). An RCM analysis can be complemented by Reliability Block Diagrams, RBD, which is a method explained in Annex C and described in detail in standard IEC 61078:2016.

2.4 General Key Concepts for Equipment Analysis

2.4.1 Concept of Reliability

Reliability is defined as the probability that a product, system, or service will perform its intended function adequately for a specified period of time or will operate in a defined environment without failure.

It is expected that any equipment can fulfil the functions for which it was designed. These expectations of functionality and availability are met according to the reliability level of that component. When reliability is low, it will likely be unavailable for long periods or become unusable more frequently due to eventual failures.

Increasing reliability in systems can be achieved through the following steps (Moubray, 1997):

- using various types of know-how to prevent or reduce the occurrence, number, and frequency of failures and their effects;
- identifying and correcting failures;
- understanding that some failures are impractical to correct and therefore having to operate with them. Many of them are of high complexity or high cost with minor functional or operational impacts;
- gathering all information and history of failures and breakdowns and evaluating reliability indices through statistical methods and deciding on them.

The mathematic definition of reliability is represented by the function $R(t)$, which gives the probability of an asset being in good operating condition in an interval $[0, t]$.

2.4.2 Concept of Maintainability

An additional relevant concept in the domain of asset and maintenance management is maintainability. The standard EN 13306:2017 defines maintainability as the "ability of an asset, under well-defined conditions of use, to be maintained or restored, in such a way that it can fulfil a required function, when maintenance is carried out under defined conditions, using prescribed procedures and resources". It can be quantified with the parameter Mean Time To Repair, MTTR, a mathematical forecast of repair time in each period, that is obtained by the sum of the fault repair times in that period divided by the number of faults. Maintainability is also susceptible to improvements across the asset's life (EN 13306:2017).

2.4.3 Concept of Failure

Standard EN 13306:2017 defines failure as "when an asset is unable to perform a specific function, excluding instances during preventive maintenance or other planned interventions, as well as due to insufficient external resources". Following a failure (event), the asset experiences a breakdown or fault state (continuous state).

The concept of failure is commonly used interchangeably with the concept of fault, but there is a clear distinction between the two that must be addressed. Fault refers to "the state of an item characterized by inability to perform a required function, excluding when it is during preventive maintenance or other planned actions, or due to lack of external resources". This definition is proposed by the standard IEC 62059:2008.

When the performance of a function deviates from the target value (or theoretically correct performance) while still satisfying the minimum requirements, then an error is present. A failure may originate from an error and an error may not always develop and culminate into a failure. When the failure occurs, the item is said to have entered a fault or failed state (Moubray, 1997).

Mathematically, it is the complement of the Reliability function and is designated as $F(t)$, with $f(t)$ as the probability density function for failure.

A failure distribution is an attempt to describe mathematically the length of life of a component, system, or structure. Multiple families of distributions have been used for the failure of materials due to fatigue and the life length of both mechanical and electronic components, and for each failure law it is possible to define the failure rate function, $\lambda(t)$, in case $F(t) < 1$.

Some common distributions to model failure behaviour are the following (Moss, 2005):

- Exponential distribution;
- Gamma distribution;
- Weibull distribution;
- Modified extreme value distribution;
- Truncated normal distribution;
- Log-normal distribution.

It is important to note that the log-normal distribution has a failure rate function that is increasing at first and then converges to zero, therefore it is more suitable to describe the length of time to repair an equipment (Moss, 2005).

Equations (2.2) through (2.4) reflect the most important concepts introduced above.

$$F(t) = 1 - R(t) \quad (2.2)$$

$$F(t) = \int_0^t f(x) dx \quad (2.3)$$

$$\lambda(t) = \frac{f(t)}{1 - F(t)} \quad (2.4)$$

2.4.4 Degradation Curves

In reliability engineering, understanding the degradation of components and systems over time is paramount for effective maintenance and performance management, combining empirical and historical data as well as statistical modelling. The probabilistic failure behaviour of these systems often follows predictable patterns, one of which is the bathtub curve (Moubray, 1997).

The bathtub curve is a classic concept and appears in reliability engineering when concerning the justification of burn-in strategies for improving system reliability and is divided into three iconic regions as depicted in Figure 6.

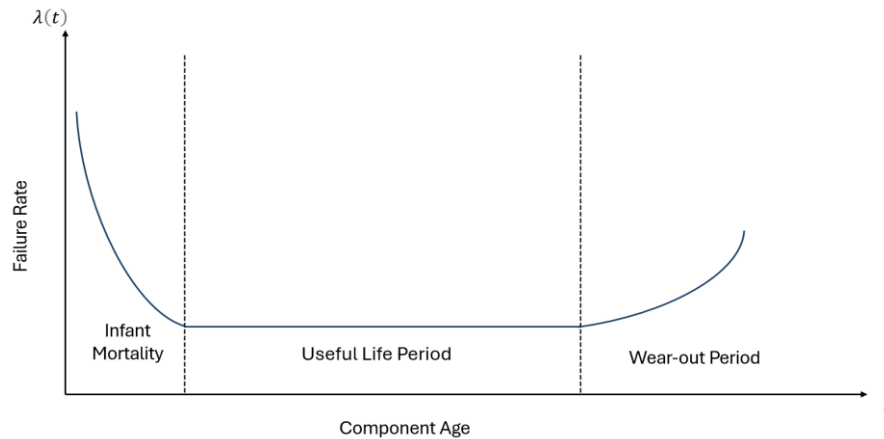


Figure 6 - Bathtub degradation curve. Adapted from (Smith, 2011).

During the initial phase of a component's life, infant mortality failures are characterized by a decreasing hazard rate with a steep slope. The hazard rate improves over time due to constant and successive corrections and changes, thus reducing the incidence rate of failures and improving reliability. Many components are already delivered to the end customer after this phase, as they are thoroughly tested and have already improved on design deficiencies such as poorly managed manufacturing processes, lack of standardization in quality control, use of defective materials, and improper material handling in assembly, storage, and transportation.

The next region is referred to as the useful life period and is characterized by a constant and controlled failure rate at which the asset's reliability is optimized. However, it is important to note that some authors argue that the apparent constant failure rate is merely a consequence of the superposition of the multiple individual failure mechanisms that do not necessarily exhibit a constant hazard rate when analysed individually.

Finally, the last region is the wear-out period, which is associated with an increasing hazard rate, and consequently a decrease in reliability. This is mostly due to an increase in the

number of failures related to wear and ageing of components, thus the objective should be to delay this region as much as possible (Gaonkar et al., 2021).

However, the bathtub curve is hardly a good representation of failure trends as there are a total of six degradation curves, represented in Figure 7, as proposed by Nowlan and Heap. They further emphasized that effective maintenance is contingent upon identifying and quantifying all failure modes in terms of their likelihood of occurrence and consequences (Nowlan and Heap, 1978).

The type of degradation curve is primarily determined by the type of component: electrical, mechanical, or system assembly, as well as its operational context. Even so, the same component can show different behaviours varying significantly depending on factors such as its location of operation and its utilization patterns (example of daily operating cycles). Additionally, the distinction between repairable and non-repairable components further influences degradation characteristics (Wiseman, 2014).

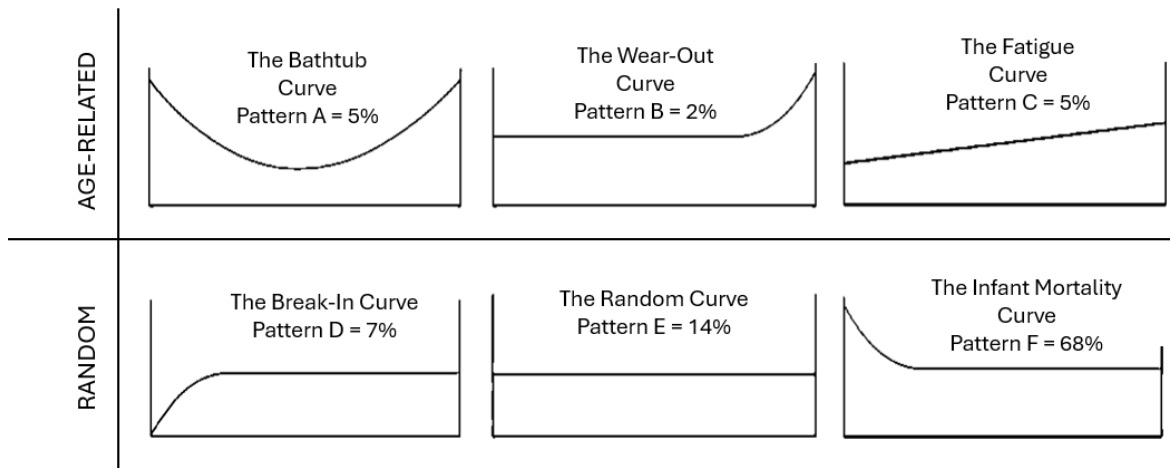


Figure 7 - Degradation curves. Adapted from (Wiseman, 2014).

Now focusing on the other possible behaviour patterns, curve B shows a constant or slowly increasing conditional probability of failure that ends in a pronounced wear-out zone. Current data points out that it is more suitable for mechanical systems due to their well-defined useful life period. Meanwhile, in pattern C the conditional probability of failure is increasing consistently, but it is not possible to identify a wear-out region (Moubray, 1997).

In opposition to the first three curves which apply to models of age-related failures, curves D, E and F are used for systems with random failures and no identifiable wear-out zones. Specifically, patterns E and F are commonly used to model the behaviour of electrical systems or any other repairable components (Moubray, 1997).

Any maintenance strategy should be based on an accurate description of the appropriate failure pattern, as well as any relevant potential indices. This analysis of failure patterns is essential to adequately define the steps for RCM implementation.

2.5 RAMS

The complexity of the railway systems is continuously increasing in the current industrial environment which translates into an increase in requirements and expectations in terms of reliability, availability, maintainability, safety, and cost optimization. Therefore, it has been imperative to define certain guidelines to aid in system analysis (Patra, 2007).

These started with the application of RAMS guidelines with the US railways in the early 1980s and then established in the European railways in the early 1990s with the modification

and introduction of systems engineering in railway projects. This solidified the position of RAMS as a powerful element in decision-making and maintenance management in the global railway industry (Park, 2014).

RAMS targets a crucial aspect of system operation, encompassing a range of engineering principles, methodologies, tools, and techniques applied throughout the system or equipment's lifecycle concerning risk management. In essence, it encapsulates the system's ability to function as required while ensuring safety and availability serving as both a qualitative and quantitative measure of the system's reliability, including its subsystems and components.

To comply with the objectives delineated in the RAMS approach, organisations must prioritise adequate maintenance policies and integrate them with the specific requirements for the asset, which extend beyond technical considerations and are mandatory to establish minimum acceptable thresholds for reliability, availability, maintainability, and safety. This underscores the significance of RAMS in ensuring the operational effectiveness and safety of systems and equipment (EN 50126:2017; Cotton et al., 2003).

The standard EN 50126:2017 "Railway applications – The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS)" was developed to bring in a structured approach to managing the methodology in the railway sector.

As it was applied and experience accumulated over the years, it became clear that some revisions and reorganization were needed to offer a consistent and coherent framework for RAMS that could be applied across all areas of railway operations, ranging from Command, Control, and Signalling, Rolling Stock, and Electric Power Supply for Railways (Fixed Installations).

Central to the standard are processes for defining and demonstrating RAMS requirements throughout the entirety of the asset's lifecycle, as these form the cornerstone of RAMS management and promote a shared understanding and approach within the railway community (EN 50126:2017).

The standard proposes a V-model procedure, as seen in Figure 8, organised into three different stages (design, installation, and operation) to define the necessary steps to ensure the optimal maintainability of the asset. Contractors and clients must maintain continuous communication and information flow at all steps of the procedure with validation and rigorous risk analysis for it to provide fruitful results (IRIS Guideline 3: Maintenance, 2020).

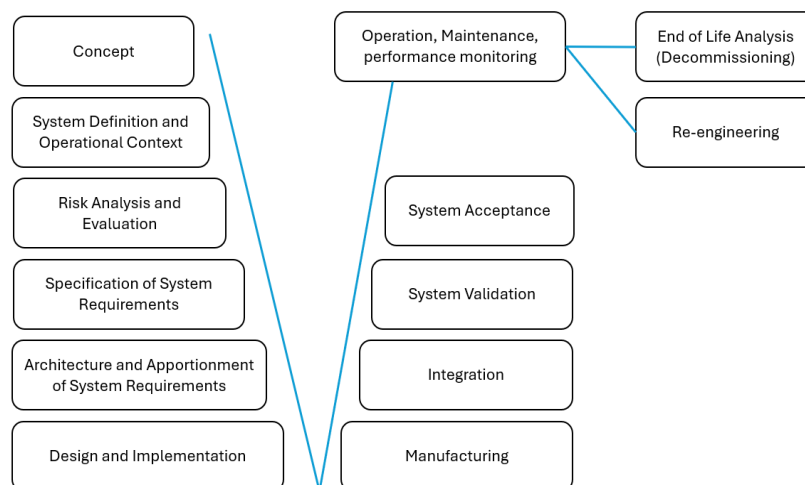


Figure 8 - V-cycle in accordance with EN 50126:2017. Adapted from (IRIS Guideline 3: Maintenance, 2020).

EN 50128:2011 is a certification standard issued by the European Committee for Electrotechnical Standardization, CENELEC. This European Standard specifies “the process

and technical requirements for the development of software for programmable electronic systems for use in railway control and protection applications".

The objective of this European Standard is to uphold safety standards across all stages of the lifecycle of railway equipment and systems software where there are safety implications (particularly those used in railway control and protection systems) by outlining specific requirements that must be adhered to. Although the likelihood of malfunctions occurring may be minimal, the consequences of a single safety-related failure can be severe, potentially impacting numerous individuals, justifying the need to adhere to the standard EN 50128:2011.

EN 50129:2018 standard is part of the legislative package on RAMS of the railway industry, issued by CENELEC. In specific, it applies to systems with electronic technology related to safety for railway signalling applications.

This European Standard aims to define the conditions that must be satisfied so that a product, system, or electronic installation can be reasonably accepted as safe. Accordingly, this supports its safety assurance strategy being based on three fundamental pillars:

- evidence of correct management of quality in the processes of the product life cycle;
- evidence of correct management of safety in the processes of the product life cycle;
- evidence of the technical and functional safety of the product, system, or installation.

This evidence should be presented in documentary form, a safety study, that confirms that all three pillars are in control and completely justified. The safety study must follow the structure defined in the EN 50129:2018 standard and can be divided into three categories:

- generic products: characterized by being independent of the final application;
- generic applications: characterized by being able to be reused in classes or types of applications having common functions;
- specific applications: used only for a particular installation with environmental conditions and a context of use compatible with the conditions of general application.

The combined application of EN 50126:2017, EN 50128:2011 and EN 50129:2018 standards defines certain objectives in terms of Reliability, Availability, Maintainability and Safety (RAMS) and facilitates access to international markets for greater competitiveness. Attending to the scope of this project, a greater emphasis will be placed on standard EN 50126:2017.

3 RCM Implementation

This chapter expands on the thorough overview of asset management and maintenance by delving into the practical application of Reliability-Centred Maintenance. It begins by analysing concepts such as asset functionality and availability, followed by a list of maintenance activities and actions. Key approaches such as Failure Modes and Effects Analysis and Failure Modes, Effects, and Criticality Analysis are discussed, as well as risk management and RAMS. The chapter also examines Life Cycle Costing, circular economy principles, and the planning and documentation required for a successful RCM program, as well as potential obstacles to its proper implementation and comparisons of the RCM II and RCM III frameworks.

3.1 Asset Functions and Availability

Functional analysis is of utmost importance in a system reliability study as it promotes comprehensive knowledge of the various functions of each functional block of the system. Particularly, this helps delineate the inherent boundaries and interfaces with other systems and with the environment, and any interrelationships that may take place. The minimum performance of a given asset is the performance standard that should be incorporated in the function description (Rausand and Hoyland, 2004).

According to Rausand and Hoyland, the different types of asset functions can be categorized as follows:

- **Essential functions:** the mandatory functions required to fulfil the intended purpose of the functional block and are the primary reasons for installing the functional block;
- **Auxiliary functions:** the frequently less obvious functions that are required to support the essential functions, though these can be as important as the essential functions and their failure can be more safety-critical than a failure of an essential function;
- **Protective functions:** the functions intended to protect people, equipment and the environment from harm and damage. These can be further classified as safety functions, environment functions or hygiene functions according to the scope of application;
- **Information functions:** these comprise condition monitoring, various gauges and alarms, and many more similar devices;
- **Interface functions:** which are applied to the interfaces between the functional block in question and other functional blocks and can be either active or passive;
- **Superfluous functions:** if they serve no practical purpose and can be due to modifications over time, due to the functional block's operating context differing from the intended one or due to planned design characteristics (common in electronic devices with their multiple and appealing optional features). Nonetheless, the failure of these functions could potentially lead to the failure of other critical functions.

As previously noted, the primary objective of maintenance is to ensure systems fulfil their functions for as long as possible by minimizing downtime and repair costs while mitigating any consequences. This demands the use of indicators quantifying the respective periods of system operation and downtime, introducing the topic of availability (Rausand and Hoyland, 2004).

Availability is defined as the readiness for usage of a system, which can be calculated as the probability of the system being in operable condition when needed, as seen in Equation (3.1). Alternatively, it can be calculated using the concepts of Mean Time Between Failures (MTBF) and Mean Time to Repair (MTTR), as seen in Equation (3.2) (Rausand and Hoyland, 2004). Standard EN 13306:2017 defines MTBF as a mathematical prediction of the mean time between failures, representing the average operating time between consecutive failures of equipment or systems.

$$Availability = \frac{Time\ available\ for\ production - Downtime}{Time\ available\ for\ production} \quad (3.1)$$

$$Availability = \frac{MTBF}{MTBF + MTTR} \quad (3.2)$$

It should be mentioned that when studying the lifetime of an asset, Mean Time To Failure, *MTTF*, is related to a non-repairable unit, whereas *MTBF* is related to repairable systems. Both are analytically described by the same equation, Equation (3.3) (Rausand and Hoyland, 2004).

$$MTBF = \int_0^{+\infty} t \cdot f(t) dt \quad (3.3)$$

3.2 Maintenance Tasks and Actions

To deal with failures and mitigate their consequences it is possible to define certain maintenance actions and tasks tailored to the asset following the RCM methodology.

3.2.1 Proactive Tasks

Proactive tasks are appropriate for systems where the failure consequences are significant and are carried out before entering a fault state, integrating techniques from preventive and predictive maintenance strategies. The RCM methodology proposes the terms scheduled on-condition, scheduled discard, scheduled restoration, the combination of tasks and one-time changes (Moubray, 1997).

Scheduled restoration tasks, or scheduled rework tasks, involve periodically restoring an asset to its initial condition regardless of its state at the time the task is performed, including overhauling an entire assembly line at or before a specified age limit. These tasks are technically feasible if (Moubray, 1997):

- there is an identifiable age where the probability of failure increases;
- most assets survive past this age (in case of possible safety and environmental consequences, all assets must survive past this age);
- capabilities and resistance to failure are restored to the original levels.

Scheduled discard tasks involve discarding an asset or component at a given period, regardless of its current state. These tasks are technically feasible only if there is an identifiable age where the probability of failure increases and if the replacement cost and intervention period are both technically and economically viable. The frequency at which these tasks should be performed is governed by the age at which the component shows a rapid increase in the conditional probability of failure, thus the need for that age to be identifiable. According to John Moubray, the limits of life can be divided into the safe life limit, where the goal is to prevent failures with safety and environmental consequences, and the economic life limit, where only the life cycle cost of the asset is considered (Moubray, 1997).

Scheduled on-condition tasks are performed on assets to check for potential failure so that further action can be taken to ensure they continue to meet desired performance standards, commonly referred to as predictive maintenance strategies. There are three major inspection techniques (Moubray, 1997):

- monitoring techniques;
- quality variation verification techniques;
- sensory technical inspections (human senses).

Overall, on-condition tasks are viable if (Moubray, 1997):

- a clear potential failure can be defined;
- the P-F interval is minimally consistent;
- it is feasible to monitor the system at intervals shorter than the P-F interval;
- the failure has no direct consequences if it is hidden;
- there are positive environmental or safety consequences;
- they are cost-effective in cases where safety is not involved.

3.2.2 Default Actions

Default actions are actions designed to be put into practice when it is not possible to define an effective proactive task for the given asset. There are different types of default actions, and these include spare part optimization, fault-finding through periodic checks of evident and hidden functions, redesign with changes to hardware, software or in the process itself, and no scheduled maintenance ("wait and see"), where the effort to anticipate or predict is not technically feasible or not economically viable. This last approach is only applied to components with a random failure distribution or with hardly any data on failure patterns (Moubray, 1997).

An additional type of default actions is the walk-around check, which is very similar to a functional check, but with a greater emphasis on management rather than technical details. These default actions allow to spot accidental damage and any problems related to negligence or ignorance, particularly with the usage of hazardous materials. In general, it is also a good way to ensure compliance with operational standards and assess whether the maintenance routines are being correctly applied (Moubray, 1997; Basson and Aladon, 2019).

In more detail, fault-finding tasks (functional checks) fall outside the scope of predictive, preventive, or corrective maintenance, as they accept that the system will inevitably spend some time in a failed state, and are performed to ascertain if certain functions, which can be hidden, are operational or not. These tasks only apply to hidden or unrevealed failures, which in turn only occur in protective equipment.

The frequency of this periodic investigation, referred to as Failure-Finding task Interval, FFI, depends on the asset's availability and reliability, as seen in Equation (3.4). In contrast, preventive and predictive maintenance tasks are based on the P-F interval and the corresponding service life (Moubray, 1997).

$$FFI = 2 \times (1 - Availability) \times M_{TIVE} \quad (3.4)$$

Where:

FFI, Failure-Finding task Interval

M_{TIVE} , MTBF of the protection device

RCM specialists have proposed alternatives to this calculation, through methods such as voting systems, multiple and independent fully redundant systems or even with more rigorous methods. However, the value obtained for FFI must always be analysed critically as the interval can be too long or too short and consequently the task is inadequate. Failure-finding tasks are technically feasible if (Moubray, 1997):

- it is possible to perform the task;
- it does not lead to an increase in the risk of multiple failure;
- it is practical to do the task at the required interval.

A multiple failure occurs when protective equipment is already in a failed state and the protected function fails. The probability of this occurring is given by Equation (3.5) (Moubray, 1997).

$$PMF = PFPPF \times AUPD \quad (3.5)$$

Where:

PMF, Probability of a multiple failure

PFPPF, Probability of failure of the protected function

AUPD, Average unavailability of the protective device

The biggest challenge when it comes to calculating FFI or other indicators is having accurate data available to perform the calculations. When data is not easily accessible, then it must be obtained from other sources, such as the manufacturer, databases for commercial use, or estimated based on the performance of similar equipment. Nevertheless, for the railway sector in particular, most systems are vehicles of low-volume series or prototypes which further hampers this calculation and analysis, so internal fleet knowledge is the most reliable source.

Redesign tasks cover any actions that when performed lead to a change to the specification of any asset, altering its drawing or part list. New components can be added, or the asset itself can be changed or relocated. As it is quite a broad concept, it also applies to training, in the sense that the capability of the person undergoing training is being redesigned in a way that will affect the operation of the plant in a better way. These modifications must be planned cautiously to avoid creating more problems in the system, so the following issues must be addressed (Moubray, 1997):

- What to consider first: design or maintenance?
- What is the relationship between the asset's inherent reliability and the desired performance?

Finally, in the case of a failure (evident or hidden with multiple failure) that does not pose a threat to safety or the environment, then the decision is to perform no scheduled maintenance. The assets are kept operating until a functional failure eventually occurs, and only then are they repaired or replaced. This does not mean the organization can neglect the asset in question, it simply means that scheduled maintenance is not viable enough to be carried out. Redesigning can still be recommended, under certain circumstances (Moubray, 1997).

3.2.3 P-F Curve

While many failure modes are not age-related, they typically exhibit some form of warning indicating that they are in the process of occurring or are about to occur. In the case that enough evidence can be found that a given asset is approaching functional failure, it may be possible to avert it from failing completely and mitigating possibly catastrophic consequences (Moubray, 1997).

Figure 9 illustrates the final stages of failure. This concept is called the P-F curve, and it traces the progression of failure from its inception, through a stage where it becomes detectable (point P), and then, if left unaddressed, keeps deteriorating at an accelerating rate towards functional failure (point F) (Moubray, 1997).

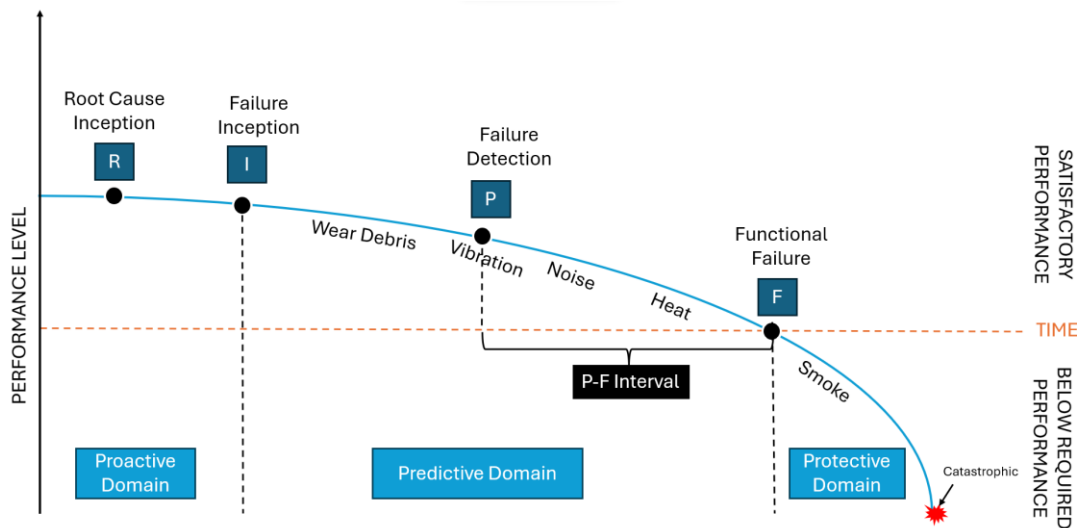


Figure 9 - P-F curve and P-F interval. Adapted from (Green, 2023).

The period between the initial detection of a potential failure and the point of functional failure is known as the P-F interval or time available before breakdown. Ideally, this interval should allow sufficient time for decision-making and the execution of maintenance tasks. Other important intervals that are represented in Figure 9 are R-I (Failure Gestation Time), I-P (Failure Elapsed Time), and I-F (Failure Development Time) (Green, 2023).

Although assets vary in their fundamental characteristics, it is essential to adapt maintenance techniques accordingly and there are some commonly employed methods to assess an asset's condition including lubricant and sampling analysis, corrosion monitoring, motor current analysis, acoustic emissions detection, vibration analysis, infrared thermography, process parameter trending, process control instrumentation, visual or physical inspections, and ultrasound testing. By utilizing these inspection methods, it becomes feasible to monitor changes in an asset's physical condition over time to aid in extending the interval between failures and facilitate the detection of critical points in the performance curve (Moubray, 1997).

While the presented P-F curve may appear to imply a constant P-F interval, this is not always the case. In fact, the variation can be quite large and introduce significant errors in maintenance management. In such instances, it is advisable to employ a shorter task interval to identify potential failures within a more feasible period. If the P-F interval shows considerable inconsistency, making it challenging to establish a reasonable task interval, a change in approach for that failure mode is recommended (Moubray, 1997).

The failure mode of an asset is dependent on various factors, many of which are affected by equipment design, setup, and operating environment. Consequently, the P-F curve is unique to each asset and can be influenced by a multitude of variables. Nonetheless, it is a valuable tool for maintenance professionals, aiding in the optimization and streamlining of planning processes, thus, leveraging the P-F curve helps enhance efficiency in maintenance operations while ensuring quality service delivery at an affordable cost (Brightly, 2023).

3.3 FMEA and FMECA

Failure Mode and Effects Analysis (FMEA) and Failure Mode, Effects, and Criticality Analysis (FMECA) techniques are widely embraced across various industries and provide a flexible analytical framework to apply throughout different phases of a product's lifecycle. These analyses serve to support and strengthen reliability and efficacy across domains such as design, development, manufacturing, and service provision (EN 60812:2018).

There are three major types of FMECA, defined as follows:

- **Design FMECA:** carried out to eliminate failures during the design phase, taking into account all types of failures during the equipment's lifecycle;
- **Process FMECA:** focused on problems stemming from manufacturing, maintenance and operational contexts;
- **System FMECA:** for potential problems and bottlenecks in larger processes, such as entire production lines.

For instance, within the automotive, aerospace, medical and other manufacturing sectors, both design and process FMEAs hold significant importance, with the documentation of such analyses being a customary requirement for their respective suppliers. Often, software solutions are used to facilitate the development of FMEAs (Falck, 2010; Kececioglu, 1991).

Beyond the analytical utility, the FMEA/FMECA reporting structure serves as a centralized repository for reliability-centric data concerning systems or processes to facilitate the management of reliability growth policies by organizing information related to product failures, pinpointing observed failure modes during testing, and proactively identifying potential future failure modes. Each potential failure is ranked by the severity of its effect so that corrective actions may be taken to eliminate or mitigate its risk (Ćatić and Glišović, 2019).

The difference between FMEA and FMECA is the Criticality aspect, whose evaluation entails a qualitative assessment of the severity or significance of the failure mode's impact and the need to mitigate it by prioritizing specific maintenance actions or design improvements. Criticality can be quantitatively evaluated based on a few parameters, as seen in Equations (3.6) and (3.7), and can be further complemented with a calculation of the Risk Priority Number (Ferreira, 2016).

$$C_m = \beta_m \times \alpha \times \lambda_p \times t \quad (3.6)$$

$$C_i = \sum_{m=1}^M C_m \quad (3.7)$$

Where:

β_m , Failure effect probability of each failure mode;

α , Failure mode ratio;

λ_p , Failure rate of each failure mode;

t , Operating hours of each failure mode;

M , Number of failure modes associated with each component i ;

C_m , Criticality of a failure mode, or Modal Criticality;

C_i , Criticality of an item.

Nowadays, the distinction between FMEA and FMECA has become blurred with the concepts being used interchangeably, though they are fundamentally different as explained (Stamatis, 1995).

A typical FMECA worksheet provides a quick visibility of the analysed failure modes to help in identifying potential failure points which can be eliminated or minimized with redesign (Arnzen, 1966).

The FMECA procedure involves several steps (Rausand and Hoyland, 2004):

- listing the subsystems and parts of the system in a hierarchical scheme (through functional blocks, for example);
- listing and description of all failure modes for the part under consideration, specifying performance standards;
- performing a criticality assessment to measure the risk level for each fault in terms of factors such as the probability, the severity and the detectability of a failure;
- ranking the modes of failure concerning the previous assessment;
- taking action on the high-risk problems;
- checking the effectiveness of the action adopted and revised risk analysis.

Applying the FMECA methodology aims to (Rausand and Hoyland, 2004):

- identify all failures of the system and the inherent causes, which can be done through Internal Functional Analysis;
- assess the impact of each failure mode at the various functional levels of the system under analysis in a transparent manner;
- evaluate the Criticality of each failure, defined as its influence on the system's normal operating performance levels as well as any possible consequences in terms of reliability and safety;
- calculate the Risk Priority Number (RPN) for each of the identified failure modes and rank the values, comparing them to a selected RPN threshold, to define a preliminary plan of action for reliability improvement and risk control.

Whenever any improvements are agreed upon and implemented, the FMECA worksheets need a revision accompanied by an update in the RPN calculation. Supplementary problem-solving tools, such as flow charts, Pareto charts, and brainstorming, are recommended during the review process.

3.3.1 Details on Failure Modes

One important step in any FMECA analysis is to identify and characterize the failure modes for the asset in question through extensively studying the asset's functions and functional failures, in a way to prevent or anticipate the event of a failure. A failure mode can thus be defined as any event that is reasonably likely to lead to a failure state. Some examples of failure modes are wear and tear, human error (anthropometric, human sensory, physiological or psychological factors) design faults, deterioration, lubrication problems, and fatigue. The underlying mechanisms can be due to mechanical, chemical, radioactive, electrical, or thermal factors (Davis et al., 2008).

In terms of the asset's performance, which is a function of the built-in capacity and desired performance level, there are three possible scenarios that can cause the occurrence of a failure (Moubray, 1997):

- When performance capacity falls short of the desired level;
- When the desired performance rises beyond the initial capacity;
- When the asset is not capable of performing its intended functions from the outset;

The description of a failure mode must be sufficiently detailed to enable an appropriate maintenance technique to be selected for it and identified at the level of causation. Not all failure modes should be considered to avoid "analysis paralysis", so the failure modes that should be prioritized are (Moubray, 1997):

- Failure modes that have already occurred previously in the equipment or in similar equipment, in the same operating context;
- Failure modes that are already subject to proactive maintenance routines;
- Any other failure mode that has not yet occurred but is likely to occur, in the current operating context.

Dominant failure modes are those that are responsible for a significant proportion of all failures of a given piece of equipment. Meanwhile, hidden failure modes are the ones whose failure will only become evident when requested due to a given event or when another failure occurs that highlights the hidden function. The latter is common in functional blocks that work only under certain circumstances, meaning that the component might be unavailable long before it is needed or noticed.

Additionally, there should be a distinction between partial and total failures as the inherent failure mode is different, and so are the consequences.

Afterwards, it is required to evaluate the failure effects, which describe what happens when each failure mode occurs, in sufficient detail to include all the information needed to support the evaluation of the consequences, such as (Basson and Aladon, 2019):

- When is the failure most likely to occur (start-up, normal operation, after maintenance)?
- How often would it happen if no attempt is made to prevent it (probability)?
- What evidence (if any) is there that the failure has occurred?
- In what ways (if any) does it pose a threat to safety or the environment?
- In what ways (if any) does it affect production or operations?
- What physical damage (if any) is caused by the failure?
- What must be done to repair the failure?
- Does it cause any secondary damage?
- What is the revenue loss (if any)?

The multiple consequences of failures across the various domains within an organization, including operations, logistics, quality, safety, and even the environment, paired with their significance drive the increasing interest in preventing them in the most cost-effective way that is reasonably achievable.

The significant advantage of applying the RCM logic lies in its ability to enable a more meticulous analysis of failure modes and their consequences, for a more tailored decision planning and intervention. This process classifies the consequences of failures into four major groups (Moubray, 1997):

- Hidden failure consequences: when there is no direct impact, but leads to the organisation being more exposed to multiple failures with serious, often catastrophic, consequences, usually associated with non-fail-safe protective devices;
- Safety (if it could harm someone) and environmental consequences (if it could lead to a breach of any corporate, regional, national, or international environmental standard);
- Operational consequences: if it affects production (output, product quality, customer service or operating costs in addition to the direct cost of repair);
- Non-operational consequences: if they do not affect neither safety nor production, only involving the direct cost of repair.

3.3.2 Risk and Risk Priority Number

Standard ISO 31000:2018 defines risk as the combination of the probability of a negative event (harm) occurring and its severity once it occurs, measuring the effect of uncertainty, as expressed in Equation (3.8). The risk space or risk matrix is the two-dimensional

combination of these two variables, categorizing risks as Acceptable, Tolerable or Unacceptable based on the calculated value.

$$Risk = Probability\ of\ Occurrence \times Severity \quad (3.8)$$

The risk space provides users with guidance on whether a particular risk warrants further mitigation or can be accepted without significantly compromising safety. However, relying solely on a two-dimensional definition of risk neglects other crucial decision-making factors. These factors include the ability to detect hazards before harm occurs (detectability), the practicality of corrective measures from both an economic and technical standpoint and the asset's overall value or importance (Dionne, 2013).

One of the methods for quantitatively determining criticality is the Risk Priority Number (RPN), which ranks the chance of the failure-mode occurrence (O), the severity of its failure effect (S), and the chance of the failure being undetected (D) on a numeric scale most commonly ranging from 1 to 10. The ranks for the three parameters depend on the application and FMECA standard that is used, meaning that the RPN values should not be compared between two different FMECA procedures nor used as a benchmarking tool between companies.

The criteria to define each of the global risk indicators goes by the guidelines provided in the standard EN 60812:2018. Risk is assessed here by a subjective measure of the severity of the effect and an estimate of the expected probability of occurrence over a predetermined period, as seen in Equation (3.9):

$$RPN = O \times S \times D \quad (3.9)$$

Where:

O, Probability of occurrence (sometimes the term Frequency is used)

S, Severity of the failure effect

D, Detectability

In practice, assessing RPN factors using conventional tables is not always straightforward. Maintenance staff experts often find it challenging to provide a precise numerical evaluation of these quantities, due to their intangibility and inherent subjectivity when evaluated. Despite being considered a "quantitative" approach, the technique relies heavily on qualitative assessments, projected failure rates, and other factors that are estimates, making the RPN approach less precise and applicable. In addition, the RPN scale is not continuous and can be highly sensitive to small variations in the value of one of the parameters when the others are already high (Bowles and Peláez, 1995).

Afterwards, it is possible to create a matrix to assess criticality based on the RPN value. One of the objectives of this method is to pinpoint the most critical areas, indicators, or criteria requiring intervention, thereby reducing the RPN value through appropriate tasks chosen with that goal in mind. RPN values for future scenarios are merely highly probable estimates to achieve and not fundamentally accurate.

Commonly, organizations employ an RPN threshold to determine which failure modes require corrective action and which risks are acceptable. However, it is always necessary to analyse the failure mode thoroughly and critically as there are situations where, even if the RPN value is low, the severity of the failure mode may be too high to be disregarded. Overall, the acceptable values for RPN are an engineering decision tailored to the specific organization under a well-defined context.

Figure 10 depicts a three-dimensional visualization of the severity matrix, colour-coded based on RPN thresholds for a given context of application.

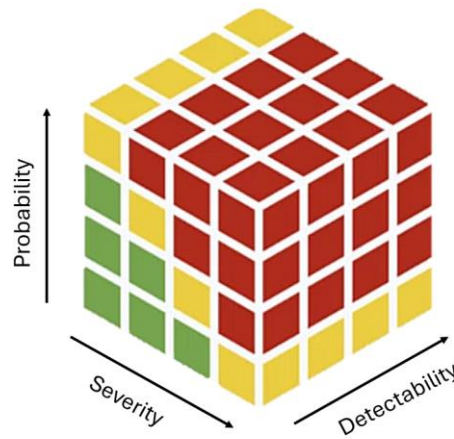


Figure 10 - Three-dimensional risk matrix. Adapted from (SoftComply, 2018).

A modified version has been proposed to provide a more consistent assessment of risk and criticality when parameters can be quantified on a logarithmic scale, leading to a continuous scale of values. This method is called Alternative Risk Priority Number, ARPN, and the value can be calculated using Equation (3.10) (Braband, 2003).

$$ARPN = O + S + D \quad (3.10)$$

Where:

- O, Probability of occurrence
- S, Severity of the failure effect
- D, Detectability

3.4 Risk Management

In any management role, there is an inherent need to make decisions that strike a balance between available resources and potential risks. Therefore, the significance of risk assessment becomes apparent in management and industrial settings where decisions must simultaneously meet the demands of asset reliability and the constraints of declining resources.

Assessing the impact of failures, often referred to as criticality, typically serves as the initial step in conducting a risk assessment. Various methods can be employed for risk assessment, though one of the most used approaches is FMECA, as previously mentioned. This method involves a bottom-up analysis, which can be complemented by a top-down Fault Tree Analysis (FTA), resulting in a formal logical analysis that illustrates "the combination of events that results in the occurrence of a specified system-level event".

The International Standard ISO 31000:2018 defines risk management as the "coordinated architecture (principles, framework, and process) for managing risks effectively", while a risk management process is "a systematic application of management policies, procedures and practices to the activities of communicating, consulting, establishing the context, and identifying, analysing, evaluating, treating, monitoring and reviewing risk".

Following the standard, the risk management process is an integral part of management across the entire organisation and is tailored to its business processes, while being embedded in its culture and practices. Figure 11 is a simplified representation of a risk management process.

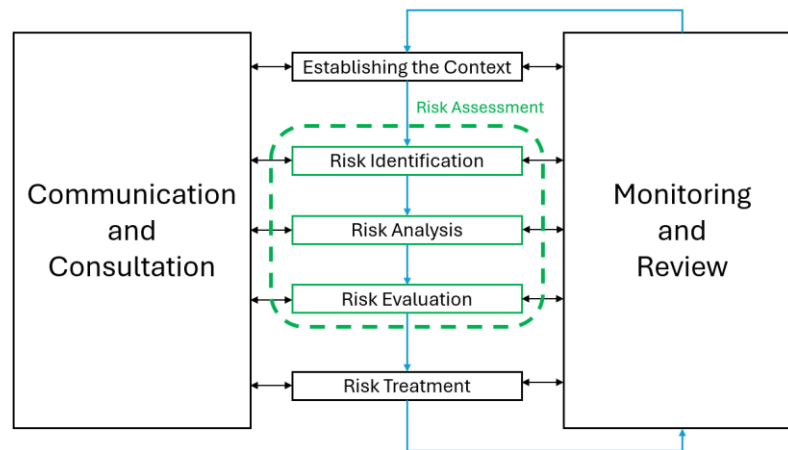


Figure 11 - Risk management process. Adapted from (SAE JA 1011:2002).

Another useful metric to assess risk is the Hazard Risk Index (HRI) which is commonly employed in military organisations for risk management. However, while adequate for general risk management purposes, this method has a significant drawback in that it may obscure critical information necessary for prioritisation within a category. Consequently, a Hazard Risk Assessment (HRA) can be conducted for risks that are deemed unacceptable or have been identified through the HRI process. Additionally, due to the lack of formalised procedures or written guidelines, the effectiveness of the HRA process relies heavily on the skills and expertise of individual analysts (Bowles, 2003).

Figure 12 depicts the As Low as Reasonably Practicable (ALARP) principle, illustrating the balance point (trade-off) between risk mitigations and risk exposures. The trade-off point represents the level of risk that is deemed tolerable and cannot be further reduced without incurring costs that outweigh the benefits gained or where implementing a solution becomes impractical.

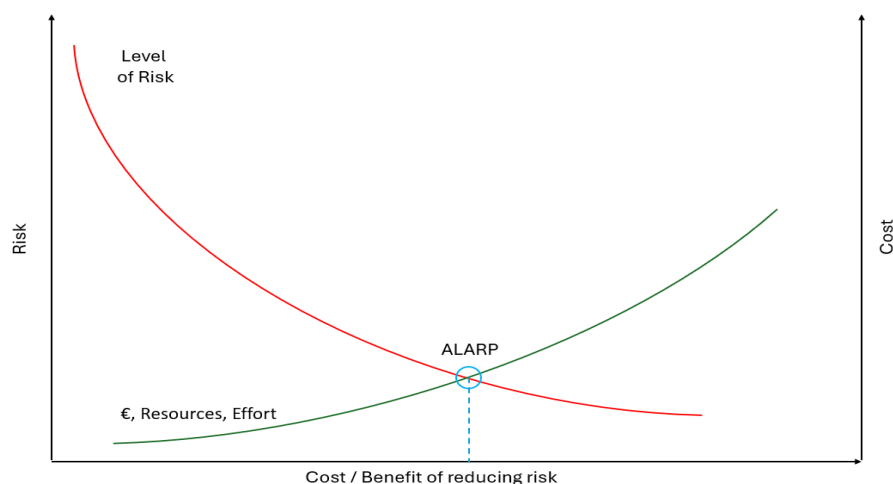


Figure 12 - ALARP principle in risk analysis. Adapted from (Amaral, 2016).

3.5 Life Cycle Costing

Life Cycle Costing, LCC, is a critical and complex indicator in an effective and thorough RAMS process. It is a (cumulative) cost management approach related to the development of a product from concept to decommissioning (whole product life cycle). These costs include all the direct and indirect expenses for acquisition, operation, maintenance, and disposal. Operating

and maintenance costs are reoccurring, while acquisition and disposal costs are nonrecurring (IRIS Guideline 3: Maintenance, 2020).

LCC analysis is useful at any point in the life of a system for proper asset management, though conducting it earlier on may provide additional benefits because it provides an understanding and forecasting of total costs, allowing for changes and improvements to the project. Technical management views costs as a loss of revenue due to poor maintenance, production loss, labour costs, downtime, and other factors. Due to its relevance, the standard EN 15341:2019 defines the major Total Maintenance Costs as follows:

- remuneration of maintenance, logistics, and administrative human resources;
- additional charges (insurance, supervision, fees, and taxes);
- consumables and spare parts (including all costs, including logistics and transportation);
- tools and equipment;
- energy and auxiliary systems;
- service providers, rented facilities;
- depreciation of equipment, workshops, spare parts warehouse;
- training and professional development;
- consulting services.

In essence, a significant portion of maintenance and asset ownership costs is often invisible, indirect, and relative to operational decisions and policies. This highlights that the most difficult step in assessing costs is often obtaining detailed and precise information on all cost components, interest rates, and inflation rates. Therefore, it is sometimes necessary to use stochastic simulation models, like Monte Carlo simulation.

3.6 Circular Economy

Despite its evolution and diversification, the industrial economy has failed to diverge from its initial linear model of resource consumption which follows a ‘take-make-waste’ pattern. Companies extract and harvest resources, transform them into products through manufacturing operations, and sell them to consumers who ultimately discard them after fulfilling their purpose. This model is outdated and unsustainable, highlighting the urgency for companies to take responsibility and implement more efficient and environmentally friendly strategies. This new development is encapsulated in the concept of circular economy (Ellen MacArthur Foundation, 2013; Ellen MacArthur Foundation, 2022).

Ellen MacArthur Foundation (2022) defines circular economy as “a system where materials never become waste and nature is regenerated”. All resources are continuously kept in circulation through maintenance and transformative processes like reuse, refurbishment, recycling, and composting. It is supported by the transition to favouring renewable energy sources and three basic principles:

- eliminate waste and pollution;
- circulate products and materials continuously (at their highest value);
- regenerate nature.

The emergence of the circular economy model is based on reengineering asset management practices to fulfil both internal and global sustainability goals and tackle climate change. These innovative practices include crafting asset systems with inherent regenerative capabilities and diminishing reliance on global supply chains, among other measures (Ellen MacArthur Foundation, 2022).

Operating within the circular economy framework involves adopting a system-centric thinking approach for sustainability which allows organizations to establish connections between crucial drivers, networks of stakeholders, and value chains. This framework is

summarized in the butterfly diagram, Figure 13, with the intrinsic connections between the two cycles at play, the biological and technological cycles.

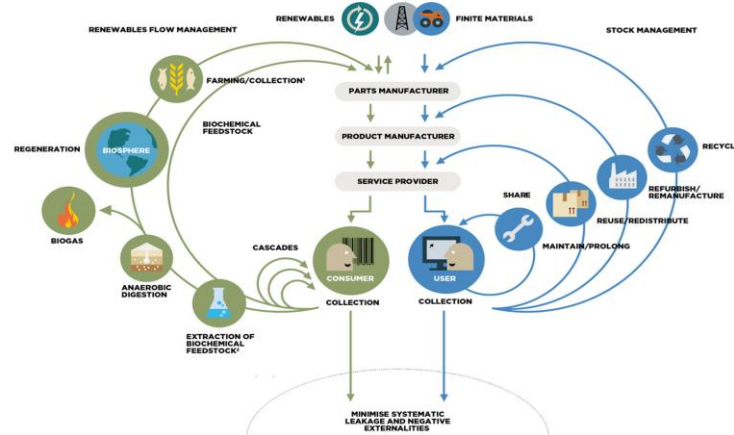


Figure 13 - The circular economy model (Ellen MacArthur Foundation, 2022).

Within the circular economy model, maintenance assumes a pivotal role in satisfying the objectives of this model, from enhancing equipment performance to promoting circularity. The maintenance techniques put in practice can be CBM, TPM, and RCM, performed within a Lean perspective to bolster availability and avoid failures with catastrophic consequences. Furthermore, their adoption facilitates the incorporation of Predictive Analytics, aligning with the broader concept of Industry 4.0 and establishing a solid foundation for innovative business models (Sobral and Ferreira, 2018).

3.7 Contribution of RCM to Asset Management

RCM is an essential aspect of asset management which offers an organized framework for establishing failure management protocols for physical assets to enable long-term and dependable operations. RCM not only improves asset reliability and decreases breakdowns, but it also increases productivity, lowers costs, increases safety, and improves environmental performance, making it a significant asset in a variety of sectors (Nadarajan, 2014).

Proper implementation of RCM must always follow multiple industry standards and regulations, which then ensures that organizations adhere to optimised maintenance practices and properly document all steps of the methodology. The dynamic process of RCM involves continuous monitoring and improvement, using feedback from maintenance activities and asset performance to refine strategies and achieve improvements in asset reliability and management practices (Breland et al., 2010).

Overall, RCM's systematic and analytical approach to maintenance not only improves asset reliability and performance but also optimizes maintenance costs and enhances the overall effectiveness of asset management. This approach ensures that maintenance activities are both effective and efficient, contributing to the long-term success and sustainability of an organization's asset management program.

Annex A provides more detailed information on RCM, particularly the importance and goals of RCM review groups, and the planning and documenting procedures.

Annex B extends on a thorough comparison between RCM II and RCM III methodologies, highlighting the similarities and differences.

4 Case Study - Y25 Bogie Frame

After discussing the theoretical background of the scope of this dissertation, where the emphasis is put on the FMEA/FMECA risk assessment technique and RCM methodology, this fourth chapter introduces and describes the case study of the Y25 Bogie for freight wagons. The chapter provides an overview of the Bogie model, followed by a functional breakdown and the application of an FMECA to highlight critical failure modes to be prioritised in maintenance plans. The choice of RCM over any other maintenance methodology, such as TPM, is presented and justified in this chapter.

4.1 Context

This dissertation expands upon the work performed by (Bastos, 2024) by carrying out an extensive examination of the Y25 bogie within the complex landscape of asset and maintenance management. The maintenance methodology used is RCM as it focuses on finding the best maintenance strategy with a focus on critical components, though TPM is still a suitable option.

RCM ensures that resources are allocated efficiently to prevent system failures and downtime. Maintenance tasks are defined and prioritised according to the criticality of a given failure mode with given causes and effects, leading to optimised maintenance plans that address the maintenance needs of the equipment. Nonetheless, RCM integrates well with TPM, enhancing the planned maintenance pillar of TPM by providing a structured approach based on reliability analysis, meaning that the results obtained could be further supported by a TPM analysis (Nakajima, 1988).

Pivotal to this research is the creation of an FMECA, which will examine every aspect of the bogie's functionality, potential vulnerabilities, and criticality parameters supported by the calculation of the RPN index and definition of plausible action tasks to reduce this value. The final goal of this assessment is to obtain the appropriate authorisation for its market introduction while strictly adhering to established Technical Specifications for Interoperability (TSI) rules, allowing the bogie to be suitable to run in the European Union rail system.

To accomplish these goals, the following documents had to be analysed:

- Directive (EU) 2016/797 of the European Parliament and of the Council on the interoperability of the rail system within the EU;
- Freight Wagons TSI Commission Regulation (EU) No. 321/2013 and its amendments;
- Guide for the application of the WAG TSI.

As the bogie that was designed is a freight bogie, in accordance with Directive (EU) 2016/797, the bogie must comply with the requirements set forth by the Technical Specifications for Interoperability (TSI) to ensure interoperability and safety in freight rail transport. The applicable TSI for freight wagons is The Commission Regulation (EU) No 321/2013 of March 13th, 2013, including all its amendments.

The Interoperability Directive defines the design operating state as “the normal operating mode and the foreseeable degraded conditions (including wear) within the range and the conditions of use specified in the technical and maintenance files.” The Directive further classifies the foreseeable degraded conditions according to different levels and categories, which will not be analysed in the current work.

The Directive (EU) 2016/797 defines the rail system as an integrated system that includes freight wagons and must be verified for consistency. This consistency is compared to the rolling stock subsystem specifications, network compatibility, subsystem interfaces, and

initial operating and maintenance standards, as defined by the Directive. The technical file must include design values for network compatibility. The TSI for freight wagons guarantees that the basic characteristics required for interoperability and safe integration are harmonised, including those for determining compatibility between a unit and the network. According to given key criteria the functional and technical specifications of the rolling stock (freight wagons) subsystem are defined and classified into structures and mechanical parts, gauging and vehicle track interaction, braking, environmental conditions, and system protection. These specifications do not enforce specific technical solutions, except where necessary for interoperability and compliance with essential requirements.

All TSIs include a specific chapter dedicated to maintenance rules, and maintenance is considered a crucial subsystem according to Directive (EU) 2016/797. Compliance with the standard EN 50126:2017 is widely recognized as a recommended practice within the railway sector. This standard is mentioned in the application guide for the TSI for Wagons, which significantly facilitates the certification of components and subsystems. Furthermore, following the application of the RAMS standard, all other practices of RCM are adhered to, ensuring the efficient and safe operation of the railway system.

Thus, strict adherence to standards and technical specifications, such as the Commission Regulation (EU) as stated above and the standard EN 50126:2017, not only ensures regulatory compliance but also promotes excellence in the maintenance and operation of freight bogies, contributing to a safer and more reliable rail transport system. This justifies the need for an extensive review with a deep understanding of all the standards and guidelines that were stated.

Overall, the following objectives are highlighted, demanding a comprehensive analysis and study of the standards during the design phase, development of the FMECA and action plan:

- **Certification and Market Authorization** – Commitment to ensure the bogie meets all the necessary regulatory requirements outlined in Directive (EU) 2016/797 for interoperability. This must include rigorous testing and compliance checks to obtain official certification and authorization for market placement.
- **Interoperability Across the European Union** - Design and manufacture a bogie that is fully interoperable across the continent. This means it must be capable of operating seamlessly on rail networks throughout all EU member states. To achieve this, the bogie will adhere to standardized technical specifications, ensuring compatibility with various national rail systems, and enhancing cross-border rail transport efficiency.

Following a structured approach to the FMECA as an integral part of an RCM project is significant in the industrial context to define suitable maintenance programmes to be adopted by the Entity in Charge of Maintenance, ECM, as defined in Directive (EU) 2016/798. The ECM is responsible for maintaining vehicles. Each vehicle must be assigned to an ECM unit to operate on the European rail network, ensuring enhanced safety in rail traffic. The ECM guarantees roadworthiness, operational safety, expertise, and legal compliance.

4.2 Application of FMECA Methodology

4.2.1 Planning Stage of FMECA

Planning an FMECA involves considering why the analysis is to be performed, what item or process elements are to be analysed under what scenarios, and how the analysis should be most effectively and efficiently performed. Managers and stakeholders should be consulted, as appropriate, so that their objectives and interests in the analysis are properly met and guarantee dynamic involvement and commitment. The entire FMECA workflow presented

strictly adheres to the guidelines provided by standard EN 60812:2018 and can be consulted in Annex D.

The output of the planning phase is a plan that describes a tailored cost-effective application of the FMECA for the context that (EN 60812:2018):

- defines the objectives and scope of analysis;
- identifies the analysis boundaries and use scenarios;
- defines decision criteria for the treatment of failure modes;
- determines how the analysis will be documented and reported;
- specifies how resources will be allocated to the analysis activities.

The planning stage starts with the statement of the objectives and purpose of the analysis to ensure the outcome is valuable and satisfies organizational expectations. The FMECA applied to the bogie aims to perform a comprehensive study on the bogie and its subassemblies, to identify means of improving its conceptual design, and to list opportunities for reliability improvement to comply with TSI to certify the bogie and allow it to be introduced to the market, as stated before. The ultimate deliverable is intended to be a worksheet with detailed information on functions, failure modes, consequences of failures (both local and global effects), root causes, RPN assessment, and plausible action tasks to reduce RPN. This deliverable is of paramount importance to the effective implementation of the RCM methodology.

Additionally, as outlined by EN 60812:2018, the planning stage of an FMECA requires careful consideration of resources (informative, personnel and physical resources). This includes identifying skilled personnel with the knowledge to contribute to the FMECA, the time required to gather data, and the materials needed to conduct a thorough analysis, ranging from databases to field operating experience data on failures and details on every component.

The adoption of definitions according to a standard proves to be quite useful to unify the whole work and guarantee there is uniformity and no misunderstandings of the concepts being used. According to standard EN 60812:2018, the following definitions are presented:

- **Function** – the purpose or intended task that a component, system, or process is designed to perform within a larger context;
- **Failure Mode** – the way in which a component or system fails to perform its intended function;
- **Local effects of Failure** – consequences or impacts that a failure of a specific component or subsystem within a larger system can have on its immediate surroundings or functions;
- **Global effects of Failure** – broader or system-wide consequences that result from the failure of a particular component or subsystem within a larger system;
- **Failure Cause** – “set of circumstances that lead to failure”.

Having detailed the FMECA planning stage, in which the methodology, terminology and decision criteria with the associated implications are rigorously outlined, the analysis stage is the appropriate next step, allowing for a deep study of the functional breakdown, failure modes and their potential ramifications.

4.2.2 Analysis Stage of FMECA

Following the planning stage, a functional breakdown of the system under analysis is required to form functional subsystems and identify the basic components that allow the system to function. The identification of subsystems or machine components must be as thorough as possible since the omission of even a seemingly irrelevant element can adversely affect the FMECA and the intended results and benefits of this analysis. The breakdown will stop

whenever a Line Replaceable Unit (LRU) is identified, and the final component tree can be seen in Figure 14. Annex H provides the same component tree translated into Portuguese.

LRUs concentrate on the operational and maintenance aspects of system reliability. These modular components or assemblies are intended for rapid and easy replacement or servicing in operational locations (lines), reducing downtime and maintenance expenses (Deursen, 2020).

In the context of RCM, identifying Functionally Significant Items (FSI) is crucial as it allows for the prioritization of components that are vital to system operations. By pinpointing these critical items, maintenance efforts can be more effectively directed towards preventing failures that would have the most significant impact on system performance and safety. This targeted approach not only enhances overall reliability and efficiency but also optimizes resource allocation, reduces downtime, and extends the lifespan of key assets (Rausand and Hoyland, 2004).

While LRUs serve an important role in aiding effective maintenance and repair procedures, they may not always correspond directly to FSI. Some FSIs may be LRUs, but not all LRUs are FSIs. Nonetheless, LRUs make a major contribution to system availability and supportability, which improves overall dependability and operational efficiency and are the focus of the FMECA chapter.

It should be noted that it is not feasible to list all the possible failure modes that can compromise the functionality of the system, thus only the most relevant ones will be presented for the FMECA analysis. Additionally, for some rolling stock components, it is possible to identify more than one failure mode present at once, but failure modes should be recorded separately.

As stated in the MIL-STD-1629A:1980, an FM relates to the way a component fails to fulfil its intended function thus its description must abide by the following key points:

- relate to how the failure is observed;
- describe the manner the failure occurs;
- describe the impact/effect of the failure on the component;
- relate to performance measurement of the component.

CEN/TR 17696:2021 is a Technical Report issued by the European Committee for Standardisation (CEN). This document offers guidelines providing methods, approaches, suggestions, and best practices relevant to the railway industry to ensure that safety-critical components and systems are properly assessed and maintained to reduce risks. Furthermore, this paper strives to develop a common understanding of the criteria used and provide practical help in defining plans to fulfil the maintainability objectives.

In this work, the CEN/TR 17696:2021 guidelines are employed to define the most critical to safety components of the bogie and thus provide a more thorough explanation of these elements, that cannot be contemplated on the FMECA table. According to the document, safety-critical components are “components for which a single failure has a credible potential to lead directly to any train collision or derailment of trains resulting in the death of at least one person or serious injuries to five or more persons or extensive damage to rolling stock, the infrastructure or the environment; and any other accident with the same consequences which has an obvious impact on railway safety regulation or the management of safety”. To clarify, the definition of extensive damage is also provided, referring to “damage that can be immediately assessed by the investigating body to cost at least two million € in total” (CEN/TR 17696:2021).

The identification of these components is performed with a risk-based analysis attending to the intended use and environment, normal or degraded mode of operation, and return on

experience. Based on these guidelines, the following safety critical components have been elected (CEN/TR 17696:2021):

- Axle Box Bearings;
- Axles;
- Braking System;
- Lubrication System;
- Primary Suspension Springs;
- Seals.

Axle Box Bearings

Out of all the mechanical components of an axle box, bearings are the most design-critical due to their vital impact on operating safety, reliability, and economics of railways. Bearings in an axle box reduce friction, support loads, facilitate smooth rotation, minimize wear and tear, and absorb shock and vibration, all of which are essential for the efficient and safe functioning of vehicles (Evans, 2011; Jesus, 2018).

Bearing analysis is also extremely difficult due to the large number of engineering parameters associated with bearing design, with every engineering decision needing to comply with technical standards. The most widely used types of bearings are rotary motion bearings, ball bearings, tapered roller bearings and linear motion bearings. Each type is suited for a specific context due to their different design specifications (SKF, 2011).

Bearings are projected to work for a finite life due to inevitable signs of metal fatigue on the bearing's rings or rolling elements. Therefore, manufacturers commonly assign bearings a theoretical/nominal life, L_{10} , which is the fatigue life, expressed in the number of revolutions or converted to the number of operating hours, that 90 percent of a statistically significant large group of identical bearings operating under identical conditions are expected to reach, or even surpass. Though this indicator is a reasonable estimate for most generic applications of bearings, the reliability of this mechanical component is conditioned by a multitude of additional factors, such as lubrication, degree of contamination, proper mounting, and other operational conditions, which translates to the need to correct the L_{10} indicator accordingly (SKF, 2011).

There is extensive data on the reliability of these types of bearings and based on the literature, TBU (tapered roller bearing units) are the most common in railway applications and were the chosen type for the Y25 Bogie case study. In specific, to comply with the geometrical constraints of the Bogie, the bearings used were from the TBU 120 series (Bastos, 2024).

When conducting the FMECA analysis, some other failure modes stand out with possible consequences on the stability and safety of the vehicle and thus demand a more thorough explanation.

Proper lubrication of the bearings is imperative to have a smooth motion by reducing the friction between the moving parts. Bearing maintenance usually involves a comprehensive vibration signal analysis that can distinguish the normal vibrations of the bearings from the transmission paths and environmental noise that blends in and decreases the detectability of potential FM (Li et al., 2018).

Additionally, in most applications of bearings in the railway industry, there is a flow of current that leads to the formation of micro craters on the surface of the mechanical elements. The localized deformation or cratering of the surface is the result of impacts of extremely small particles travelling at high velocities (carrying kinetic energy) that transfer this energy on contact.

Axles

Axles are a crucial component of railway vehicles since they play a vital part in assuring the vehicle's safety, performance, and reliability. As the principal structural component that connects the wheels, axles bear the vehicle's weight and smoothly transmit traction and braking forces from the wheels to the rail (Jönsson, 2002).

Axles must be mechanically strong enough to survive the significant static and dynamic loads encountered during operation, such as carrying the train's weight and sustaining the forces exerted during acceleration, deceleration, and cornering. Furthermore, due to the repeating nature of the loads, axles must be very fatigue-resistant, allowing them to withstand millions of load cycles without cracking or failing. Axles must also be able to withstand impact forces resulting from track imperfections or unexpected loads. High impact resistance reduces the likelihood of a sudden failure under unexpected stress. The surface quality of axles is critical because faults can serve as commencement places for fractures and corrosion, resulting in probable failures. Maintaining surface integrity requires rigorous examination and maintenance. The material used for axles must meet strict specifications for tensile strength, cleanliness, and consistency. High-quality materials ensure that the axle is durable and reliable under a variety of operating circumstances (CEN/TR 17696:2021).

These properties of axles must conform to the specifications referenced in technical standards, which define the decision criteria for permissible stress and the calculation methods that must be validated to guarantee system reliability.

A verification procedure must be in place during production to guarantee that there are no defects that have a detrimental impact on safety due to changes in the mechanical properties of the axles. This includes testing tensile strength, impact resistance, surface integrity, other material properties, and cleanliness, with batch sampling for every characteristic. Some standards prescribe the most suitable verification methods for ensuring end-product quality, detailing the number of samples to be tested and the procedures for dealing with modifications to the design or changes in the axle material manufacturer (CEN/TR 17696:2021).

Braking System

The braking system is an integral component of the bogie and thus its design specifications must comply with the minimum reliability, maintainability, and operational safety requirements, such as performing controlled braking without losing much braking power over time and being failure-safe. There are multiple braking methods, namely service braking, emergency braking, immobilisation braking, and park braking, while the complexity of the braking system can range from pneumatic or disc pump to electromagnetic or regenerative. It is comprised of brake pads, brake blocks, brake block holders, and a brake steering system, and other mechanical parts designed in such a way as to equally distribute the braking force applied on the wheels. Additionally, a spring-actuated weighting valve (proportional load valve) is mounted on the bogie which transmits a pneumatic signal that is proportional to the load (weight) of the vehicle and allows it to regulate the braking force (Bastos, 2024).

This system's function is to reduce the speed or even immobilise the vehicle during service, emergency, or park operation in an efficient, safe, and progressive manner within the pre-set acceleration values. It works by converting the kinetic energy to heat in a very short time and then either absorbing or dissipating the heat through energy transfer. Braking operations are controlled by the driver by the driving handle or the brake application button.

The braking system plays a crucial role in ensuring the safety of the railway network. Consequently, the design of a unit's braking system must undergo a rigorous risk assessment following the Commission Implementing Regulation (EU) No 402/2013 to address the potential

hazards associated with the complete loss of braking capability. The severity of this hazard is classified as catastrophic under two conditions (CEN/TR 17696:2021):

- when it affects only the unit itself due to a combination of failures;
- when it affects the braking capability of multiple units due to a single failure.

Additionally, the TSI enforces a risk assessment for the braking system that must adhere to the standards set by Commission Implementing Regulation (EU) No 402/2013 on risk evaluation and assessment (the Common Safety Method regulation). The risk assessment can be based on the following accepted principles (CEN/TR 17696:2021):

- Application of codes of practice and risk evaluation;
- Use of reference systems and risk evaluation;
- Explicit risk estimation and evaluation.

The braking system of the bogie from the case study is made from grey cast iron due to this material's economic advantages and overall good properties, ensuring functionality with high efficiency. Nevertheless, only this brief explanation will be provided for the braking system in favour of other components of the bogie since the braking system is purchased directly from certified suppliers that guarantee the components already comply with the required regulations.

Lubrication System

The analysis of the lubrication system must reflect the conjoined analysis of three elements: the lubricant itself, the components to be lubricated, and the components that guarantee there are no leakages (such as seals). A generic failure mode, namely "Inadequate lubrication", can be attributed to any of these three elements, depending on the context.

The selection of adequate lubricating oils for the lubrication system of the axle box roller bearings must comply with the standard EN 12081:2017 which defines the minimum requirements to ensure certain performance and quality levels. To attain approval, the lubricating oils must provide satisfactory results with no abnormality in performance and service tests leading to the acceptance of their technical documentation. The optimum bearing performance and maximum service life can only be obtained when the right quantity of lubricating oil is applied with the right periodicity (EN 12081:2017).

Besides selecting the appropriate grease, it is imperative to ensure it is stored properly to avert its contamination and leakage, which are commonly identified failure modes of the lubricant, as the reliability of this element is directly impacted by its degree of cleanliness. Most lubricating oils are in the liquid state and thus easily contaminated by moisture or solid particles (SKF, 2024).

The harsh operating conditions of a lubricant lead to its inevitable deterioration over time with a loss of its properties, which can be further aggravated due to factors such as heat, moisture, internal or external contamination, entrapped air, or other incompatible gases. Of these degradation mechanisms, which can be physical or chemical, two common ones will be explained in further detail (Livingstone, 2019):

- **Oxidation** - due to the reaction of the lubricating oil with oxygen which leads to an increase in its viscosity, formation of varnish, sludge and sediment, breakdown of the base oil, corrosion, and loss of foam properties, among others;
- **Thermal breakdown** – this process is a consequence of the dissipation of heat by the lubricating oil, which can sometimes be overheated and lead to its vaporization, decomposition, or generate insoluble by-products, with the loss of some additives or changes to its thermodynamic properties, particularly the viscosity.

Primary Suspension Springs

Springs are mechanical components used to exert force, provide flexibility, and store or absorb energy in the form of forces and vibrations (damping). The suspension system aims to avoid derailment and to uncouple vibration and noise between the wheelsets and the vehicle body. The reliability of the springs is a direct consequence of their material, design considerations, manufacturing processes, and the operating environment.

The helical springs from the bogie's primary suspension system were carefully selected based on structural design analysis, specifying their shape, material, dimension, and other mechanical properties. This analysis had to consider multiple factors to ensure the springs can withstand any solicitations during their useful life, such as loads and displacements over time, operating temperature, resonance vibrations, and corrosion, among others (Bastos, 2024).

This subsystem includes some inherent redundancy, as the vehicle can still operate with the failure of one set of springs if the other set is still in normal operating conditions. Nevertheless, the work performed was thorough enough to consider the different scenarios at hand and compare the consequences of these events to the RPN.

Seals

A seal is a device placed between two surfaces to restrict the flow of fluid from one region to another. Seals are required for both static and dynamic applications, and seals such as O-rings can be used for both applications. Static seals, such as gaskets and sealants, are used to prevent leakage through a mechanical joint when there is no relative motion of mating surfaces other than that induced by environmental changes. A dynamic seal is a mechanical device used to control the leakage of fluid from one region to another when there is a rotating or reciprocating motion between the sealing interfaces (Carmody, 2014).

The reliability of a seal design is determined by the ability of the seal to restrict the flow of fluid for its expected life in a well-defined operating environment. This component must be compatible with the fluid. The failure rate of this type of component can be estimated based on parameters obtained from engineering drawings, design standards or actual measurements, while most other factors have a negligible impact on reliability.

The primary failure mode of a seal is leakage, meaning the seal is no longer able to restrict the flow of fluid. Further details are explored in the FMECA worksheet.

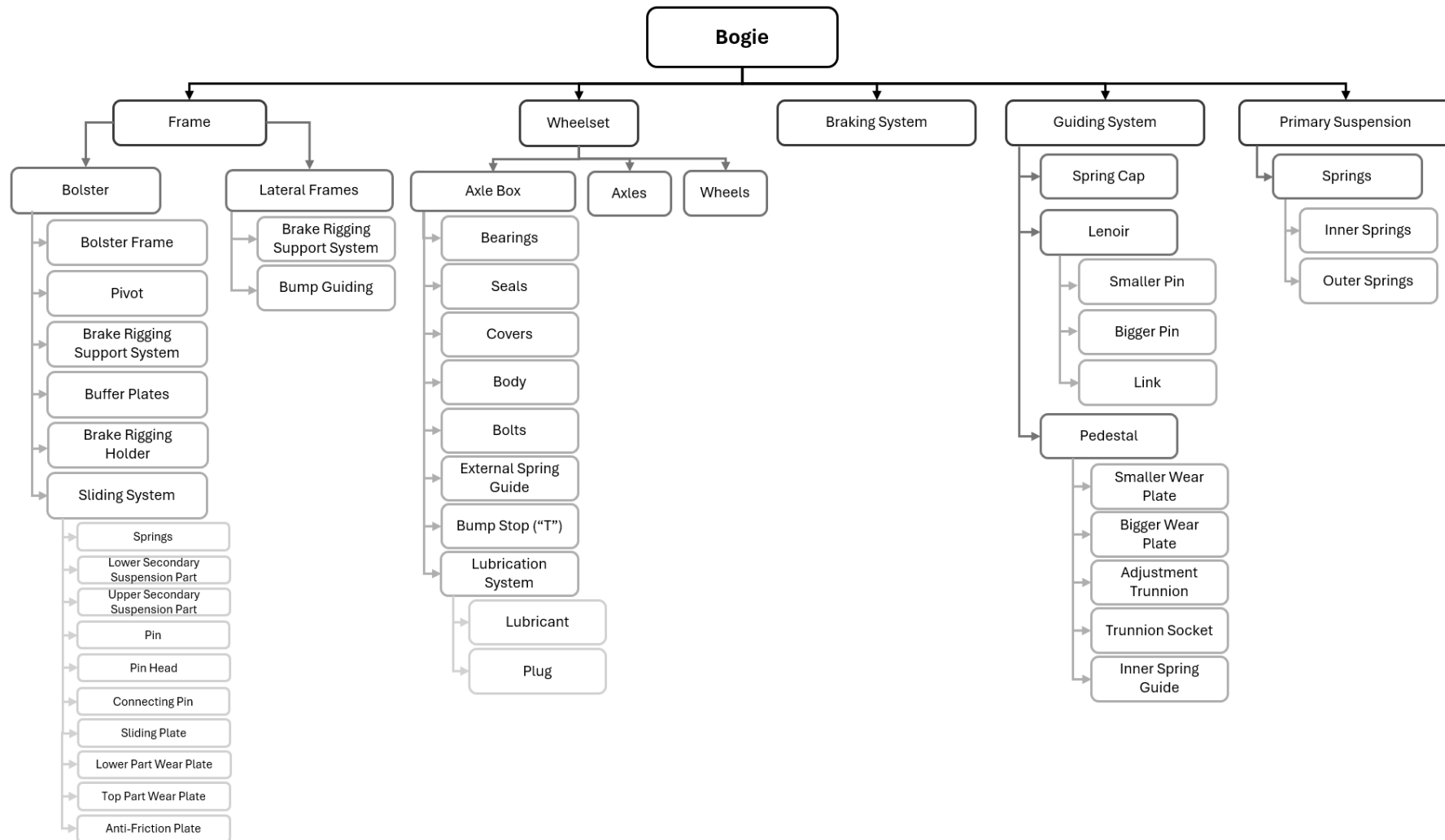


Figure 14 - Functional breakdown of the Bogie system.

4.2.3 FMECA Outputs

Certain assumptions and standards were necessary to streamline the RPN calculation. UIC Guidelines and Standard EN 60812:2018 were paramount in establishing a general methodology to evaluate and rank each RPN parameter. Even so, these guidelines assume there is high-quality empirical data on system failures for a correct classification, which was not possible for the limited timeframe of this dissertation. As such, it was imperative to consult maintenance databases and past projects in similar application domains to allow for reasonable failure rate and reliability estimates. A project called “Innovative Monitoring and Predictive Maintenance Solutions on Lightweight Wagon” which was developed from 2016 to 2019 was the primary reference for data to estimate RPN and propose adequate maintenance actions, as its Work Package 4 deliverable (“Cost-driven and reliability-driven analysis of wagon condition data”) contains detailed information on system failures that is quite similar and applicable to the bogie under analysis. Annex E presents the detailed information provided by the UIC Guidelines and Standard EN 60812:2018 required to estimate the RPN parameters.

For the cases where there was no existing reference to support the values attributed to the RPN parameters, standard operating conditions were assumed and the RPN parameters were estimated through comparison with the known reference values. Consequently, there is an inherent subjectivity in the results obtained that was already expected and unavoidable.

In terms of assessing the Severity of each failure mode, different values were attributed considering the local and global effects associated with each FM that occurs due to a certain failure cause. As such, the same FM for the same component may have different values for the severity parameter, if the effects of said FM vary according to the underlying failure cause. Higher values for severity are more suitable for FM that lead to greater deterioration of the component or that translate into damage to other components of the bogie system. Certain FM that can lead to derailment are considered the most severe and thus will have a maximum value for Severity (10).

When it comes to assessing the Detectability number, UIC provides some guidelines based on the control criteria for inspection of each failure mode, which includes visual checks, measurements, hammer blow tests, operating tests, and actuation of the component in question (commonly known as “Pull or Move”). The inspection methods were listed in ascending order of the Detectability number. However, due to the lack of empirical data and maintenance reports, this value had to be estimated according to reasonable criteria. Lower Detectability ranks refer to failure modes that can be more easily identified through visual inspection of the current state of the component, while higher ranks (close to 10) are reserved for failure modes with little to no effects on the surface of the component and can only be identified if it is solicited (EN 60812:2018).

Using the methodology described above, an evaluation of the RPN number was performed for all the failure modes identified for all components from the functional analysis. The threshold for acceptability of the RPN number was set at $RPN = 250$ according to what is suggested by the UIC guidelines, though this value is also subjective and can vary according to specific reliability requirements. Failure modes corresponding to an RPN higher than this threshold are identified as “in need of maintenance action”, which consists of checking the possibility of creating a tailored action plan to reduce the RPN associated with the considered failure mode, through a reduction of its Severity, Occurrence, or Detectability (EN 60812:2018). Furthermore, all FM with a maximum Severity value must also be evaluated to define the appropriate maintenance plans and actions. The most critical failure modes that were identified (RPN higher than 250 or Severity equal to 10) are present in Table 1, with a specific example to be discussed in Table 2.

Table 1 – Examples of the most critical FM identified for the bogie system

Component			Codif.	Function	Failure Mode	Cause	Severity		Detectability		Frequency		RPN	Action	Severity		Detectability		Frequency		New RPN
Frame	Bolster	Brake Rigger Holder	BFBSS	Offer a stable platform for better stability of the brake rigging system and prevent the components from falling off.	Cracking	Fatigue damage starting as microcracks	unsafe with warning	9	very low	7	moderate: sometimes there are failures	5	315	Monitor the component more often and replace it if needed to avoid fatigue initiated failures	very high	8	moderate	5	very low: relative very few failures	2	80
Primary Suspension	Springs	Inner / Outer Springs	BPSI	Damping and Shock Absorption	Fracture (assuming failure of Outer / Inner Springs)	Misalignment and harsh operating conditions	unsafe without warning	10	high	3	low: relative few failures	3	90	Immediately replace the springs that have already failed and ensure their proper installation	moderate	6	very high	2	very low: relative very few failures	2	24
Wheelset	Wheels		BWAW	Ensure contact with railway tracks to allow for running even with freight load	Wear of wheel's flange	Rail faults	unsafe without warning	10	low	6	moderate: sometimes there are failures	5	300	Monitor the condition of the railway tracks and plan interventions to minimise possible damage to the vehicle	high	7	moderate high	4	very low: relative very few failures	2	56
Wheelset	Axle Box	Bearings	BWABB	Support loading. Smooth movement of the train	Noisy or Overheated Bearing	Corrosive agents	unsafe without warning	10	very low	7	moderate: seldom there are failures	4	280	Monitor equipment more often to ensure it is still in good operational condition	moderate	6	high	3	very low: relative very few failures	2	36
Wheelset	Axle Box	Bearings	BWABB	Support loading. Smooth movement of the train	Noisy or Overheated Bearing	Distorted bearing seals	unsafe without warning	10	very low	7	moderate: seldom there are failures	4	280	Constant monitoring of the condition of the bearings to ensure functionality	very high	8	moderate high	4	very low: relative very few failures	2	64
Wheelset	Axle Box	Bearings	BWABB	Support loading. Smooth movement of the train	Bearing seizure	Loss of lubricant	unsafe with warning	9	little	8	moderate: seldom there are failures	4	288	Constantly monitor the state of the lubricant	moderate	6	moderate high	4	low: relative few failures	3	72
Wheelset	Axle Box	Body	BWAB	House and enclose the axle bearings, protecting them from contaminants	Fatigue Damage	Cyclic loading	unsafe with warning	9	very low	7	moderate: seldom there are failures	4	252	Monitor the component more often and replace it if needed to avoid fatigue initiated failures	very high	8	moderate high	4	very low: relative very few failures	2	64

Table 2 - Specific details for a FM of the Wheelset Axle Box Bearings

Component			Codif.	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure	Cause	Severity 1.: B 2.: C		Detectability 1.: B 2.: C &		Frequency 1.: B 2.: A		RPN
Wheelset	Axle Box	Bearings	BWABB	Support loading. Smooth movement of the train	Noisy or Overheated Bearing	Seizure, surface cracks.	At the limit, leads to derailment	Corrosive agents	unsafe without warning	10	very low	7	moderate: seldom there are failures	4	280

Due to the dimension of the FMECA table, which can be fully consulted in Annex J, only an illustrative example will be presented and justified in detail, as seen in Table 2. One of the components of the Wheelset subsystem is the Axle Box Bearings, which were also identified as critical to safety components during the analysis stage of the FMECA. As presented earlier, the function of bearings is to support loads and allow for smooth movement of the vehicle. These components can fail (meaning their function is impaired) due to a variety of failure modes associated with different failure causes, such as seizure due to inadequate heat removal capability or due to the loss of lubricant or, as the example to be analysed shows, the failure mode can be “Noisy or Overheated Bearing” caused by the presence of “Corrosive agents” that interact with these components and promote their degradation.

In this case, due to the interaction between the bearings and the corrosive agents, the bearings will show signs of seizure paired with surface cracks (“Bearing seizure” was identified as another FM with its effects and RPN), which can lead to derailment of the train. As stated earlier, derailment is extremely dangerous causing severe damage to the train and can result in deaths. Therefore, the Severity parameter is maximum (10). This FM can occur due to other causes (as discussed in the FMECA spreadsheet) and due to the similarities between them in terms of effects, every case has the same value for Severity and Detectability, with different Frequency according to the nature of the underlying cause. The value for Detectability was estimated to be 7 (relatively high) considering the practical difficulties of assessing the presence of corrosive agents that can be causing damage and leading to bearing failure. The value for Frequency was estimated to be 4 (slightly below average), assuming that since bearings are critical to safety components there should always be handled with extreme caution to ensure they can operate under normal conditions with enough lubrication and without corrosive agents. This results in an RPN of 280 which is above the threshold and should have high priority when defining the mitigation plan due to its high Severity.

Some mitigation actions were identified to target the most critical failure modes to reduce their RPN achieved by a decrease in at least one of the parameters needed to calculate the RPN. Most mitigation actions proposed rely on improving the monitoring of the state of the equipment and ensuring that the equipment is properly aligned and assembled. Consequently, the detectability value decreases as there are more opportunities to detect the occurrence of a failure during a monitoring action, and the frequency of the failure mode decreases as the component can be preventively replaced and thus will not fail, and the severity can also decrease given that it is possible to take appropriate measures in response to the state of the asset even if the consequences of the failure remain as severe. Another key mitigation action that can be performed is giving proper training to the operators to ensure the components are properly aligned and assembled and that there are fewer defects during welding operations, leading to a decrease in the frequency of these failure modes. The prioritisation of the implementation of these actions should follow the RPN value: the higher the RPN value, the higher the priority of implementing said action.

There are a multitude of other actions that could be proposed tailored to the system under analysis but given the lack of data and inherent subjectivity in this analysis only these more generic actions were proposed.

4.3 Conclusions of the FMECA

In the case that there was high-quality data on the failure rate or MTBF of all components and systems, it would be possible to create a Reliability Block Diagram, RBD, for the bogie system and assess the reliability and availability of the whole system. The data available was not sufficient to perform this analysis but a brief overview is provided in Annex C. One way to promote the documentation of real-time data and help in the transition to CBM

techniques is the development of sensor technologies that can be installed directly in the railway infrastructure and vehicles, as discussed in Annex G.

Welding processes are widely used in the fabrication of a bogie and the assembly of its components and as identified in the FMECA spreadsheet welding defects are one of the major causes that lead to failure of welded components. Attending to the importance of having a deep understanding of welding processes and welding defects, Annex F provides a review of this topic, identifying and characterizing the six major types of welding defects.

5 Life Cycle Cost

The Life Cycle Cost (LCC) analysis comprises two primary stages: an initial technical assessment of the asset, which includes data on failures, availability, and other relevant metrics translated into annual costs; and a subsequent financial evaluation aimed at estimating cash flows to provide a significant indicator and support investment decisions for the problem under investigation.

Numerous studies in the literature investigate using LCC in the railway sector and it has only been growing in importance and complexity worldwide. This concept applies to railway infrastructure, its assets, and vehicles. For example, the state of the rolling stock also affects the wear and tear on the infrastructure, establishing the necessary maintenance and renewal requirements, especially since asset deterioration is the main driver of failures and maintenance demands in railway systems. Other factors influencing life cycle costs include maintenance strategies (corrective, preventive, or condition-based), labour market prices, material costs, and other concerns to be studied further (Calle Cordón et al., 2018).

Railway infrastructure and vehicle assets have long life cycles and once installed are expensive and difficult to modify. As a result, it is critical to adopt a lifecycle perspective in cost analysis. Companies and scholars are increasingly recognizing the importance of assessing asset LCC in making informed decisions in both investment and management sectors. Nonetheless, the importance of a comprehensive asset management approach is significantly undervalued thus justifying the pertinence of a chapter dedicated to the theme.

5.1 Model Definition and Assumptions

The specific context and items being analysed significantly influence the detailed cost breakdown structure of an LCC model. For this case, a crucial cost element to incorporate is the hidden costs associated with the downtime of freight vehicles, which is a metric that will have to be estimated based on literature research due to the absence of real data to perform the calculations.

Nevertheless, certain assumptions and modelling choices are necessary, particularly concerning operational, maintenance, and hidden costs. The LCC model used is as follows (INNOWAG, 2017):

- **Operational Costs:** Initial analysis suggests that changes to the LCC will be neutral regarding the wagon's power consumption. This is because these wagons do not directly consume power for their systems, as the locomotive provides the power needed for movement and braking. Additionally, since the wagon's sensors are self-powered, no extra power is required. Operational costs related to track access charges were excluded from the LCC calculation.
- **Maintenance Costs:** Maintenance activities are split into corrective and preventive maintenance, excluding predictive maintenance due to the inherent difficulty in obtaining reasonable estimations for the cost parameters. Corrective maintenance addresses unplanned failures, which not only halt the wagon and require repairs but also disrupt the railway network, affecting service operators. Preventive maintenance, on the other hand, focuses on routine maintenance to avoid such disruptions.
- **Hidden Costs:** The expenses arising from unplanned stoppages are categorized under the hidden costs section of the LCC. These costs are not directly related to maintenance activities (such as the expense of replaced parts) but instead reflect the consequences of failures or delays in goods delivery and disruptions in the railway network, which can result in slowdowns, delays, and cancellations.

Figure 15 is a schematic representation of all the cost components that need to be computed to perform the LCC analysis and then it becomes imperative to define all the assumptions necessary for the calculation, particularly how and where to obtain the values used in the calculation.

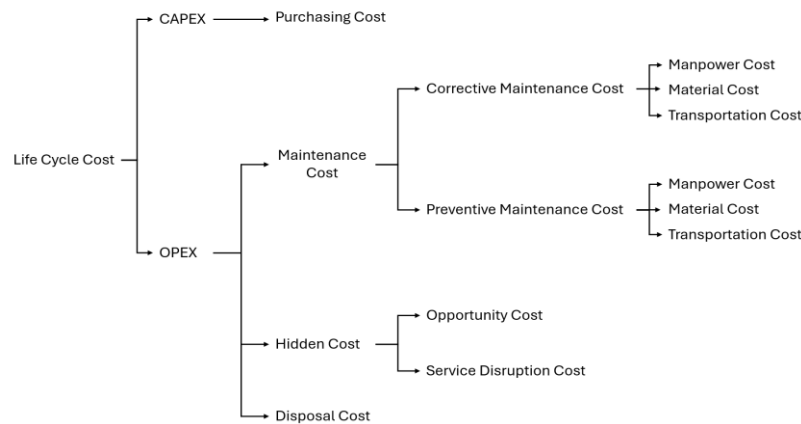


Figure 15 - LCC Model for the Bogie. Adapted from (INNOWAG, 2017).

As seen in Figure 15, two major groups of costs need to be assessed to perform LCC, those being Operational Expenditure (OPEX) and Capital Expenditure (CAPEX). It is important to rigorously define both concepts to make the economic evaluation viable.

Capital expenditures (CAPEX) are investments in the company's fixed infrastructure and are depreciated over time. These are essential for expanding services to customers. On the other hand, operational expenditures (OPEX) cover the ongoing costs required to keep the company running, such as technical and commercial operations, administration, and more. Unlike CAPEX, OPEX does not contribute to the company's infrastructure and therefore is not subject to depreciation (Verbrugge et al. 2006).

For the component useful life, multiple sources in the literature argue it can be 30 years (Bortoli et al., 2020). This was the value used for the current analysis as a reasonable estimate. Ideally, useful life should increase over time accompanying the development trends of new technologies and optimised maintenance policies.

The purchasing cost is defined as the initial cost to purchase the components under analysis. In case a whole functional subsystem is analysed, the total purchasing cost is the sum of the costs of each element.

Corrective maintenance costs will be calculated as the product between the mean cost for an intervention of corrective maintenance per failure, taking into account mobile and stationary intervention, and the expected number of failures based on the available data for the failure rate and assuming 8760 operating hours per year (full 24 hours per day).

Preventive maintenance costs entail the cost contribution to LCC of planned maintenance activities performed on each component, following detailed maintenance policies tailored to the asset in specific. Manpower cost must reflect the hourly cost of the manpower, the number of technicians needed for each maintenance activity and the average duration of each maintenance activity. Material cost is calculated as the total cost for the required quantity of materials to be purchased and this value is needed to estimate the number of interventions.

Hidden costs are the combination of two types of costs and derive from unforeseeable failures that can cause interruption of service. Opportunity cost refers to the money loss due to the inability to deliver the goods due to the failure of the freight wagon. Each failure mode has a different impact on the state of the train and only some of them lead to a full stop of the train. Therefore, the contribution of each failure mode to opportunity costs must be considered. The

number of days lost will be calculated based on the MTTR of each failure mode and the number of failures associated with it, based on the MTBF. According to the sources used for the underlying data of this analysis, the opportunity costs are proportional to the number of days lost, based on a parameter that is given by the length over buffer and a coefficient unique to each type of freight wagon. For this project, the opportunity costs will be estimated as 17.55 times the number of days lost (13.5 mean length over buffer x 1.3 average wagon coefficient).

For a more comprehensive opportunity cost calculation, it would be necessary to define alternative investment options, evaluating both inherent costs and benefits to establish a comparison. Given the degree of uncertainty and variability in these alternatives and related costs, the estimate based on the INNOWAG is supported. The reference project performed the LCC analysis across three subsystems: primary suspension system, wheelset, and braking system. Since the analysis is similar across all subsystems, it was chosen to only present the LCC for the primary suspension system.

The scenario that was considered had no downtime due to the occurrence of a failure in the primary suspension system, following the INNOWAG project. Consequently, all hidden costs obtained were null and the highest contributor to cost was the purchasing cost with preventive maintenance costs higher than corrective maintenance costs. This is a consequence of having to purchase more components to be readily available to replace failed ones as soon as the failure is detected when performing preventive maintenance (INNOWAG, 2017). The results obtained are presented in Figure 16.

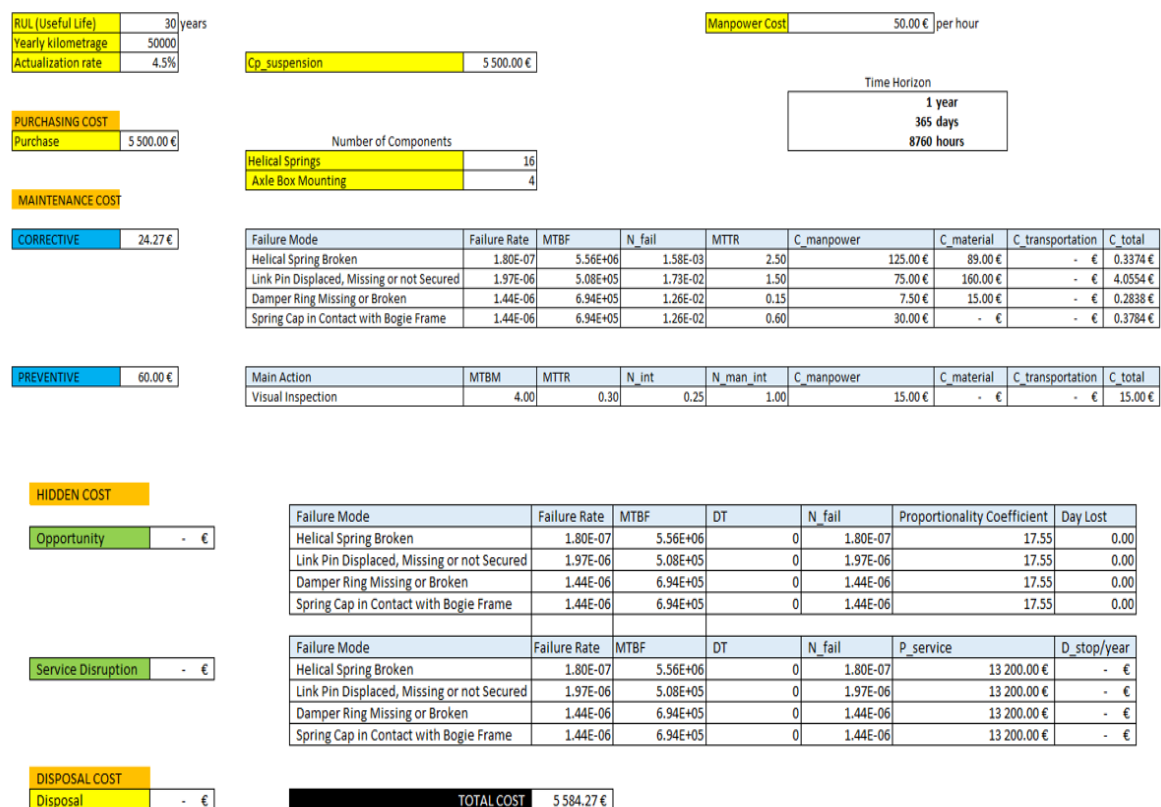


Figure 16 - LCC example for the primary suspension system.

From the LCC analysis, it is possible to conclude that installing a monitoring system to enable real-time condition monitoring can reduce unexpected stops of freight wagons and aid in detecting potential failure modes so that maintenance can be scheduled proactively to ensure a higher lifespan of the component. Therefore, adapting the maintenance programmes proves to be a profitable option that should be adopted as soon as reasonably possible. Nonetheless, the results are always conditioned by the context of application and the assumptions made have

a noticeable effect on the values obtained. In addition, the evaluation of benefits is always challenging due to the insufficient data that is readily available and some assumptions are simplified (for example, maintenance actions can lead to an increased lifespan of the system which is not considered in this calculation).

5.2 Example of NPV Calculation

After calculating all the total costs of the LCC of the selected components, it is imperative to translate these values into the Net Present Value (NPV), considering the values of cash flows generated across the different years of life of the component. As NPV refers to the value created by the project, after paying back and fully remunerating all the capital that was invested, it makes the comparison of LCC between the different components much easier.

The NPV calculation for the primary suspension system will be demonstrated, following the LCC analysis performed previously. This is an illustrative example that establishes the general assumptions and formulas required to expand the NPV calculation to any other component or subsystem. NPV can be calculated according to Equation (5.1), though its correct application demands the identification of a few different parameters, namely the discount rate and the useful life, which is the planning time horizon for the analysis (Shapiro, 2005).

$$NPV = CF_0 + \sum_{t=1}^n \frac{CF_t}{(1+r)^t} \quad (5.1)$$

Where:

CF_0 is the Cost of the Initial Investment

r is the discount rate

n is the useful life

CF_t is the Cash Flow generated at year t

The assessment of the discount rate is difficult because it is dependent on the field in which the investment is going to be evaluated, whether private or public, on the historical moment, on the country, and on the interest rate of banks and credit institutions. A brief market research was performed for the Portuguese market, and it points out that using the same interest rate as the Italian market (4.5% per year) is a good estimation, considering the similar characteristics of both European countries and close their geographical location.

Substituting the known values for the discount rate and useful life under the stated assumptions and knowing that the purchasing cost in the initial investment at time $t=0$ and maintenance costs starting to be accounted at $t=1$, it is possible to obtain the equations needed to calculate the NPV of the corrective and preventive maintenance actions, as given in Equations (5.2) and (5.3). The detailed results at each year are given in Annex I.

$$NPV_{preventive} = \sum_{t=1}^{30} \frac{60}{(1+0.045)^t} = 977.33 \text{ €} \quad (5.2)$$

$$NPV_{corrective} = \sum_{t=1}^{30} \frac{24.27}{(1+0.045)^t} = 395.33 \text{ €} \quad (5.3)$$

Given these results, the total NPV for the primary suspension system is **6872.66€** and maintenance costs are responsible for approximately **20%** of this value. This indicates that maintenance costs have a noticeable impact on (cumulative) total costs and thus it is imperative to optimise maintenance plans.

6 Conclusions and Future Works for Improvement

6.1 Conclusions

The research conducted within the scope of this dissertation has greatly contributed to a deeper understanding and awareness of the importance of railway systems in the national railway sector as railway systems play a key role in the economic, social, and environmental landscapes. This work emphasizes the complexity and value of maintaining and improving the railway system reliably and safely, highlighting the impact that RCM has on asset and maintenance management.

One of the key inferences of the research is the considerable effort required during rolling stock testing and certification, owing to the multiple industry standards required for its market certification and interoperability. The stringent standards in the railway industry demand a meticulous approach to ensure that all components fulfil the appropriate safety and performance criteria, which entails extensive testing, documentation, and validation steps.

Additionally, this dissertation sheds light on the groundbreaking engineering work that is a railway bogie. The bogie itself is one such example of the advanced engineering and innovative designs that are required in rail systems as it consists of many components with complex designs and functions. In addition, the study has also unveiled how these mechanical, structural, and dynamic factors interact with each other to achieve safe and efficient performance. The detailed analysis of the bogie design, particularly its functional breakdown that was required to perform the FMECA, helps to understand some of the intricate principles of railway systems engineering perfectly aligned with the concepts of Mechanical Engineering.

A significant challenge identified in this research is the lack of empirical data on failure rates in railway systems. This problem has necessitated reliance on expert opinions and extensive literature reviews to obtain useful information on failure modes, effects, root causes, and values for failure rates. In particular, the visit to Medway was quite enriching and was an invaluable opportunity to clarify practical doubts concerning railway terminology, and details on failure modes and causes. Therefore, the existence of readily available comprehensive data is mandatory for future research projects and there should be an effort to create and update maintenance databases for the railway system. Enhanced data availability would improve the accuracy of reliability assessments and support the development of more effective maintenance strategies, especially because the RPN calculation was based on estimations.

The importance of developing a thorough maintenance plan, incorporating different assumptions and scenarios paired with an economic analysis, has also been a central theme of this dissertation. Effective maintenance planning is essential for maximizing the reliability and lifespan of railway systems while minimizing costs and downtime and the LCC analysis has demonstrated the value of scenario-based planning and economic analysis in identifying the most cost-effective and efficient maintenance strategies.

Finally, some concepts of sensors and energy harvesting technologies were introduced to facilitate the transition to Condition-based Maintenance while emerging as a potential solution to facilitate data gathering. Sensors enable real-time monitoring of asset conditions, allowing for more precise and timely maintenance actions which can further aid in enhancing the reliability, safety, and cost-effectiveness of maintenance programmes.

In conclusion, this dissertation has provided a comprehensive examination of the key aspects of RCM for the national railway sector, covering both its benefits and inherent barriers. The insights gained from this research offer valuable contributions to the field and pave the way for future advancements in railway system reliability and maintenance practices, as well as providing a solid foundation for any project based on the fabrication of a bogie.

6.2 Future Works for Improvement

In this section, potential directions for future research and improvements based on the findings and limitations (time, data and resources) of this study are discussed.

In future research projects, it would be beneficial to actively participate in RCM teams and meetings at railway undertakings offering a more enriching and active experience in the railway industry. This active involvement would provide invaluable insights into the practical challenges and decision-making processes involved in implementing RCM strategies within real-world railway operations.

Furthermore, incorporating real data from a specific case study or reliable maintenance databases would greatly enhance the dissertation's practical relevance and applicability, leading to a more rigorous calculation of metrics such as the RPN. This empirical approach would enable more informed decision-making and facilitate the identification of targeted maintenance actions tailored to the unique characteristics of the case study.

Another promising opportunity for future research is the study of sensor techniques in the context of bogie maintenance. While this dissertation introduced some of the key concepts and technologies, investigating the implementation of sensor technologies within a real bogie environment would benefit the assessment of their efficacy in enabling condition-based maintenance strategies. Exploring the practical implications and challenges associated with sensors and energy harvesting systems for railway systems would contribute to advancing the state-of-the-art in railway maintenance practices.

Additionally, conducting comparative analyses of different maintenance strategies and methodologies based on different scenarios and assumptions could provide enriching conclusions about their relative effectiveness and cost-efficiency.

Furthermore, exploring the integration of emerging technologies, such as artificial intelligence and predictive analytics, into RCM frameworks holds promise for enhancing maintenance decision-making and optimizing asset performance. Harnessing the power of advanced data analytics and machine learning algorithms for simulations could provide railway operators with more knowledge of asset health and performance trends, enabling proactive maintenance interventions and predictive maintenance forecasting.

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ANNEXES

ANNEX A - Details on RCM

Review Groups

An organization's RCM process starts with the critical decision of selecting which assets are covered by the scope of the project, particularly which ones will benefit the most from this methodology, and then outlining the expected advantages and estimating the needed resources.

Furthermore, a crucial aspect of conducting an effective RCM analysis is the establishment of a review group to address the set of seven questions inherent to the process. This demands a collective effort extending beyond the expertise of a few individuals, leading to the formation of interdisciplinary teams comprising members from both maintenance and operations to ensure diverse perspectives and expertise.

The objective of defining review groups is to assemble a team that can provide most, if not all, of the information needed to support the RCM methodology. Ideally, the optimal group should consist of five or six members and remain consistent throughout the analysis of any single asset, as constant changes in its composition can lead to redundant discussions or the loss of valuable information. A typical RCM review group follows this structure (Moubray, 1997):

- Facilitator;
- Operations Supervisor;
- Operator;
- Specialist (usually an external entity);
- Maintainer;
- Maintenance Supervisor.

In the context of RCM, facilitators are highly expert entities that oversee the comprehensive understanding and application of the process within the group. Their role is to guide the group to consensus, maintain commitment, and ensure the process's timely completion as intended by managing time, and the various administrative, logistical, and management components involved (Moubray, 1997).

Due to being the most important position in the team, a facilitator is required to have a strong background and extensive training in RCM with a reasonable understanding of the processes and technologies related to the assets under review. The skills required extend to being able to identify the asset systems that should be included; the information needed to conduct a successful analysis; and the people who can contribute the most and thus must participate in the team. Hence, facilitators need to continuously manage the overall process both inside and outside all meetings, which is more easily achieved when they are full-time employees at the organization, rather than outsiders (Moubray, 1997).

Planning of an RCM Programme

An RCM-based maintenance plan involves the establishment of various kinds of roles, support systems, and communication routines, all seen from various management perspectives. The project must be planned as thoroughly as possible before work starts, while still being realistic and providing benefits to the organization. Managers and supervisors of the areas affected are encouraged to follow the planning in close consultation (Afefy, 2010).

Its implementation starts with the selection of the system and an initial data collection, followed by the definition of system boundaries, functional blocks, functions, and functional failures. Then, analytical methods such as FMECA are employed to evaluate and define a prioritised list of maintenance tasks. Finally, the recommendations are put into practice and monitored so that the feedback can be used to improve further programmes. The facilitator in

charge is responsible for scheduling meetings for further discussion and workflow redesign whenever appropriate (Moubray, 1997).

Figure A1 illustrates the generic steps necessary to describe the systematic RCM approach.

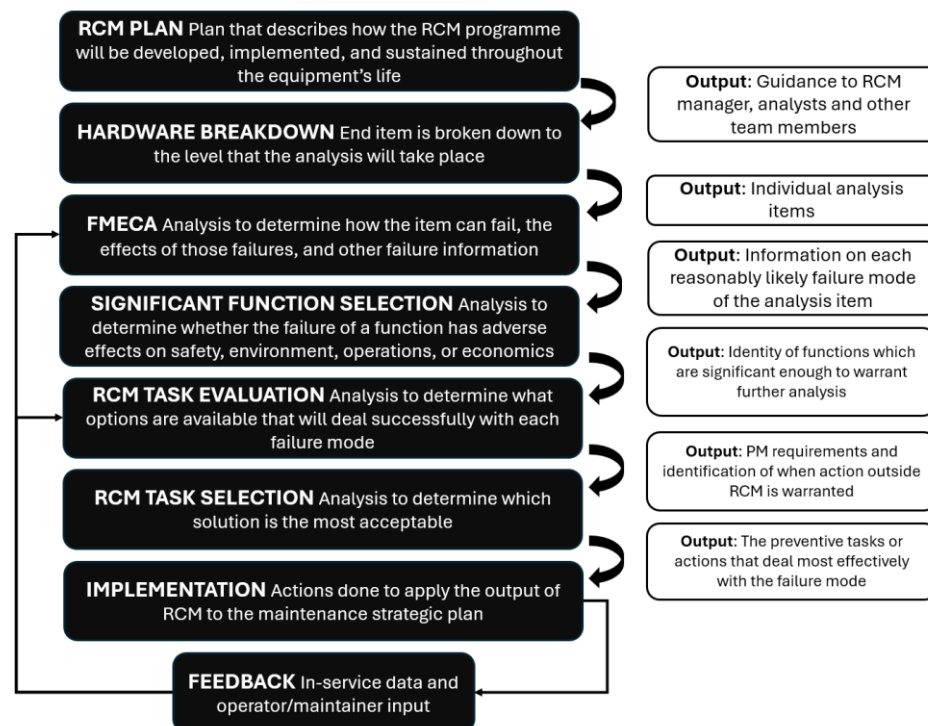


Figure A1 - RCM process map. Adapted from (NAVAIR, 2005).

Any organization that employs RCM should take great care to ensure that the people who apply it know what they are doing and how they are doing it and can come up with sensible decisions for better processes (Moubray, 1997).

An RCM audit is a formal review of the contents of the documentation required at the different stages of the process, particularly the Information and Decision Worksheets. This analysis includes the perspectives of both the “method” and the “content”. The methodological review aims to verify the correct application of the RCM process. Content review, on the other hand, ensures the accuracy of information gathered and conclusions drawn regarding the asset and the associated process (Moubray, 1997).

The audits are recommended to be carried out as soon as possible since the sooner the decisions are implemented, the sooner the organization can take advantage of the associated benefits. Additionally, the auditor, which is the entity responsible for the audit, should be external to the RCM team to provide an impartial contribution to the problem-solving process.

The implementation of this logic can be achieved through one of three different ways. These are the task force, selective and comprehensive approaches.

RCM Documentation

To conduct a thorough RCM analysis, a set of documents must be elaborated, of which the decision diagram, FMECA worksheet, and the decision and information worksheets are notorious. A sensible analysis of these documents allows the maintenance engineers to devise an effective maintenance programme with adequate prioritization tailored to the asset in question and to the objectives of the organization (Moubray, 1997).

The Information Worksheet is a structured document for systematically gathering and organizing essential details about the equipment or systems undergoing analysis used to guide the whole process. One aspect that must not be overlooked is the level of detail at which it is conducted. If it is too vague and superficial then no useful conclusions can be extracted, and if it is exhaustively detailed then it becomes incomprehensible and inaccessible (Moubray, 1997).

Typically, it consists of several key sections, as follows:

- Equipment/System Identification section, providing basic information such as the equipment's name, identification number, location, and any other pertinent identifying details;
- Functional Description section, which outlines the functions or duties performed by the equipment or system, particularly its primary purpose within the operational context;
- Functional Failures section, where potential failures that could occur in the equipment or system are identified and described in terms of their impact on its ability to perform its intended function and leading to the creation of a list of failure modes;
- Failure Consequences section, assessing the potential impact of each failure mode on safety, environmental concerns, operational performance, and economic considerations.

This document should also reference current maintenance practices for each failure mode, documenting details such as the frequency, types of inspections, and any preventive or corrective actions taken. An example of this document can be seen in Figure A2 (Basson and Aladon, 2019).

RCM3™ Information Worksheet © 2018 Aladon V2.0		Location ID K-03-001-00BZ		No	Compiled by
		Location Description Benzene Storage & Supply System		Ref.	Reviewed by

Function	Failed State	Failure Mode		Failure Effect	
		Cause	Mechanism		
1 To supply benzene on demand to the process at a minimum rate of 300 gallons/min.	A Does not supply benzene at all	1 Pump impeller stuck.	Jammed by foreign object.	Local Failure Effect	A foreign object is present in the system if object enters the pump, blocks the impeller.
				Next-Higher-Level Effect	The pump motor trips on overload and the in the control room. With the pump down benzene to the process.
				End Effect	Repair time up to 4 hours to replace the impeller would be lost at a cost of \$5,000. The impact during the 5 hours between delivery cycle.
				Potential Worst-Case Effect	If the existing protection fails, the motor will greatly increased. Although it is unlikely that damage and downtime will be high.

Figure A2 - RCM Information Worksheet (Basson and Aladon, 2019).

The Decision Diagram, Figure A3, integrates all the decision processes into a single organized and strategic framework and is applied to each of the failure modes listed on the information worksheet to arrive at the best maintenance policy to be used in each scenario. At its core it can be seen as a sequence of several steps represented as groups of nodes, each depicting different decision points throughout the maintenance strategy development process. Functional failures within the systems or equipment are defined and classified as either hidden or evident (group H), along with an assessment of their potential consequences, considering

factors such as safety (group S), environmental impact (group E), operational disruptions (group O), economic implications and technical feasibility of the possible maintenance tasks.

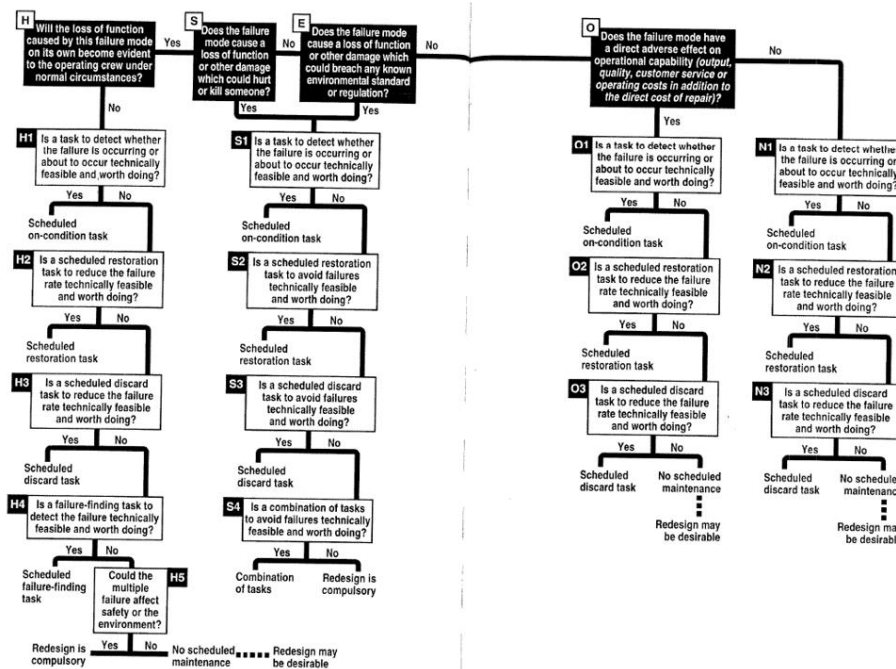


Figure A3 - RCM Decision Diagram (Moubray, 1997).

Figure A5 illustrates an example of the RCM decision spreadsheet, which is a powerful tool to answer the basic questions of the methodology, as well as record the following:

- what routine maintenance (if any) should be carried out, how often and by whom;
- for which failures should a one-off change be considered to reduce the risk to a tolerable level;
- which failures occur in protection systems, where optimisation will reduce the risk of multiple failure to a tolerable level;
- when and where can a deliberate decision be made to let failures happen.

As proposed by Basson, this document is organised into twenty-seven columns, following a given criterion. The first columns are labelled "F" (Function), "FS" (Failed State) and "FM" (Failure Mode) and serve to identify the failure mode under analysis. The next thirteen columns answer the questions that serve as the basis of RCM. In detail, the column headed "1" is used to determine whether the failure is evident or hidden, and then the next three columns "ES/HS," "EE/HE," and "EO" are used to record the answers to the questions concerning the risk associated with each failure mode (consequence category). The next three columns from "HP1" to "HP3" record whether a proactive task has been selected, and if so, what type of task. If no proactive task can be found that would reduce intolerable risks to a tolerable level or when tolerable risks cannot be reduced cost-effectively, it becomes necessary to answer the questions related to the optimization of existing protective devices, the combination of tasks, and one-time changes. The next columns, from "HP4" to "EO4", are used to record the answers to these questions. The last eleven columns record the proactive task or risk management strategy that has been selected (if any), the frequency with which it is to be done and who has been selected to do it, and the revised risk (Basson and Aladon, 2019). Figure A4 shows the classification of risk categories according to the answers recorded in the Decision Worksheet.

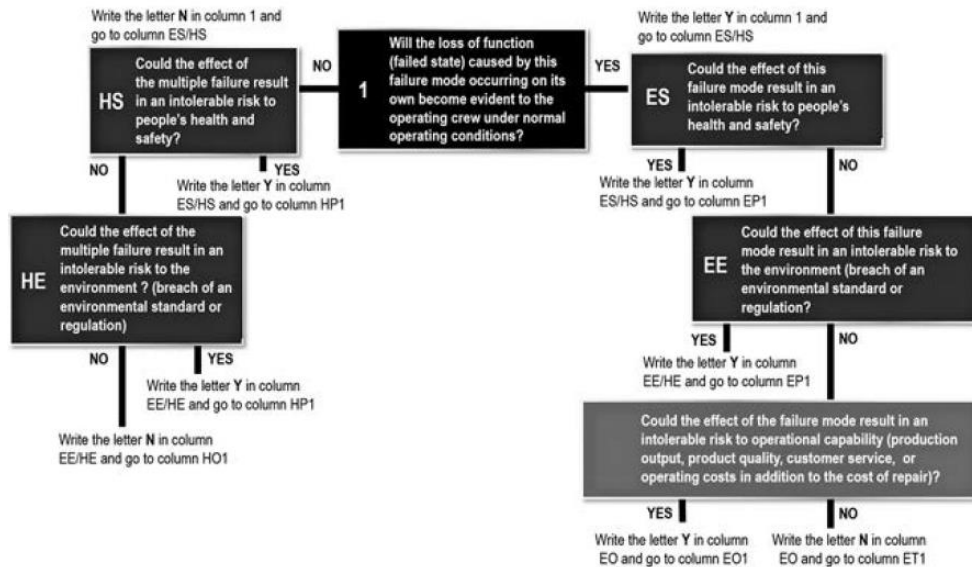


Figure A4 - Decision Worksheet to record Risk Categories (Basson and Aladon, 2019).

RCM3™ Decision Worksheet		Location ID		No	Compiled by	Date	Sheet	
© 2015 Aladon V2.0		Location Description		Ref.	Reviewed by	Date	of	

Reference	Risk Category Evaluation			Risk Management Strategy Evaluation										Risk Management Strategy Description	PM Task Details					Revised Risk Ranking						
F	FS	FM	1	ES	HS	EE	EO	HP1	HP2	HP3	HP4	HP5	HO4	EP4	EP5	EO4	Initial Task Int	UOM	Trade Code	Qty	Dur (Hrs)	Mod Type	Prod	P	C	R

Figure A5 - RCM Decision Worksheet (Basson and Aladon, 2019).

Barriers to RCM

RCM is a dynamic methodology employed to define optimal maintenance strategies. Nonetheless, the approach faces some barriers in terms of resources (physical and technical) and implementation practices that need to be outlined and studied to help the organization define new strategies to work around them.

Firstly, the formulation of a maintenance strategy entails inherent uncertainties as decision-making processes often rely on incomplete or absent empirical data on failures and maintenance tasks. In these cases, assessments of the probability and consequences of failure modes are usually based on speculative judgment of the data patterns, meaning that they can be inaccurately evaluated by overvaluing indicators such as MTTR and MTBF, or obfuscating other failure modes of greater importance (Moubray, 1997).

Secondly, the assets under consideration and the operational environment they are inserted in can undergo continuous evolution, necessitating frequent updates on the strategy or the planning will become obsolete.

It is usually a long-term goal with a short-term expectation and its success is directly influenced by the credibility of the expert, their knowledge, and capability and impact as a team leader.

The challenge of gathering high-quality maintenance failure data has been studied by H. L. Resnikoff who defended that the analysis of failure data trends is imperative to define

efficient maintenance plans. However, said data only exists when there are equipment failures which the organisation intends to prevent or mitigate. This is especially relevant for critical failures that demand immediate intervention, which in turn results in more scarcity of information on said failure modes (Moubray, 1997).

Additional obstacles are identified as follows (Moubray, 1997):

- Organizational Resistance to Change, as the implementation may require changes in organizational culture, processes, and roles, facing resistance to change from employees who are accustomed to traditional maintenance practices;
- Skill and Knowledge Gap, since it requires specialized knowledge and skills in reliability engineering, maintenance optimization, and data analysis, which can be limited or the personnel is not readily available;
- Integration with Existing Systems, enterprise resource planning (ERP) systems, and other software platforms, which can be difficult when ensuring seamless data flow and communication within the organization.

Transition from RCM II to RCM III

Extending beyond the aviation sector, the establishment of standards such as SAE JA 1011 ("Evaluation Criteria for Reliability-Centred Maintenance RCM Processes") and SAE JA 1012 ("A guide to the RCM Standard") pushed RCM as an organization-wide maintenance protocol. Thus, RCM III emerges as a continuation of Moubray's work by Marius Basson introducing a novel dimension and approach to maintenance and risk analysis.

While many questions from RCM II are equally addressed in RCM III, the latter emphasizes studying the operational context earlier and in greater depth, considering failure modes, risk effects, and operational consequences. Thus, the RCM III logic added an eighth question with a significant emphasis on risk assessment and management: "What can be done to reduce or manage tolerable risks in a cost-effective manner?" (Basson and Aladon, 2019).

Functional analysis in RCM III focuses more on compliance with environmental and safety standards, including considerations such as cleaning, reuse, recycling, and disposal when characterizing primary and secondary functions. The methodology not only considers local effects, failure modes, and evidence but also describes potential worst-case effects and extends beyond the scope of RCM II through a more consistent and improved root cause failure identification to target root causes (Basson and Aladon, 2019).

In contrast to RCM II, which focuses on preserving system functions while minimizing consequences, RCM III incorporates approaches and analyses based on the ISO 31000:2018 standard, ISO 55000:2014 standard, and probabilistic risk at the component level, leading to recommendations for redesign. This comprehensive risk approach accounts for all associated costs, providing a holistic view of maintenance and assisting organisations in mainstreaming reliability.

Another difference in the methodologies is at the level of the decision diagram. In RCM II, the logical decision leads to predictive and preventive maintenance tasks, failure-finding strategies, redesign, and unscheduled maintenance. RCM III, on the other hand, already prioritises the reliability of the protected function and incorporates criteria for dealing with hidden physical and economic failures into the decisions.

In essence, the RCM III methodology builds upon the already solid foundation of RCM II by complying with more international standards, offering a more thorough approach across multiple industry sectors with a sharper emphasis on addressing both physical and economic risk concerns (Basson and Aladon, 2019).

ANNEX B - Comparison between RCM II and RCM III (Basson and Aladon, 2019)

RCM Element	RCM2 (SAE JA 1011)	RCM3 Highlights	Reason for additions / changes	Improvements and advantages
Operating Context	Mentions and considers the Operating Context (OC) throughout the process. Operating Context is considered when failure modes are identified and when failure management strategies are developed (Failure consequences are different when OC varies). SAE JA1011 ¹ mentions the OC as important but not necessary a requirement.	The Operating Context is the FIRST step and question that must be answered in RCM3: <i>What are the conditions under which the equipment is expected to operate?</i> The OC is not just important, but essential for developing a sensible and defensible risk management program.	The Operating Context <i>must</i> be defined prior to the FMEA, listing functions and performance standards, failed states, failure modes and failure effects is all based on the OC. The inherent risk posed by each failure and everything impacting the performance of an asset, are influenced by and derived from the OC.	Defining the Operating Context is undeniable the first step of the RCM process and all assumptions and decisions are based on the OC, making RCM3 compliant and exceeding requirements of SAE standard. Risk assessment and risk management must be performed within the context – according to ISO 31000 ² (ISO Standard for Risk Management). True optimization is only possible when the OC is defined.
Functions	Requires the definition of Primary and Secondary Functions with associated standards of performance - Performance standards should be defined (where possible) - Specific about the definition of functions for protective devices	Requires the definition of Primary and Secondary Functions with associated standards of performance - Performance standards should be defined (where possible) - Specific about the definition of functions for protective & detective devices - Expands Secondary Functions to include cleanliness, regulations, regulatory requirements, recycle / repurpose / reuse	The expectations of modern equipment have changed with the changing expectations of the people who own and operate the equipment. Expectation further changed with new advanced technologies and innovation, through interconnectivity, mobility and predictive technology. Rising pressure from governments and societies with regards to sustainability and environmental integrity, places higher demands on reusable energy and focus on sustainable operations.	Requirements for asset performance now includes elevated consideration for sustainability and environmental integrity. The focus is now more on what the equipment's role is in society as a whole rather than a siloed view of the organization who owns and operates the equipment. The performance standard for initial capability (inherent reliability) is now drawing the attention to defect elimination and longer asset life while meeting regulations and regulatory requirements.
Functional Failures	Functional failures are acknowledged as "failed states": - General failed state - Total failure - Partial failure	Now defined as "Failed State" and acknowledges the differences between: - General failed state - Failing state - Failed state - End state (as part of the failure process)	The general failed state, the failing state (process of failing), partial failure (failed state where equipment no longer meets performance criteria) are now clearly defined and distinguished from the end state (total failure). The RCM3 process deals with all possible failures at the appropriate level.	Agreement between different disciplines (e.g. engineering, operations and maintenance) can be reached much faster and therefore the process of identifying appropriate risk management strategies, is much quicker (saving time and money). The new definition encourages the use of new maintenance techniques and technology.
Failure Modes	Defines a Failure Mode as the event that causes the Functional Failure /	Defines a Failure Mode as a 'cause' and 'mechanism' that causes the Failed	RCM review groups (and facilitators) are forced to define at least one or	Consistent and improved root cause failure identification is now possible,

RCM Element	RCM2 (SAE JA 1011)	RCM3 Highlights	Reason for additions / changes	Improvements and advantages
	Failed State. The facilitator / review group must constantly be reminded of the correct level of detail (not to describe failure effects / symptom of the failure).	State. This allows the facilitator / review group to identify root causes consistently and with the correct level of detail. The failure mechanism also ties in with the degradation mechanisms (terminology used in RBI).	more failure mechanisms for each failure mode ensuring the level of detail is sufficient and appropriate for developing risk management strategies that are both technically feasible and worth doing. Failure causes are events causing the failed states while failure mechanisms are the conditions leading to the failures (e.g. corrosion, normal wear and tear, etc.).	even for inexperienced facilitators. Templating of like type equipment is easier to perform, more information is carried over. Integration with other risk-based approaches (e.g. RBI) are now easy to achieve. Root causes are identified and treated and no longer the symptoms associated with failures.
Failure Effects	Failure Effect is defined as one statement (one paragraph that describes what will happen if the failure mode occurs and nothing was done to prevent it). It requires the facilitator to record the physical effects of each failure by asking the following questions: • What evidence (if any) that the failure has occurred? • In what ways (if any) it poses a threat to safety or the environment? • In what ways (if any) it affects production or operations? • What physical damage (if any) is caused by the failure? • What must be done to repair it?	Like RCM2, Failure Effects are described if no maintenance is being performed and no attempt is made to prevent them, but the effects are now separated in three levels: Local Effect, Next Higher-Level Effect and End Effect. RCM3 also describes Potential Worst-Case Effect (where protection is also in a failed state – allowing for true zero-base analysis). It does so by asking the following questions: • When is the failure most likely to occur? • How often the failure would occur if no attempt is made to prevent it? • What evidence (if any) that the failure has occurred? • In what ways (if any) it poses a threat to safety or the environment? • In what ways (if any) it affects production or operations? • What physical damage (if any) is caused by the failure? • What must be done to repair it? • Does it cause any secondary damage? • What is the revenue loss (if any)?	Separating the effect description makes it possible to distinguish more easily between the specifics of complex failure effects. Reporting on failure effects (assessing the consequence severity) to different levels in the organization is more granular and less time is spent during the analysis and the subsequent analysis audit meetings. Describing failure effects are far easier and the separation allows the different disciplines in the review group (engineering, operations and maintenance) to focus on their areas of expertise and knowledge. The first question now truly considers the Operating Context and when failures are more likely to occur. (e.g. storm events, start-up, take-off or landing, following maintenance intervention, etc.)	Easier and more comprehensive templating at equipment type level (Local Effect descriptions included in the analysis template). Indicators easier to define (clear difference between what operator / maintenance personnel sees vs. what management wants to see). Potential worst case describes multiple failure conditions separate and with appropriate level of detail. The focus is on increasing the reliability of the protected function/system as a first priority. True zero-base analysis now possible without considering protective systems to mitigate inherent risk. Using consequence definitions as defined in the organizations risk framework, allows everyone to relate and understand the effects of failure and the risk it poses. It is now possible to quantify inherent risk and develop risk mitigation strategies for intolerable risks.

RCM Element	RCM2 (SAE JA 1011)	RCM3 Highlights	Reason for additions / changes	Improvements and advantages
Consequences vs. Risk	Considers the consequences of failure and categorizes them in four categories: Safety/Environmental, Operational, Non-Operational and a single category of hidden failure consequences. All failures are treated and consequences are evaluated based on the four categories.	Considers evident <i>Physical</i> and <i>Economic</i> Risks and separates the Hidden Risks in two categories, <i>Hidden Physical</i> and <i>Hidden Economic</i> Risks. <i>Physical</i> Risks are risks impacting health, safety or the environment while <i>Economic</i> Risks impact operational capability and financial well-being.	Assessing and managing risks allow the review team to distinguish between <i>tolerable</i> and <i>intolerable</i> risks as defined by the organizations risk framework. Not all risks are intolerable and therefore not all failures need to be analyzed – saving time and valuable resources.	This is valuable in high risk environments. Improved integrity and improved planning for testing protective devices are possible. The focus is on the devices that could impact safety vs. operations and improves the understanding of the economic impact (of functional tests) and risk of the same.
Inherent Risk	Follows a subjective approach to risk management and addresses risk only when failures (or multiple failures) impact safety or the environment. RCM2 is a process to determine what must be done to an asset system to preserve its functions (while minimizing or avoiding failure consequences).	RCM3 addresses risk directly and the risk management approach is based on ISO 31000 Standards for Risk Management. RCM3 is the process used to determine what must be done to an asset system to preserve its functions while minimizing the risks associated with failures to a tolerable level. RCM3 further considers a probabilistic risk assessment at component level when compulsory redesigns or one-time changes are required. Every reasonably likely failure mode is assessed and quantified in terms of its inherent risk. Less likely failure modes are considered based on inherent risk.	Inherent risk is quantified in relative terms as if no maintenance is being performed and if protection associated with failure is unavailable (zero-base). RCM3 is aligned with ISO Standards for Asset Management and Risk (ISO 55000 ³ and ISO 31000). RCM3 considers risk mitigation through addressing the probability and the consequence severity both as proactive risk management strategies. This provides more ways to proactively deal with intolerable risk and more decisions are made (fewer compulsory redesigns). For tolerable risks, the default risk mitigation strategies (no scheduled maintenance, spare part policies, etc.) are true default actions. Further risk reduction (for tolerable risk) may be considered provided it can be achieved in a cost-effective manner. This truly makes risk management strategies feasible and worth doing.	The revised risk achieved through the new RCM3 decision process, demonstrates the impact of risk mitigation - both on cost and risk exposure. It allows for proper and formal assessment to determine requirement for one-time changes (redesigns) based on the relative risk. Risk is quantified in relative terms and less compulsory redesign decisions are made – this allows the review group to make more decisions (less open-ended results) and it leads to a more defensible failure management program. Once risk management strategies have been defined, especially for failure modes posing intolerable risks, it is possible to determine the risk and financial impact of the recommendations. Less likely failure modes are evaluated based on the real risk they pose, leading to realistic asset management strategies.

RCM Element	RCM2 (SAE JA 1011)	RCM3 Highlights	Reason for additions / changes	Improvements and advantages
Decision Diagram	The RCM2 Decision Diagram treats all Hidden Functions the same (single approach). The decision logic considers predictive and preventive maintenance tasks as proactive failure management strategies and failure finding, redesigns and no scheduled maintenance as default actions. A combination of tasks is also seen as a default action and consequence mitigation is achieved primarily through optimizing protective devices (protected functions). For any proactive maintenance task (PM) to be considered, the PM must be both technically feasible (according to the failure characteristics) and worth doing (reduces the consequences to an acceptable level).	RCM3 incorporates additional criteria to identify <i>Hidden Physical and Economic Risks</i>. A true zero-base analysis is only possible if protection related to the failure under consideration is ignored. Focus is placed on reliability of the protected function first. Failure-finding intervals are optimized through increasing reliability of the protected function (when applicable) as the primary concern. Dependency on protective devices are reduced. The worth doing criteria for different risk criteria is significantly different from the RCM2 decision logic. Any <i>Physical Risk</i> must be reduced to a tolerable level. <i>Economic Risks</i> are considered (first) and not cost only. The mitigation strategy must reduce intolerable operational risk (now quantified) in order to be considered. The RCM3 process leads to more defensible risk mitigation.	For hidden failures having an intolerable <i>physical risk</i>, risk thresholds are used to determine the failure-finding intervals. For hidden failures having an intolerable <i>economic risk</i>, the cost of doing failure-finding is compared to the cost of the multiple failure and intervals are optimized based on cost. Functional checks designed for protective devices that fail (not fail-safe devices) are now included (where applicable). The focus in RCM2 could be (and has been) misinterpreted as being biased towards protective devices present in the system (especially standby and redundant equipment), which resulted in "No Scheduled Maintenance" decision for the protected function. This meant that the risk to the organization is drastically increased during repair time when the protected function failed (risk of multiple failures).	The criteria for <i>Hidden Economic Risks</i> determine the optimum interval for failure finding (providing highest availability) at the lowest cost. The cost of the failure-finding task must still be acceptable to the user, otherwise a one-time change may be considered to reduce the overall cost of multiple failures (where applicable). Improved integrity through functional testing for protective systems that fail (based on risk tolerance). The RCM3 decision diagram focus on the protected function as a priority. The need for a protective device and failure-finding intervals are only considered AFTER the integrity of the protected function has been addressed. These decisions are all risk based.
SAE JA 1011/1012 International RCM Standard	RCM2 complies fully with the minimum requirements of the SAE JA 1011 and SAE JA 1012 RCM standards.	RCM3 complies fully with the minimum requirements of the SAE JA 1011 and SAE JA 1012 Standards and goes beyond these requirements. RCM3 aligns with ISO 55000 and ISO 31000 Management Systems.	To align and integrate RCM with recognized and adopted International Management Systems. To mainstream RCM with International Asset Management Systems.	RCM3 now aligns with new and emerging standards making the results easier to defend. International standards and management systems are rarely challenged. RCM3 will become the new standard.

ANNEX C - Reliability Block Diagrams

A Reliability Block Diagram (RBD) is an invaluable tool to elucidate the logical interaction, hierarchy, and interdependencies among components in any system. It is a schematic representation that delineates how the reliability of each component impacts the overall system's performance, with each block signifying a specific component with its respective probability of failure or failure rate. However, while this method is a simple and intuitive representation with only 'AND' and 'OR' gates, it struggles when dealing with various combinations of failures, repairs, and event priorities (Verma et al., 2016).

To create a dependable RBD it is required to accurately reflect the system's logical behaviour to ensure that each block is statistically independent. This logical behaviour dictates how the blocks connect to form a path to success within the diagram and can be configured in one of three ways: series, parallel, or k-out-of-n structures (Ximing, 2005; Morelli et al., 2007).

Series System

A system is said to have a series configuration (an 'AND' gate in Failure Tree Analysis, FTA) when it only operates if every single component and its associated functions are operational. In other words, the failure of any one component translates to the failure of the entire system.

Figure C1 illustrates the RBD configuration of a series system comprising n components.

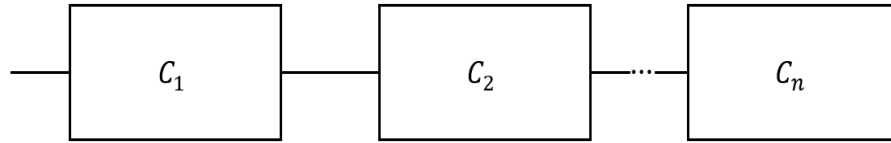


Figure C1 - RBD of a series system.

If the functional independence of components is assured, the reliability and instantaneous availability of a system at a given time for this type of system can be calculated by Equations C.1 and C.2, respectively.

$$R_s(t) = \prod_{i=1}^n R_i(t) \quad (C.1)$$

$$A_s(t) = \prod_{i=1}^n A_i(t) \quad (C.2)$$

Since the reliability of each component is in the interval $(0; 1)$, the reliability of the series system, $R_s(t)$, is always lower than the reliability of its least reliable component.

Parallel System

A system is said to have a parallel configuration (an ‘OR’ Gate in FTA) when it can operate as long as at least one of its components is operational, which means the failure of the system only occurs when all the elements fail. Consequently, this type of system has redundancy (active total redundancy). The RBD configuration of a parallel system with n components is depicted in Figure C2. The reliability of the parallel system is always higher than the reliability of its most reliable component.

Assuming the independence of events, the reliability and instantaneous availability of a system at a given time for parallel systems can be calculated using Equations C.3 and C.4, respectively.

$$R_p(t) = 1 - \prod_{i=1}^n [1 - R_i(t)] \quad (\text{C.3})$$

$$A_p(t) = 1 - \prod_{i=1}^n [1 - A_i(t)] \quad (\text{C.4})$$

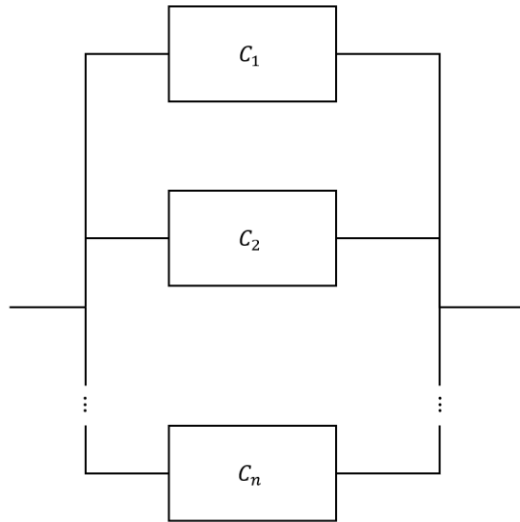


Figure C2 - RBD of a parallel system.

k-out-of-n System

The other type of system is the *k-out-of-n* system, which can be seen as a combination of both series and parallel systems. For this type of system to work, at least k elements must be operational, out of a total of n elements (given that $n > k$). It is commonly referred to as a partial redundancy system. In the case that $k = 1$ it is equivalent to a parallel system, and if $k = n$ it is equivalent to a series system.

Figure C3 depicts the RBD model of a *k-out-of-n* system, while Equations C.5 and C.6 allow us to calculate the reliability and instantaneous availability of this type of configuration under the assumption that all components are statistically identical and functionally independent.

$$R_{k/n}(t) = \sum_{i=k}^n \binom{n}{i} [R(t)]^i [1 - R(t)]^{n-i} \quad (\text{C.5})$$

$$A_{k/n}(t) = \sum_{i=k}^n \binom{n}{i} [A(t)]^i [1 - A(t)]^{n-i} \quad (\text{C.6})$$

Since all the elements are assumed to be identical, the equations used for the reliability and availability are based on the Binomial Distribution. Equation C.7 shows how to calculate the binomial coefficient, which represents the number of different combinations of i elements from a set of n .

$$\binom{n}{i} = \frac{n!}{i! \times (n-i)!} \quad (\text{C.7})$$

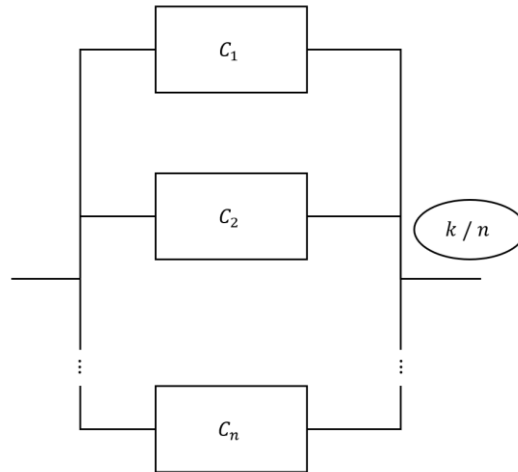
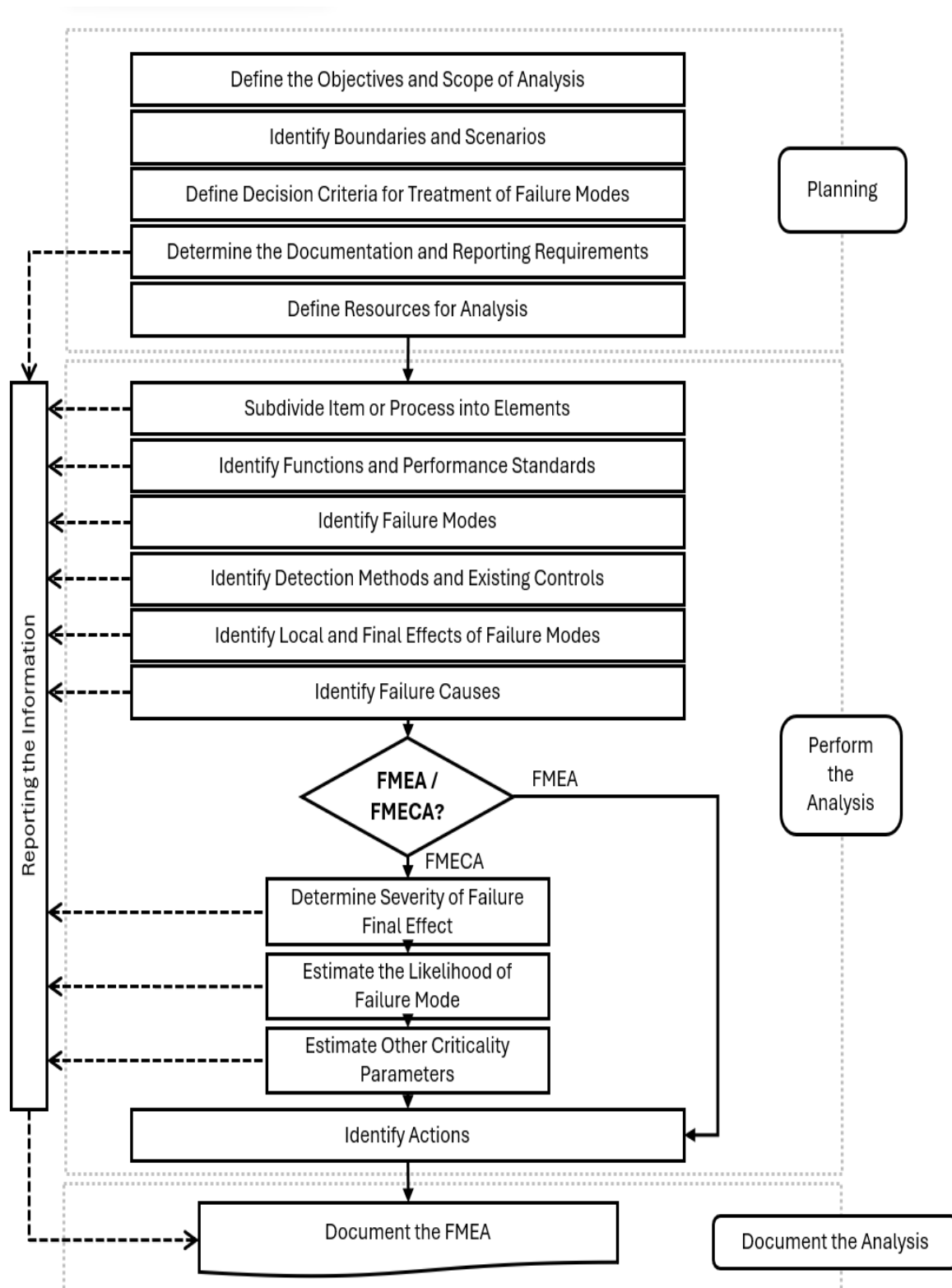


Figure C3 - RBD of a *k-out-of-n* system.

ANNEX D - FMECA workflow

According to standard EN 60812:2018.



ANNEX E - Classification of RPN parameters

The criteria used to classify the RPN parameters is according to UIC Guidelines and standard EN 60812:2018.

Rank	Impact	Criteria	Example
1	No Impact	No recognisable effect.	
2	Very Little	Error is noticed by few passengers. Minor changes in structure and dimensions which are below limits.	
3	Little	Error is noticed by few passengers and there are impacts on rolling stock and infrastructure in the long term.	
4	Very Low	Error is noticed by many passengers. Due to the failure there is an impact on the quality of rolling stock and on the infrastructure in the long term.	
5	Low	Error is noticed by all passengers. Due to the failure there is an impact on the quality of rolling stock and on the infrastructure in mid term. Due to the failure there is an impact on the quality of rolling stock and on the infrastructure in the short term.	Less comfort, minor damages on transported goods, eventually higher noise level, increase of maintenance costs.
6	Moderate	Error is noticed by all passengers. Loaded goods can get damaged.	
7	High	Risk of very few light injured people and risk of significant impact on environment and operation. Operation on the line is closed or the line capacity is declined for hours. The loaded goods can get damaged.	Small derailment in a shunting yard.
8	Very High	Risk of few injured people and severe impact on environment. Operation on the line is closed for weeks. Part of the train is destroyed.	Major derailment in a shunting yard.
9	Unsafe with warning	Risk of multiple injured people and few dead people. The impact on the environment is very high. Operation on the line is closed for weeks. Large parts of the train are destroyed.	
10	Unsafe without warning	Risk of many dead and numerous injured people or the impact on the environment is catastrophic. Operation on the line is closed for weeks. The train is destroyed.	Derailment (Viareggio).

Rank	Impact	Probability - number of failures per operating hour
1	Little - failure is implausible	$< 10^{-9}$
2	Very low: Relatively very few failures	$[10^{-9}; 3 \times 10^{-8}]$
3	Low: Relative few failures	$[3 \times 10^{-8}; 8 \times 10^{-7}]$
4	Moderate: Seldom there are failures	$[8 \times 10^{-7}; 2 \times 10^{-6}]$
5	Moderate: Sometimes there are failures	$[2 \times 10^{-6}; 5 \times 10^{-6}]$
6	Moderate: Often there are failures	$[5 \times 10^{-6}; 10^{-5}]$
7	High: Repeating failures	$[10^{-5}; 2 \times 10^{-5}]$
8	High: Repeating failures in short cycle	$[2 \times 10^{-5}; 4 \times 10^{-4}]$
9	Very high: Failures in short cycle are nearly not avoidable	$[4 \times 10^{-4}; 8 \times 10^{-3}]$
10	Very high: Failures in very short cycle which are not avoidable	$\geq 8 \times 10^{-3}$

Rank	Detection	Criteria
1	nearly certain	With a very high probability a failure will be detected in a very early initial stage.
2	very high	With a high probability a failure will be detected in a very early initial stage.
3	high	With a high probability a failure will be detected in an early initial stage.
4	moderate high	With a high probability a failure will be detected after initial stage.
5	moderate	With a moderate probability a failure will be detected while existing a short while before getting critical.
6	low	A failure will be detected while existing a while just before getting critical.
7	very low	A failure will be detected while existing for a long while just before getting critical.
8	little	A failure will be hardly detected in a very late stage.
9	uncertain	The detection of a failure before becoming critical is uncertain.
10	nearly uncertain	The detection of a failure nearly is not possible.

ANNEX F - Overview of welding and welding defects

According to ISO 25901-1:2016, welding is defined as a “joining process in which two or more parts are united producing a continuity in the nature of the workpiece material(s) employing heat or pressure or both simultaneously, and with or without the use of filler materials (welding consumables added during the process)”. Under ideal conditions with optimized parameters, this process will be permanent with the atomic junction of both surfaces in contact with the joint’s mechanical properties equal to those of the base metal, at worst. The result of this process is known as the weld, which includes both the heat-affected zone and the welded material.

Heat and pressure are crucial in the welding process by driving off absorbed layers of gases, moisture, or organic contaminants; promoting differential thermal expansion or, at least, thermal decomposition to disrupt the continuity of the layers; altering material properties to facilitate plastic deformation; fracturing brittle oxide or tarnish layers to expose clean base material (Shravan et al., 2023; Müller, 2023).

Welding processes can be categorised into two major groups: autogenous welding and brazing or soldering. Further classification can be based on the relative position of the parts to be welded: butt joint, fillet weld joint, or lap joint (Granjon, 2002).

On one hand, autogenous welding is the process of uniting two or more constituent elements of a joint at the same melting temperature as the base material. This type of welding is classified as fusion welding (or liquid state welding), solid state welding (or pressure welding), and micro-welding in the case of very small dimensions. Fusion welding is done without applying pressure, whereas solid-state welding applies pressure, either statically or dynamically, without melting any of the joint's constituent elements.

On the other hand, brazing is the process of connecting two metallic elements using a liquid filler substance with a lower melting temperature than the base materials, which does not contribute to the development of the joint by melting. The capillary action draws the molten filler metal into the joint, where it solidifies upon cooling, creating a strong bond between the base metals. It is often used to join dissimilar metals or materials that cannot be welded using traditional fusion welding methods due to differences in melting points or other factors (Almacinha and Morais, 2020).

The base metal's alloy composition also influences the possibility of a cold crack forming, as it pertains to material hardenability. High cooling rates increase the likelihood of creating a hard, brittle structure in the weld metal and Heat Affected Zone, HAZ. A material's hardenability is often represented in terms of its carbon content or, when other elements are considered, its Carbon Equivalent value, CE.

CE is an empirical value expressed in weight percentage that relates the combined effects of different alloying elements used in the making of carbon steels to an equivalent amount of carbon. This value justifies the different mechanical properties of steels of varying compositions and can be calculated using Equation F.1, with each different atomic element represented by its respective symbol in the Periodic Table (Alhassan and Bashiru, 2021).

$$CE = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15} \quad (F.1)$$

The representation (in technical drawings, for example) of a welded joint between two pieces should include indications such as the weld location, type and nature of the weld seam, dimensions of the weld seam, and any other relevant information.

An ideal welding process achieves perfect continuity between the welded elements so that it is impossible to distinguish and differentiate between them, though it is not feasibly

achieved in practice. Welding processes and techniques have been constantly evolving to apply to a wider range of materials, joints, and operational contexts, with most of the novel current ones being an adaptation of the most generic ones.

Overall, to ensure the quality of any welding process the following four requirements are proposed (Houldcroft, 1988):

- Provide enough energy to facilitate the union between materials, either by fusion or pressure;
- Include a mechanism to remove superficial contamination from the joint faces;
- Avoid contamination due to exposure to the atmosphere and mitigate the related effects;
- Control of weld metallurgy.

The significance of welding procedures emphasises the vital function of highly skilled personnel with deep expertise in the field, in conjunction with meticulous inspection protocols and strict adherence to carefully developed guidelines, all of which are critical to safeguarding the accuracy, safety, and excellence of each welded connection. Inability to adhere to these standards may give rise to compromised weld integrity, increased structural failure risk, and substantial hazards to both personnel and the surrounding environment.

Welding defects can greatly affect weld performance and durability. The nature of the underlying root cause of defects can be chemical, geometrical, structural, or physical. Understanding the various defects, their consequences, and their causes can help to ensure higher-quality and longer-lasting welds by following prompt corrective measures. Upon detection of welding defects, an evaluation should be performed to determine its severity and appropriate action to be taken. Even seemingly minor weld defects can compromise the integrity of a structure, rendering it unfit to carry out its intended purpose.

The scope of international standards for welding defects is to allow for a precise classification and description of any possible imperfections in the welding process. Welding defects can be classified into six different groups, as follows (Rizvi and Alib, 2019):

- cracks;
- cavities;
- solid inclusions;
- lack of fusion and penetration;
- geometric imperfections;
- miscellaneous imperfections.

Cracks, microcracks, and other planar discontinuities

These are undesirable flaws that result from localised ruptures in solid states due to cooling effects or pressures that can be hazardous if they are subjected to fatigue loading conditions. A fresh welding procedure can fix cracks that develop in the base metal, the weld seam, or the HAZ. The cracks can be radial, transverse, or longitudinal. Longitudinal cracks run parallel to the direction of the weld. They are typically produced by an issue with the weld metal's hardness and because the weld's components cool at different speeds. In opposition, a transverse crack is a crack in the base metal beginning at the toe of the weld. They are caused by transverse shrinkage stresses and often indicate a brittleness problem in the HAZ.

Other types of discontinuities include cold cracking and lamellar tearing which will be explained next:

- **Cold cracking** occurs after the weld metal has had time to completely harden (thus the term "cold") and arises by highly restrained welds, shrinkage, and discontinuities. These flaws can be avoided by preheating the components to be welded, welding towards areas of less constraints, and utilizing weld metal of higher ductility. They can be fixed by removing and rewelding the components together.

- **Lamellar Tearing** is a type of crack defect that typically develops beneath a welded joint in spots of high-stress concentration. It is generated when non-metallic impurities and inclusions are rolled into hot plate metal during manufacturing. Special joint design is one way to mitigate this problem, but the most important preventive measure is to specify materials of sufficient quality and test them during the receiving inspection.

Cavities

These imperfections, commonly known as porosity, are the result of imprisoned gas and non-metallic elements in the molten metal during solidification. This entrapment may be caused by contaminants or an overall poor welding technique. The pores might be distributed uniformly or localized (with a random geometric distribution).

Solid inclusions

Unwanted solid inclusions develop when extraneous materials including slag, tungsten, sulphide, and oxide inclusions are enclosed in metal. These defects are frequently connected with other welding flaws, particularly undercutting, incomplete penetration, and lack of fusion. Additionally, slag, which can lead to inclusions, can be a result of insufficient cleaning between multi-pass welds in addition to unsuitable current and electrode manipulation. These inclusions decrease the cross-sectional area strength of the joint and may act as an initiating point for significant cracking development over time.

Lack of fusion and penetration

This type of defect is an internal planar discontinuity that is difficult to identify but can be extremely harmful. It occurs when there is no cohesive link between the weld metal and the base metal, or between weld metal layers. These flaws are caused by poor welding circumstances and parameters, which include insufficient preheating, a low current, insufficient welding speed, and faulty edge preparation, among others. It can only be resolved by grinding out the problematic area and then performing a new welding process under improved conditions. Incomplete penetration is the difference between real and nominal depth penetrations.

Geometrical imperfections

Visual inspection may reveal a broad spectrum of geometrical flaws. Examples of these flaws are overlap (excess weld metal that extends beyond the weld toe or root; typically caused by poor welding technique and reduceable by carefully grinding away excess weld material and smoothing it to match the base metal), misalignment (welded pieces are not in the same required parallel plane, which can be due to varying thickness or setup problems), and undercutting (unfilled groove along the edge of the weld due to incorrect welding parameters). Their presence shows poor workmanship and might cause worry if the allowable quality control limits for inspection are exceeded.

Miscellaneous imperfections

Lastly, this broad category refers to all the defects that do not qualify for any of the other major groups, including, for example, spatter, flux residue, and grinding/chipping marks, among others (Baughurst and Voznaks, 2009).

To summarise, welding plays a crucial role in metal joining operations by offering numerous advantages such as high-strength joints, the ability to join dissimilar metals, and design flexibility, remaining an indispensable method despite its limitations (Ikpe et al., 2023). Nevertheless, by understanding the root causes and conducting suitable mitigation strategies, welders can reduce the occurrence of defects. Achieving defect-free welds demands proper training, adherence to welding standards, and continuous quality monitoring.

ANNEX G - Bogie Sensorisation

Sensor Systems

Given the ongoing demand for safer, longer, quicker, and more economical rail freight vehicles with increased loading capacity, integrating onboard sensors and detection systems appears to be a potential technique for making the best use of railway assets, especially when considering that unprotected railroad crossings and derailments due to mechanical failures represent the two most significant sources of railroad accidents globally. Nonetheless, a notorious challenge lies in the lack of onboard electric power availability on freight wagons, which serves as a major impediment to implementing these technologies.

Real-time condition monitoring provides numerous benefits, including avoiding ineffective preventive and reactive maintenance, lowering waste and costs by replacing parts only when necessary and boosting availability and safety through rapid rolling stock diagnosis. While roadside monitoring applications have advanced substantially, they remain short of offering continuous real-time monitoring. However, as cost reduction and downsizing trends in electronic devices persist, implementing wireless sensor networks onboard freight trains becomes a more appealing and practical solution to the current paradigm paired with energy harvesting mechanisms to power said devices (Pourghodrat et al., 2014).

Condition monitoring is a vital element of effective management since it enables the detection and identification of degradation in structures and infrastructure before it reaches the point of collapse or disrupts rail operations. In its most basic form, condition monitoring is the use of sensors to continuously assess the state of structures or machinery and when sensor readings exceed a specified threshold or indicate a defect, an alarm is triggered. However, this easy approach has disadvantages, such as the possibility of false alarms (alarm is triggered when there is no defect or failure) and failing to detect major breakdowns (alarm is not triggered though there are defects). It largely provides localized analysis and fails to capitalize on the expanded possibilities available through sensor networking and collective data processing. Integrated data processing provides a comprehensive perspective of an asset's state, allowing for the identification of general condition trends (Pourghodrat et al., 2014).

Wireless sensor networks (WSNs) are networks of autonomous devices distributed across space that employ sensors to monitor infrastructure, structures, and machinery. WSNs, when combined with data analytics, enable railways to convert raw data into useful insight. WSNs offer support for decisions by enabling continuous real-time data collecting and analysis, as well as recognizing defects rapidly. Data generated by distributed systems, such as sensor networks, is constantly monitored using methods such as categorization, prediction, and anomaly detection to analyse the network's current and future states (Pourghodrat et al., 2014).

Furthermore, WSN monitoring provides proactive maintenance scheduling based on predictive failure analysis, as opposed to following predetermined maintenance plans or responding to failures after they occur (Pourghodrat et al., 2014).

WSNs face numerous obstacles. For starters, they generate massive amounts of data at high rates and frequently in an unanticipated manner. This data may come from several sources, necessitating fusion for coherence. Furthermore, the behaviour of systems and structures observed by sensors is frequently complex, making interpretation difficult. As a result, thorough data management is essential for gaining an accurate system status perspective (Pourghodrat et al., 2014).

Sensor data is noisy, and sensors themselves might malfunction, particularly in severe environments, resulting in inaccuracies and communication failures. The deployment of sensor networks in challenging contexts increases the complexity. Sensor placement must be carefully

considered to avoid redundant measurements, which might bias data distribution. Furthermore, selecting the right sensor type is critical for achieving the best data quality and value.

WSNs typically operate in remote locations with limited energy sources, relying on batteries or local energy generation for power. Transmission errors within the network may result in missing data. This presents a paradox: while WSNs must minimize energy consumption, efficient communication requires energy expenditure. Balancing these factors is critical for effective WSN operation. Basic condition monitoring systems can discriminate between normal and abnormal situations (the presence or absence of problems) and show growing sophistication (Pourghodrat et al., 2014).

Transducers are devices that transform energy from one form to another. Sensors often convert mechanical signals into electrical signals. Most railway sensors are microelectromechanical systems which are small, integrated devices or systems that combine electrical and mechanical components. They are cost-effective and efficient.

Sensor design requires a delicate balance of functionality and power consumption, with more functionality frequently resulting in higher power requirements. Railway condition monitoring devices are typically used in distant or inaccessible locations where cable electricity is unavailable. As a result, sensors must rely on batteries or locally generated energy for power but have the advantage of being manufactured in such a way as to consume very low power.

To install condition monitoring systems onto freight wagons, several critical components must be addressed: power source, mechanical needs, and communications. Because locomotive electric power is not easily available for the wagon, different power sources such as batteries, power harvesting, or generation methods are required. Hardware resilience is critical for surviving the severe railway environment, with varied degrees of toughness required depending on its location within the vehicle. Additionally, communications integration must support trains' linear network structure. This can be accomplished through direct wired connections, wireless radio linkages to a locomotive hub, a node-to-node communication architecture, or direct links to a remote base hub via tailored software, or satellite connections.

Energy Harvesting

Strategic adaptation of railways, which is pivotal in global transportation, has been very quick to accompany the growing demand for railway services. In this context, energy harvesting emerges as a cost-effective and promising solution to power various trackside, on-board, and infrastructure instruments such as health monitoring sensors, signalling devices, switches, and safety equipment. Considering the scope of this dissertation, a greater emphasis is placed on the ability of energy harvesting technologies to power sensors that can be coupled to the vehicle and allow for real-time monitoring and data collection of system failures.

With the current environmental paradigm, the development of energy harvesting technology is highly favoured and a solid possibility for future sustainable railways boosted by the growth of IIoT (Fraga-Lamas et al., 2017). Self-powered technologies with systems that harvest ambient energy have attracted tremendous attention as promising directions in research, development, and innovation projects due to their potential to use real-time monitoring to achieve environmental protection, and energy saving. Smart maintenance and operation are based on abundant monitoring data to make strategic decisions for a greener and “smarter” railway network (Zhu et al, 2009; Hesham and Soltan, 2020).

To better understand the current stage of energy harvesting innovation, a thorough literature review is mandatory tracing back to the first applications of energy harvesting in the railway sector.

The introduction of the topic in the railway network system is considerably recent dating back to 2008 with a project that introduced two energy harvesting methods to generate a modest

0.5mW output of electrical power (Nelson et al., 2008). Later on, the feasibility of energy harvesting to power sensors used for condition monitoring of railway tunnels and bridges was considered by Wischke et al. (2010). Perez et al. employed a multi-degree of freedom techniques to improve the output power of harvesting devices (Perez et al., 2020). Alongside the presented studies, multiple companies started to engage directly in the development of energy harvesting from railway components through. One company developed piezoelectric energy harvesters in the form of pads which were embedded under sleepers (Innowattech, 2021).

Energy harvesting, or energy scavenging, involves extracting energy from flexible and diversified external sources like solar power, thermal energy, wind energy, chemical energy, acoustic energy, vibration, magnetic fields, and kinetic energy. This energy is then harnessed and stored temporarily to be used in real-time or for future use. Of these, conventional wind and solar energy harvesters are heavily reliant on weather and environmental conditions which leads to greater uncertainty about the energy that can be produced (non-dispatchable sources). Therefore, vibration, thermal, magnetic field, and acoustic energy sources, which can be regarded as the internal ambient energy of vehicle-track systems caused by the train system operating, are the most adequate for real-time monitoring sensors and energy harvesting (Zuo et al., 2023).

Figure G1 illustrates the potential external energy sources to be considered.

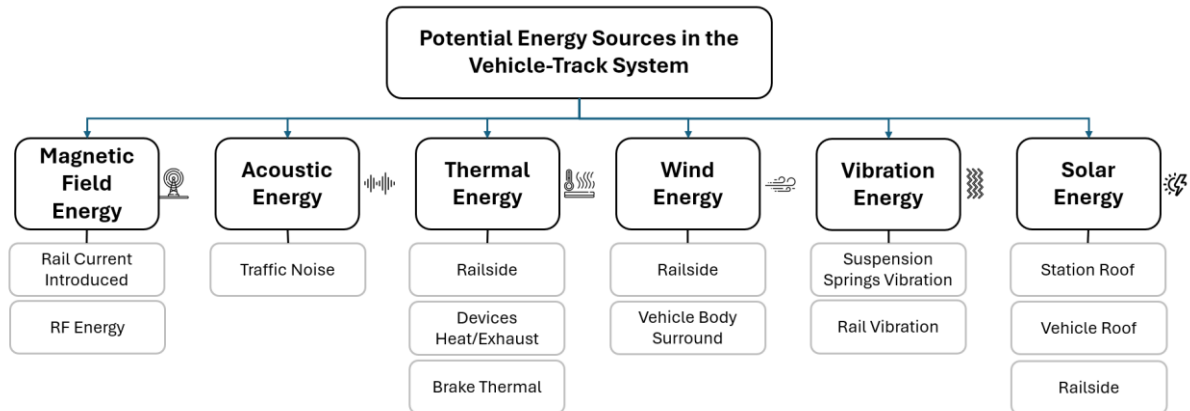


Figure G1 - Potential Energy Sources in the Vehicle-Track System. Adapted from (Zuo et al., 2023).

Energy harvesting mechanisms are methods of capturing and converting energy from various sources in the environment into usable electrical power and are often employed in situations where it is not feasible or practical to use traditional power sources like batteries or grid electricity. Having already introduced the most important potential energy sources, some of the applicable mechanisms are as follows (Zuo et al., 2023):

- Electromagnetic effect;
- Electrostatic forces;
- Magnetic induction;
- Piezoelectric effect;
- Photovoltaic effect;
- Thermoelectric Seebeck effect;
- Triboelectric effect.

Different energy sources necessitate various types of energy-collecting devices with all harvesting systems comprising three fundamental components at their core, alongside the energy source. These components are the following (Thomas et al., 2006):

- **Harvester:** Essentially a straightforward transducer that converts ambient energy from the source into usable electrical energy;
- **Interface circuit:** Responsible for maximizing energy collection from the transducer and converting it into a usable form for the intended application, through tasks such as voltage regulation, rectification, or similar processes;
- **Load:** This component can either utilize the collected energy or store it and the load can take various forms, including sensors, actuators, circuits, as well as energy storage elements like capacitors, batteries, or even a power management unit.

The areas surrounding the railway track network are subject to the presence of high winds, thus the extraction of wind energy through wind turbines is a feasible solution and offers a great opportunity to bolster renewable energies due to the low manufacturing costs paired with a significant amount of energy generation. The conventional technology used are electromagnetic generators with the development of triboelectric nanogenerators for low-power applications (Chen et al., 2018).

Aerodynamic and rolling noise and vibration have become an obvious environmental issue, particularly at high speeds. Noise manifests as dissipated energy and its reduction also improves the quality of train ride, and this reduction can be attained with the use of acoustic resonators and transducers. Unfortunately, studies suggest that the power generation for railway self-powered applications is likely to be insufficient, thus requiring further validation (Noh, 2018).

Through a comprehensive comparison between the aforementioned energy sources it was evident that each has its merits and disadvantages to be considered during the decision and implementation stages. Table G1 provides a brief list comparing the energy sources, based on the transduction type.

Table G1 - Comparison between types of transduction for different energy sources (Zuo et al., 2023)

Energy source	Transduction	Advantages	Drawbacks
Vibration energy	PE	High output voltage, high power density, low cost, simple design, easy to install	Large output resistance, low output power, poor reliability
	EM (linear)	Low output impedance, high peak power, simple design, easy to install, good reliability, low cost	Performance degradation when not resonant, avoid metallic environment
	EM (nonlinear)	Broadband, low output impedance, high power under rail or vehicle vibration, easy to install, good reliability, low cost	Performance degradation when not resonant, avoid metallic environment
	EM (rotary)	High output power, high efficiency	High cost, large volume, difficult to install, complex structure
Thermal energy	TEG	High efficiency, low output resistance, low cost, easy to install, simple design	Fewer scenarios for installation, extra cooling structure
Wind energy	EM	High output power, low installation requirements, mature technology	High construction cost (for large-scale), affected by the weather
	PE	Simple design, easy to install, low cost	Low output power, poor reliability, work only when trains pass by
	TE	Power generation in the breeze, high output voltage, low weight, low cost, easy to install	High impedance, low output current, affected by the weather
Solar energy	PV	High output power, low installation requirements, mature technology	Affected by the weather, no power at night, surface dust affects output.
Magnetic field energy	EM	High output power, low cost, easy to install	Only suitable for electrified railway, installation distance limit
	RF	High integration, good reliability, long distance information exchange	Complex design, high equipment sensitivity requirements
Acoustic energy	PE	Power generation as well as noise reduction	Combined with acoustic resonators

From Table G1 it is evident that these technologies hold immense promise, yet they are also confronted with significant challenges that demand innovative solutions for improvement in the coming years (Zuo et al., 2023).

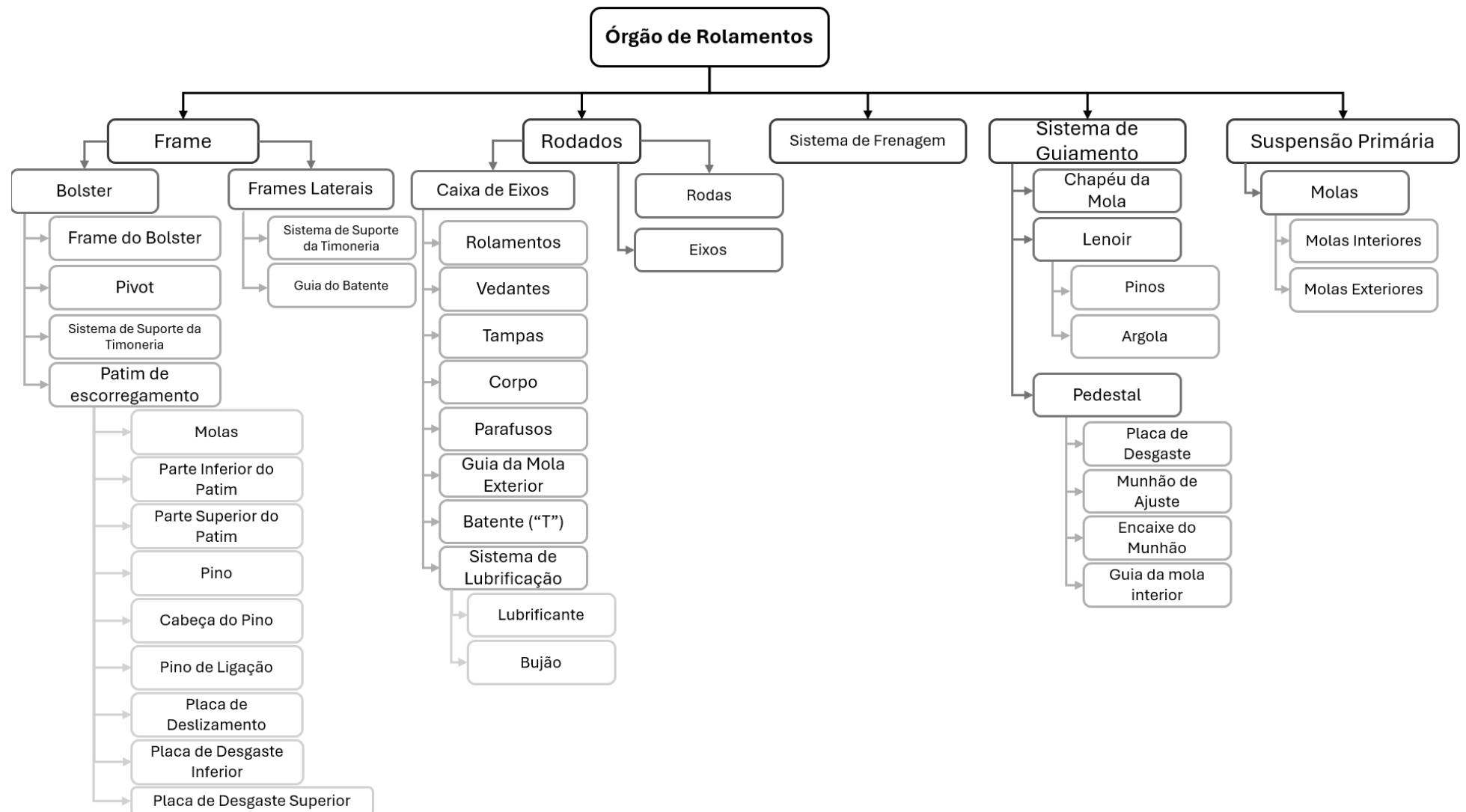
However, despite these promising trends, several weaknesses persist and must be addressed to unlock the full potential of energy harvesting technologies in the railways sector. One critical challenge is the variability and intermittency of energy sources, particularly in the case of renewable sources like solar and wind, which demands robust energy storage solutions to ensure a continuous and reliable power supply over time. Furthermore, the scalability and cost-effectiveness of energy harvesting systems remain areas of concern as the initial investment and infrastructure requirements are demanding (Zuo et al., 2023).

In addition, ensuring interoperability and standardization across different energy harvesting technologies is essential for seamless integration into the existing railway systems. This necessitates collaboration among stakeholders and regulatory bodies to establish common protocols and guidelines (Zuo et al., 2023).

In conclusion, while the future of energy harvesting in the railways sector holds great promise, addressing these weaknesses is imperative to realize its full potential. By focusing on innovation, collaboration, and addressing key challenges, we can usher in a new era of sustainable and efficient rail transportation systems powered by advanced energy harvesting technologies.

With the information available, it is safe to assume that railway energy harvesting technology is still undergoing development to improve the efficiency, practicality, ease of use and installation, reliability, and maintainability for future applications. A key development to bolster the efficiency of these technologies would be by enhancing the interdisciplinary research and systematic design, in the domains of mechanics, electronics, and materials.

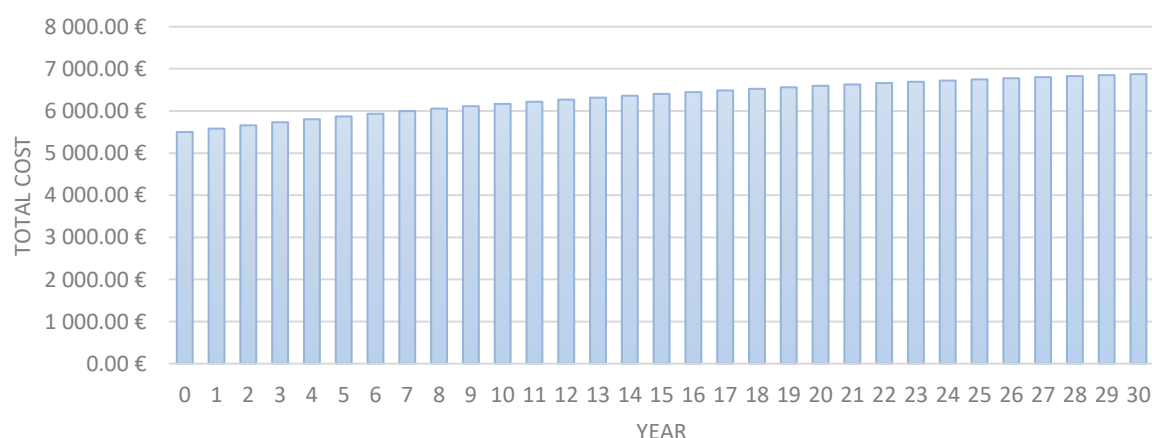
ANNEX H - Functional Breakdown of the Bogie System (PT)



ANNEX I - NPV Calculation for the Primary Suspension System

YEAR	PREVENTIVE COST	CORRECTIVE COST	TOTAL COST (CUMMULATIVE)
0	0.00 €	0.00 €	5 500.00 €
1	57.42 €	23.22 €	5 580.64 €
2	54.94 €	22.22 €	5 657.81 €
3	52.58 €	21.27 €	5 731.65 €
4	50.31 €	20.35 €	5 802.32 €
5	48.15 €	19.48 €	5 869.94 €
6	46.07 €	18.64 €	5 934.65 €
7	44.09 €	17.83 €	5 996.58 €
8	42.19 €	17.07 €	6 055.83 €
9	40.37 €	16.33 €	6 112.54 €
10	38.64 €	15.63 €	6 166.80 €
11	36.97 €	14.95 €	6 218.73 €
12	35.38 €	14.31 €	6 268.42 €
13	33.86 €	13.69 €	6 315.97 €
14	32.40 €	13.11 €	6 361.47 €
15	31.00 €	12.54 €	6 405.02 €
16	29.67 €	12.00 €	6 446.69 €
17	28.39 €	11.48 €	6 486.56 €
18	27.17 €	10.99 €	6 524.72 €
19	26.00 €	10.52 €	6 561.23 €
20	24.88 €	10.06 €	6 596.18 €
21	23.81 €	9.63 €	6 629.61 €
22	22.78 €	9.22 €	6 661.61 €
23	21.80 €	8.82 €	6 692.23 €
24	20.86 €	8.44 €	6 721.53 €
25	19.96 €	8.08 €	6 749.57 €
26	19.10 €	7.73 €	6 776.40 €
27	18.28 €	7.39 €	6 802.08 €
28	17.49 €	7.08 €	6 826.65 €
29	16.74 €	6.77 €	6 850.16 €
30	16.02 €	6.48 €	6 872.66 €

NPV Calculation for Primary Suspension System



ANNEX J - Application of FMECA to the Bogie System

Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Frame	Bolster	Bolster Frame		BFB	Ensure stability, load distribution, and flexibility of the bogie, supporting the wheels and allowing the vehicle to move smoothly along the track.	Fracture	Loss of structural integrity and uneven load distribution.	Function is impaired, potentially leading to severe safety hazards. Structural integrity is compromised and intervention is mandatory
Frame	Bolster	Bolster Frame		BFB	Ensure stability, load distribution, and flexibility of the bogie, supporting the wheels and allowing the vehicle to move smoothly along the track.	Wear	Loss of structural integrity and uneven load distribution.	Function is impaired, potentially leading to severe safety hazards. Structural integrity is compromised and intervention is mandatory
Frame	Bolster	Bolster Frame		BFB	Ensure stability, load distribution, and flexibility of the bogie, supporting the wheels and allowing the vehicle to move smoothly along the track.	Material Degradation	Loss of structural integrity and uneven load distribution.	Function is impaired, potentially leading to severe safety hazards. Structural integrity is compromised and intervention is mandatory
Frame	Bolster	Bolster Frame		BFB	Ensure stability, load distribution, and flexibility of the bogie, supporting the wheels and allowing the vehicle to move smoothly along the track.	Material Degradation	Distortion or warping of the frame, quality issues, misalignment	Function is impaired, potentially leading to severe safety hazards. Structural integrity is compromised and intervention is mandatory
Frame	Bolster	Pivot		BFP	Provide articulation and flexibility to the bogie assembly to guarantee its guidance and prevent dangerous oscillatory movements.	Wear and Tear	Damage to the component which can aggravate and lead to it breaking and rendered useless	Increased instability with uneven loading. Accelerated wear of components which can pose several safety hazards
Frame	Bolster	Pivot		BFP	Provide articulation and flexibility to the bogie assembly to guarantee its guidance and prevent dangerous oscillatory movements.	Wear and Tear	Crack propagation that can result in fractures	Increased instability with uneven loading. Accelerated wear of components which can pose several safety hazards
Frame	Bolster	Pivot		BFP	Provide articulation and flexibility to the bogie assembly to guarantee its guidance and prevent dangerous oscillatory movements.	Wear and Tear	Localized deformation or bending of the component	Increased instability with uneven loading. Accelerated wear of components which can pose several safety hazards
Frame	Bolster	Pivot		BFP	Provide articulation and flexibility to the bogie assembly to guarantee its guidance and prevent dangerous oscillatory movements.	Wear and Tear	Surface is damaged which could impair the function of this component and require intervention	Increased instability with uneven loading. Accelerated wear of components which can pose several safety hazards
Frame	Bolster	Pivot		BFP	Provide articulation and flexibility to the bogie assembly to guarantee its guidance and prevent dangerous oscillatory movements.	Wear and Tear	Surface is damaged which could impair the function of this component and require intervention	Increased instability with uneven loading. Accelerated wear of components which can pose several safety hazards
Frame	Bolster	Brake Rigging Support System		BFBRS	Guide the brake rigging system.	Fracture	Rapid crack propagation	Without proper support, the brakes may lose their effectiveness, leading to difficulty in slowing down or stopping the vehicle or an imbalance when braking.
Frame	Bolster	Brake Rigging Support System		BFBRS	Guide the brake rigging system.	Material Degradation	Accelerated wear and tear which can shorten their lifespan and increase the frequency of maintenance and replacement intervals	Without proper support, the brakes may lose their effectiveness, leading to difficulty in slowing down or stopping the vehicle or an imbalance when braking.
Frame	Bolster	Brake Rigging Support System		BFBRS	Guide the brake rigging system.	Material Degradation	Accelerated wear and tear which can shorten their lifespan and increase the frequency of maintenance and replacement intervals	Without proper support, the brakes may lose their effectiveness, leading to difficulty in slowing down or stopping the vehicle or an imbalance when braking.
Frame	Bolster	Brake Rigging Holder		BFBSS	Offer a stable platform for better stability of the brake rigging system and prevent the components from falling off.	Cracking	Loss of function. Weakening and wearing of the material, which can end up breaking.	Loss of protection and stability of the components.
Frame	Bolster	Buffer Plates		BFBBP	Provide a cushioning and damping effect to reduce impact forces and minimize damage.	Excessive wear	Loss of properties, leading to loss of the protective function.	Without effective damping, other components are more easily subject to accelerated fatigue related failures
Frame	Bolster	Sliding System	Springs	BFSSS	Damping and Shock Absorption.	Load Loss	Uneven weight distribution across the system	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Frame	Bolster	Sliding System	Springs	BFSSS	Damping and Shock Absorption.	Load Loss	Reduced load-bearing capacity and uneven weight distribution across the system. Material is more easily susceptible to breaking.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Frame	Bolster	Sliding System	Springs	BFSSS	Damping and Shock Absorption.	Fracture	Inadequate material was selected during design phase which can be incompatible with the intended operating context.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.

Existing System:						Risk - Reduction		New System:				
Risk Priority Number (RPN) limit for intensive proofings:								Risk Priority Number (RPN) limit for intensive proofings:				
Failure Causes	Severity 1: B 2: C	Detectability 1: B 2: C & A	Frequency 1: B 2: A	Risk priority number		Action	Type	Severity B	Detectability B	Frequency B	Risk priority number	
Excessive loading	moderate	6	high	3	54						0	
Corrosion	moderate	6	moderate	4	96						0	
Thermal Degradation at excessive temperatures	moderate	6	very high	2	24						0	
Welding defects, or inadequate welding techniques	low	5	very low	7	70	Strictly comply with welding standards, ensuring the operation is performed by a specialist		low	5	high	3	15
Development of cracks due to excessive loading	low	5	moderate	4	60						0	
Fatigue damage starting as microcracks	low	5	very low	7	175	Monitor the component more often and replace it if needed to avoid fatigue initiated failures		low	5	high	3	30
Misalignment or improper handling	low	5	high	3	45	Verify thoroughly if the component was properly installed and is correctly aligned		low	5	nearly certain	1	5
Corrosion / chemical degradation	high	7	moderate	5	140						0	
Manufacturing defects	high	7	moderate	4	56						0	
Improper installation and/or adjustment	low	5	high	3	30	Verify thoroughly if the component was properly installed and is correctly aligned		very low	4	nearly certain	1	4
Interaction with corrosive agents	very high	8	moderate	4	128						0	
Thermal degradation	very high	8	very high	2	32						0	
Fatigue damage starting as microcracks	unsafe with warning	9	very low	7	315	Monitor the component more often and replace it if needed to avoid fatigue initiated failures		very high	8	moderate	5	80
Misalignment	very low	4	high	3	12	Verify thoroughly if the component was properly installed and is correctly aligned		very low	4	nearly certain	1	4
Operating out of the designed operating parameters	low	5	moderate	4	60						0	
Hydrogen embrittlement	very low	4	moderate	5	40						0	
Material flaws	very low	4	moderate	4	48						0	

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Frame	Bolster	Sliding System	Springs	BFSSS	Damping and Shock Absorption.	Fracture	Reduced load-bearing capacity and uneven weight distribution across the system. Material is more easily susceptible to breaking.	Reduced damping functionality. Excessive wear on specific wheelset and suspension component and track sections.
Frame	Bolster	Sliding System	Springs	BFSSS	Damping and Shock Absorption.	Fracture	Formation of stress concentration points on the surface, where stresses are amplified leading to localized plastic deformation or crack initiation	Reduced damping functionality. Excessive wear on specific wheelset and suspension component and track sections.
Frame	Bolster	Sliding System	Springs	BFSSS	Damping and Shock Absorption.	Fracture	Weakening of the material of the component, compromising its structural integrity and leading to its damage	Reduced damping functionality. Excessive wear on specific wheelset and suspension component and track sections.
Frame	Bolster	Sliding System	Springs	BFSSS	Damping and Shock Absorption.	Fracture	Increased wear and reduced efficiency in damping. Misalignment further promotes the occurrence of failures due to other causes.	Reduced damping functionality. Excessive wear on specific wheelset and suspension component and track sections.
Frame	Bolster	Sliding System	Springs	BFSSS	Damping and Shock Absorption.	Fracture	Severe damage to the component resulting in breakage.	Reduced damping functionality. Excessive wear on specific wheelset and suspension component and track sections.
Frame	Bolster	Sliding System	Springs	BFSSS	Damping and Shock Absorption.	Fracture	Additional stresses. Severe damage to the component resulting in breakage.	Reduced damping functionality. Excessive wear on specific wheelset and suspension component and track sections.
Frame	Bolster	Sliding System	Springs	BFSSS	Damping and Shock Absorption.	Fracture	Vibration can induce cyclic loading on the spring, accelerating the propagation of fatigue cracks and reducing the component's useful life	Reduced damping functionality. Excessive wear on specific wheelset and suspension component and track sections.
Frame	Bolster	Sliding System	Springs	BFSSS	Damping and Shock Absorption.	Fracture	Severe damage to the component resulting in breakage.	Reduced damping functionality. Excessive wear on specific wheelset and suspension component and track sections.
Frame	Bolster	Sliding System	Bottom Secondary Suspension Part	BFSS2	Limit the stroke by clamping the movement to prevent wear and balance the load.	Wear	Material is weakened and cracks propagate with time	Loss of function, resulting in a change in degrees of freedom
Frame	Bolster	Sliding System	Top Secondary Suspension Part	BFSS4	Limit the stroke by clamping the movement to prevent wear and balance the load.	Fracture	Serious damage to the component, leading to complete loss of function	Loss of function, resulting in a change in degrees of freedom
Frame	Bolster	Sliding System	Pin	BFSS11	Connect the bolster to the lower and upper supports of the secondary suspension system.	Seizure of the pin	Damage to the component, likely impairing its function.	Increased instability, derailment risk, and potential service disruptions.
Frame	Bolster	Sliding System	Pin	BFSS11	Connect the bolster to the lower and upper supports of the secondary suspension system.	Seizure of the pin	Damage to the component, likely impairing its function.	Increased instability, derailment risk, and potential service disruptions.
Frame	Bolster	Sliding System	Pin	BFSS11	Connect the bolster to the lower and upper supports of the secondary suspension system.	Seizure of the pin	Damage to the component, likely impairing its function.	Increased instability, derailment risk, and potential service disruptions.
Frame	Bolster	Sliding System	Pin	BFSS11	Connect the bolster to the lower and upper supports of the secondary suspension system.	Loosening of the pin joint	Component is quite unstable and not properly placed, not functioning as intended. Can even fall out of place.	Increased instability, derailment risk, and potential service disruptions.
Frame	Bolster	Sliding System	Pin	BFSS11	Connect the bolster to the lower and upper supports of the secondary suspension system.	Loosening of the pin joint	Component is quite unstable and not properly placed, not functioning as intended. Can even fall out of place.	Increased instability, derailment risk, and potential service disruptions.
Frame	Bolster	Sliding System	Pin	BFSS11	Connect the bolster to the lower and upper supports of the secondary suspension system.	Loosening of the pin joint	Component is quite unstable and not properly placed, not functioning as intended. Can even fall out of place.	Increased instability, derailment risk, and potential service disruptions.

		Existing System:						Risk - Reduction		New System:					
		Risk Priority Number (RPN) limit for intensive proofings:					Risk Priority Number (RPN) limit for intensive proofings:				0				
Failure Causes	Severity 1: B 2: C	Detectability 1: B 2: C	Frequency 1: B 2: A	Risk priority number		Action	Type	Severity B	Detectability B	Frequency B	Risk priority number	Acceptanc e of improv- ment			
Hydrogen embrittlement	low	5	moderate	5	low: relative few failures	3	75				0				
Stress concentration due to tooling marks and rough finishes	high	7	moderate high	4	very low: relative very few failures	2	56				0				
Corrosion	high	7	very high	2	moderate: seldom there are failures	4	56				0				
Misalignment	very high	8	high	3	very low: relative very few failures	2	48	Verify thoroughly if the component was properly installed and is correctly aligned	very high	8	nearly certain	1	little - failure is implausible	1	8
Maximum load ratio exceeded	very high	8	very high	2	little - failure is implausible	1	16				0				
Suffer excessive deflection in the direction perpendicular to the axis	very high	8	moderate high	4	low: relative few failures	3	96				0				
Excessive vibration	high	7	very low	7	low: relative few failures	3	147	Monitor vibrations more frequently, as well as assess any possible effects on the vehicle at the time	high	7	moderate high	4	low: relative few failures	3	84
Stresses greater than the nominal shear stresses	high	7	very high	2	low: relative few failures	3	42				0				
Damage due to metal fatigue	moderate	6	very low	7	moderate: seldom there are failures	4	168	Monitor the component more often and replace it if needed to avoid fatigue initiated failures	moderate	6	high	3	very low: relative very few failures	2	36
Excessive loading or impacts	high	7	moderate high	4	low: relative few failures	3	84				0				
Excessive loading	high	7	high	3	low: relative few failures	3	63				0				
Internal wear debris	high	7	moderate	5	moderate: seldom there are failures	4	140				0				
Metal-to-metal contact	high	7	moderate high	4	moderate: sometimes there are failures	5	140				0				
Excessive vibration	high	7	moderate	5	moderate: seldom there are failures	4	140	Monitor vibrations more frequently, as well as assess any possible effects on the vehicle at the time	low	5	very high	2	very low: relative very few failures	2	20
Poor surface finish	high	7	moderate high	4	low: relative few failures	3	84				0				
Excessive local contact pressure	high	7	moderate	5	very low: relative very few failures	2	70				0				

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Frame	Bolster	Sliding System	Pin	BFSS1	Connect the bolster to the lower and upper supports of the secondary suspension system.	Loosening of the pin joint	Component is quite unstable and not properly placed, not functioning as intended. Can even fall out of place.	Increased instability, derailment risk, and potential service disruptions.
Frame	Bolster	Sliding System	Pin	BFSS1	Connect the bolster to the lower and upper supports of the secondary suspension system.	Loosening of the pin joint	Component is quite unstable and not properly placed, not functioning as intended. Can even fall out of place.	Increased instability, derailment risk, and potential service disruptions.
Frame	Bolster	Sliding System	Pin	BFSS1	Connect the bolster to the lower and upper supports of the secondary suspension system.	Yielding of the pin	Damage to the component, likely impairing its function.	Increased instability, derailment risk, and potential service disruptions.
Frame	Bolster	Sliding System	Pin	BFSS1	Connect the bolster to the lower and upper supports of the secondary suspension system.	Yielding of the pin	Damage to the component, likely impairing its function.	Increased instability, derailment risk, and potential service disruptions.
Frame	Bolster	Sliding System	Pin Head	BFSS2	Facilitate the secure attachment, alignment, and movement of components.	Bending or shearing	Damage to the component, likely impairing its function.	Loss of secure attachment of components, which can more easily become loose or misaligned, affecting overall stability
Frame	Bolster	Sliding System	Pin Head	BFSS2	Facilitate the secure attachment, alignment, and movement of components.	Wear and Tear	Surface is damaged which could impair the function of this component and require intervention	Loss of secure attachment of components, which can more easily become loose or misaligned, affecting overall stability
Frame	Bolster	Sliding System	Pin Head	BFSS2	Facilitate the secure attachment, alignment, and movement of components.	Wear and Tear	Surface is damaged which could impair the function of this component and require intervention	Loss of secure attachment of components, which can more easily become loose or misaligned, affecting overall stability
Frame	Bolster	Sliding System	Pin Head	BFSS2	Facilitate the secure attachment, alignment, and movement of components.	Wear and Tear	Surface is damaged which could impair the function of this component and require intervention	Loss of secure attachment of components, which can more easily become loose or misaligned, affecting overall stability
Frame	Bolster	Sliding System	Connecting Pin	BFSS1	Support and guide the springs.	Loosening of the pin	Can lead to increased clearance between the skid and the bogie and further misalignment issues.	The skid can become completely disconnected from the bogie, resulting in loss of control and stability with possible uncontrollable movement
Frame	Bolster	Sliding System	Connecting Pin	BFSS1	Support and guide the springs.	Wear	Damage to component which can impair its function.	The skid can become completely disconnected from the bogie, resulting in loss of control and stability with possible uncontrollable movement
Frame	Bolster	Sliding System	Sliding Plate	BFSS5	Protect the upper secondary suspension part and allow for sliding.	Fracture	Serious damage to the component, leading to complete loss of function	Loss of this articulation, restricting the bogie's ability to describe curves and transitions smoothly. Wheels may experience increased wear as a consequence of the uneven loading.
Frame	Bolster	Sliding System	Sliding Plate	BFSS5	Protect the upper secondary suspension part and allow for sliding.	Loosening of the plate	Uneven loading	Loss of this articulation, restricting the bogie's ability to describe curves and transitions smoothly. Wheels may experience increased wear as a consequence of the uneven loading.
Frame	Bolster	Sliding System	Sliding Plate	BFSS5	Protect the upper secondary suspension part and allow for sliding.	Excessive wear	Damage to the component which promotes further degradation.	Loss of this articulation, restricting the bogie's ability to describe curves and transitions smoothly. Wheels may experience increased wear as a consequence of the uneven loading.
Frame	Bolster	Sliding System	Lower Part Wear Plate	BFSS3	Sacrificial plates that help in guiding the moving body.	Fracture	Increased porosity of the joint, making it more susceptible to fissuration, leading to its failure. Worsening of material properties, particularly the resistance to impacts.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Lower Part Wear Plate	BFSS3	Sacrificial plates that help in guiding the moving body.	Fracture	Fissuration at the welding joint that accelerates the wear of the component. Loosening of the component.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Lower Part Wear Plate	BFSS3	Sacrificial plates that help in guiding the moving body.	Fracture	Fatigue related fissuration at the welding joint, ending in fracture.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway track and the bogie.

		Risk Priority Number (RPN) limit for intensive proofings:							Risk Priority Number (RPN) limit for intensive proofings:					0				
Failure Causes		Severity 1: B 2: C		Detectability 1: B 2: C & A		Frequency 1: B 2: A		Risk priority number	Action		Type	Severity B		Detectability B		Frequency B		Risk priority number
Wear of the pin		high	7	moderate high	4	low: relative few failures	3	84										0
Undersized pin (design flaws)		high	7	high	3	very low: relative very few failures	2	42										0
Misalignment or improper handling		high	7	high	3	low: relative few failures	3	63	Verify thoroughly if the component was properly installed and is correctly aligned	high	7	nearly certain	1	little - failure is implausible	1	7		7
Incorrect pin loads		high	7	moderate	5	low: relative few failures	3	105										0
Misalignment or improper instalation and handling		high	7	high	3	low: relative few failures	3	63	Verify thoroughly if the component was properly installed and is correctly aligned	high	7	nearly certain	1	little - failure is implausible	1	7		7
Material defects		moderate	6	very high	2	very low: relative very few failures	2	24										0
Excessive temperatures		moderate	6	very high	2	very low: relative very few failures	2	24										0
Exposure to chemicals, solvents or oxidants that lead to corrosion		moderate	6	high	3	moderate: seldom there are failures	4	72										0
Insufficient tightening torque		moderate	6	high	3	moderate: seldom there are failures	4	72										0
Misalignment or improper instalation and handling		low	5	high	3	low: relative few failures	3	45										0
Improper installation or misalignment		low	5	high	3	low: relative few failures	3	45	Verify thoroughly if the component was properly installed and is correctly aligned	low	5	very high	2	little - failure is implausible	1	10		10
Insufficient tightening torque		low	5	high	3	very low: relative very few failures	2	30										0
Excessive loading or impacts		low	5	moderate	5	low: relative few failures	3	75										0
Welding defects that lead to excessive stress concentrations.		moderate	6	moderate	5	moderate: seldom there are failures	4	120	Strictly comply with welding standards, ensuring the operation is performed by a specialist	little	3	very high	2	little - failure is implausible	1	6		6
Impacts or excessive loading, especially in the presence of welding defects.		moderate	6	low	6	low: relative few failures	3	108	Strictly comply with welding standards, ensuring the operation is performed by a specialist	little	3	very high	2	little - failure is implausible	1	6		6
Excessive overthickness that promotes stress concentration at the welding joint.		moderate	6	moderate high	4	very low: relative very few failures	2	48	Strictly comply with welding standards, ensuring the operation is performed by a specialist	little	3	very high	2	little - failure is implausible	1	6		6

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Frame	Bolster	Sliding System	Lower Part Wear Plate	BFSS3	Sacrificial plates that help in guiding the moving body.	Fracture	Fatigue related fissuration at the welding joint, ending in fracture.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Lower Part Wear Plate	BFSS3	Sacrificial plates that help in guiding the moving body.	Fracture	Fissuration at the welding joint that accelerates the wear of the component.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Lower Part Wear Plate	BFSS3	Sacrificial plates that help in guiding the moving body.	Fracture	Loss of material properties. Fissuration at the welding joint that accelerates the wear of the component.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Lower Part Wear Plate	BFSS3	Sacrificial plates that help in guiding the moving body.	Fracture	Fissuration at the welding joint that accelerates the wear of the component.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Lower Part Wear Plate	BFSS3	Sacrificial plates that help in guiding the moving body.	Corrosion	Chemical degradation of the component, eventually resulting in fracture of the joint.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Lower Part Wear Plate	BFSS3	Sacrificial plates that help in guiding the moving body.	Excessive Deformation	Loss of material properties that lead to excessive deformation even under normal operating conditions.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Top Part Wear Plate	BFSS6	Sacrificial plates that help in guiding the moving body.	Fracture	Increased porosity of the joint, making it more susceptible to fissuration, leading to its failure. Worsening of material properties, particularly the resistance to impacts.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Top Part Wear Plate	BFSS6	Sacrificial plates that help in guiding the moving body.	Fracture	Fissuration at the welding joint that accelerates the wear of the component. Loosening of the component.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Top Part Wear Plate	BFSS6	Sacrificial plates that help in guiding the moving body.	Fracture	Fatigue related fissuration at the welding joint, ending in fracture.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Top Part Wear Plate	BFSS6	Sacrificial plates that help in guiding the moving body.	Fracture	Fatigue related fissuration at the welding joint, ending in fracture.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Top Part Wear Plate	BFSS6	Sacrificial plates that help in guiding the moving body.	Fracture	Fissuration at the welding joint that accelerates the wear of the component.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Top Part Wear Plate	BFSS6	Sacrificial plates that help in guiding the moving body.	Fracture	Loss of material properties. Fissuration at the welding joint that accelerates the wear of the component.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Top Part Wear Plate	BFSS6	Sacrificial plates that help in guiding the moving body.	Fracture	Fissuration at the welding joint that accelerates the wear of the component.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Top Part Wear Plate	BFSS6	Sacrificial plates that help in guiding the moving body.	Corrosion	Chemical degradation of the component, eventually resulting in fracture of the joint.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Top Part Wear Plate	BFSS6	Sacrificial plates that help in guiding the moving body.	Excessive Deformation	Loss of material properties that lead to excessive deformation even under normal operating conditions.	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the bogie.
Frame	Bolster	Sliding System	Anti-Friction Plate	BFSSAF	Distribute load allowing the bogie to move freely.	Fracture	Loss of function and increased friction	Loss of damping and braking capacity. Degrees of freedom are compromised. Accelerated wear of both the railway tracks and the wheels.

		Existing System:				Risk - Reduction		New System:							
		Risk Priority Number (RPN) limit for intensive proofings:						Risk Priority Number (RPN) limit for intensive proofings:			0				
Failure Causes		Severity 1: B 2: C	Detectability 1: B 2: C & A	Frequency 1: B 2: A	Risk priority number	Action	Type	Severity B	Detectability B	Frequency B	Risk priority number	Acceptanc e of improv- ment			
Inadequate joint preparation allowing for its contamination with moisture or greases.		moderate	6	moderate	5	moderate: sometimes there are failures	5	150	little	3	very high	2	little - failure is implausible	1	6
Insufficient protection of the welding gas for the given environmental conditions, or inadequate welding gas for the given process.		moderate	6	moderate	4	moderate: seldom there are failures	4	96	little	3	very high	2	little - failure is implausible	1	6
Incorrect temperature control during the welding process (excessive or insufficient preheating)		moderate	6	low	6	low: relative few failures	3	108	little	3	very high	2	little - failure is implausible	1	6
Inadequate heat treatments for the welding joint.		moderate	6	low	6	moderate: sometimes there are failures	5	180	little	3	very high	2	little - failure is implausible	1	6
Inadequate chemical composition of the material (base and filler), especially under inadequate welding conditions		moderate	6	low	6	moderate: often there are failures	6	216	little	3	very high	2	little - failure is implausible	1	6
Inadequate welding conditions that lead to worse material properties than intended.		moderate	6	moderate	4	moderate: seldom there are failures	4	96	little	3	very high	2	little - failure is implausible	1	6
Welding defects that lead to excessive stress concentrations.		moderate	6	low	6	moderate: seldom there are failures	4	144	little	3	very high	2	little - failure is implausible	1	6
Impacts or excessive loading, especially in the presence of welding defects.		moderate	6	moderate	5	low: relative few failures	3	90	little	3	very high	2	little - failure is implausible	1	6
Excessive overthickness that promotes stress concentration at the welding joint.		moderate	6	low	6	very low: relative very few failures	2	72	little	3	very high	2	little - failure is implausible	1	6
Inadequate joint preparation allowing for its contamination with moisture or greases.		moderate	6	moderate	4	moderate: sometimes there are failures	5	120	little	3	very high	2	little - failure is implausible	1	6
Insufficient protection of the welding gas for the given environmental conditions, or inadequate welding gas for the given process.		moderate	6	moderate	5	moderate: seldom there are failures	4	120	little	3	very high	2	little - failure is implausible	1	6
Incorrect temperature control during the welding process (excessive or insufficient preheating)		moderate	6	moderate	4	low: relative few failures	3	72	little	3	very high	2	little - failure is implausible	1	6
Inadequate Heat Treatments for the welding joint.		moderate	6	low	6	moderate: sometimes there are failures	5	180	little	3	very high	2	little - failure is implausible	1	6
Inadequate chemical composition of the material (base and filler), especially under inadequate welding conditions		moderate	6	low	6	moderate: often there are failures	6	216	little	3	very high	2	little - failure is implausible	1	6
Inadequate welding conditions that lead to worse material properties than intended.		moderate	6	low	6	moderate: seldom there are failures	4	144	little	3	very high	2	little - failure is implausible	1	6
Excessive loading or impacts		moderate	6	moderate	4	moderate: seldom there are failures	4	96							0

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Frame	Lateral Frames	Brake Rigging Support System		BFBR	Guide the brake rigging system.	Fracture	Rapid crack propagation	Without proper support, the brakes may lose their effectiveness, leading to difficulty in slowing down or stopping the vehicle or an imbalance when braking.
Frame	Lateral Frames	Brake Rigging Support System		BFBR	Guide the brake rigging system.	Material Degradation	Accelerated wear and tear which can shorten their lifespan and increase the frequency of maintenance and replacement intervals	Without proper support, the brakes may lose their effectiveness, leading to difficulty in slowing down or stopping the vehicle or an imbalance when braking.
Frame	Lateral Frames	Brake Rigging Support System		BFBR	Guide the brake rigging system.	Material Degradation	Accelerated wear and tear which can shorten their lifespan and increase the frequency of maintenance and replacement intervals	Without proper support, the brakes may lose their effectiveness, leading to difficulty in slowing down or stopping the vehicle or an imbalance when braking.
Frame	Lateral Frames	Bump Stop		BFS	Ensure proper alignment by limiting the vertical displacement between the wheelset and the frame.	Wear	Damage to the component which can aggravate and lead to it breaking	Function of alignment is compromised, translating to a change in the degrees of freedom of the system
Frame	Lateral Frames	Bump Stop		BFS	Ensure proper alignment by limiting the vertical displacement between the wheelset and the frame.	Wear	Damage to the component which can aggravate and lead to it breaking	Function of alignment is compromised, translating to a change in the degrees of freedom of the system
Frame	Lateral Frames	Bump Stop		BFS	Ensure proper alignment by limiting the vertical displacement between the wheelset and the frame.	Wear	Damage to the component which can aggravate and lead to it breaking	Function of alignment is compromised, translating to a change in the degrees of freedom of the system
Frame	Lateral Frames	Bump Stop		BFS	Ensure proper alignment by limiting the vertical displacement between the wheelset and the frame.	Loosening	Component is easily misaligned and thus not able to perform its function as intended	Function of alignment is compromised, translating to a change in the degrees of freedom of the system
Frame	Lateral Frames	Bump Stop		BFS	Ensure proper alignment by limiting the vertical displacement between the wheelset and the frame.	Fracture	Serious damage to the component, leading to complete loss of function	Function of alignment is compromised, translating to a change in the degrees of freedom of the system

		Existing System:						Risk - Reduction		New System:									
		Risk Priority Number (RPN) limit for intensive proofings:								Risk Priority Number (RPN) limit for intensive proofings:			0						
Failure Causes		Severity 1: B 2: C		Detectability 1: B 2: C & A		Frequency 1: B 2: A		Risk priority number	Action	Type	Severity B		Detectability B		Frequency B		Risk priority number	Acceptance of improvement	
Improper installation and/or adjustment		high	7	low	6	low: relative few failures moderate: sometimes there are failures		3	126								0		
Interaction with corrosive agents		high	7	high	3	low: relative few failures moderate: often there are failures		5	105								0		
Thermal degradation		high	7	high	3	low: relative few failures moderate: often there are failures		3	63								0		
Corrosion and accelerated chemical degradation		moderate	6	high	3	moderate: seldom there are failures		6	108								0		
Misalignment or improper handling		moderate	6	nearly certain	1	moderate: seldom there are failures		4	24	Verify thoroughly if the component was properly installed and is correctly aligned		moderate	6	nearly certain	1	little - failure is implausible	1	6	
Design flaws		moderate	6	nearly certain	1	very low: relative very few failures		2	12								0		
Welding defects		low	5	high	3	very low: relative very few failures		2	30	Strictly comply with welding standards, ensuring the operation is performed by a specialist		little	3	very high	2	little - failure is implausible	1	6	
Excessive loading		high	7	very high	2	low: relative few failures		3	42								0		

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure	Failure Causes
Wheelset	Axle			B/WA	Transmit load from the body to the wheels. Maintain alignment of the wheels. Facilitate movement.	Fatigue Damage	Possible propagation in the long term and cracks in the corresponding section. Weakening of the axle material.	Steering instability. Further promotes degradation of other mechanical components.	Repeated loading, especially high loads at high speeds
Wheelset	Axle			B/WA	Transmit load from the body to the wheels. Maintain alignment of the wheels. Facilitate movement.	Fatigue Damage	Possible propagation in the long term and cracks in the corresponding section. Weakening of the axle material.	Steering instability. Further promotes degradation of other mechanical components.	Wheel and rail interaction, such as rail irregularities or curves, which can induce cyclic loading on the axle
Wheelset	Axle			B/WA	Transmit load from the body to the wheels. Maintain alignment of the wheels. Facilitate movement.	Wear and Damage of the axle Surface	Possible propagation in the long term and cracks in the corresponding section. Weakening of the axle material.	Steering instability. Further promotes degradation of other mechanical components.	Cracks of the axle bore
Wheelset	Axle			B/WA	Transmit load from the body to the wheels. Maintain alignment of the wheels. Facilitate movement.	Wear and Damage of the axle Surface	Possible propagation in the long term and cracks in the corresponding section. Weakening of the axle material.	Steering instability. Further promotes degradation of other mechanical components.	Insufficient lubrication
Wheelset	Axle			B/WA	Transmit load from the body to the wheels. Maintain alignment of the wheels. Facilitate movement.	Wear and Damage of the axle Surface	Possible propagation in the long term and cracks in the corresponding section. Weakening of the axle material.	Steering instability. Further promotes degradation of other mechanical components.	Excessive temperature
Wheelset	Axle			B/WA	Transmit load from the body to the wheels. Maintain alignment of the wheels. Facilitate movement.	Wear and Damage of the axle Surface	Possible propagation in the long term and cracks in the corresponding section. Weakening of the axle material.	Reducing load capacity and can potentially lead to catastrophic failure due to the weakened material.	Corrosion
Wheelset	Axle			B/WA	Transmit load from the body to the wheels. Maintain alignment of the wheels. Facilitate movement.	Wear and Damage of the axle Surface	Possible propagation in the long term and cracks in the corresponding section. Weakening of the axle material.	Steering instability. Poor power transmission. Further promotes degradation of other mechanical components.	Impact damage due to debris on the tracks and ballast.
Wheelset	Axle			B/WA	Transmit load from the body to the wheels. Maintain alignment of the wheels. Facilitate movement.	Fracture of the axle	Axle is broken and unusable.	There is no load transmission. System is unable to operate. Can lead to derailment.	Uneven braking forces
Wheelset	Axle			B/WA	Transmit load from the body to the wheels. Maintain alignment of the wheels. Facilitate movement.	Fracture of the axle	Axle is broken and unusable.	There is no load transmission. System is unable to operate. Can lead to derailment.	Improper installation and handling
Wheelset	Axle			B/WA	Transmit load from the body to the wheels. Maintain alignment of the wheels. Facilitate movement.	Fracture of the axle	Axle is broken and unusable.	There is no load transmission. System is unable to operate. Can lead to derailment.	Excessive rotating speed exceeding bearings' critical rotating speed causing seizure
Wheelset	Axle			B/WA	Transmit load from the body to the wheels. Maintain alignment of the wheels. Facilitate movement.	Excessive elastic deformation	Loss of roundness. Axle is broken	Misalignment with other components. Uneven and inadequate load transmission. Can lead to derailment.	Excessive bending
Wheelset	Axle			B/WA	Transmit load from the body to the wheels. Maintain alignment of the wheels. Facilitate movement.	Excessive elastic deformation	Loss of roundness.	Misalignment with other components. Uneven and inadequate load transmission.	Improper installation and handling that may have damaged the component
Wheelset	Axle Box	Bearings		BWABB	Support loading. Smooth movement of the train	Fatigue Damage	Localized cracks. Damage to bearing surface	At the limit, leads to derailment	Heavy, prolonged load
Wheelset	Axle Box	Bearings		BWABB	Support loading. Smooth movement of the train	Fatigue Damage	Seizure of the component and surface cracking.	At the limit, leads to derailment	Excessive speed
Wheelset	Axle Box	Bearings		BWABB	Support loading. Smooth movement of the train	Fatigue Damage	Seizure, surface cracks.	At the limit, leads to derailment	Repeated shock load
Wheelset	Axle Box	Bearings		BWABB	Support loading. Smooth movement of the train	Noisy or Overheated Bearing	Seizure, surface cracks.	At the limit, leads to derailment	Loss of lubricant

		Existing System:					Risk - Reduction		New System:					
		Risk Priority Number (RPN) limit for intensive proofings:							Risk Priority Number (RPN) limit for intensive proofings:				0	
Failure Causes	Severity 1: B 2: C	Detectability 1: B 2: C & A	Frequency 1: B 2: A	Risk priority number		Action	Type	Severity B	Detectability B	Frequency B	Risk priority number	Acceptance of improvement		
Repeated loading, especially high loads at high speeds	very high	8	moderate	5	moderate: seldom there are failures	4	160	high	7	very high	2	very low: relative very few failures	2	28
Wheel and rail interaction, such as rail irregularities or curves, which can induce cyclic loading on the axle	very high	8	low	6	moderate: sometimes there are failures	5	240	moderate	6	high	3	very low: relative very few failures	2	36
Cracks of the axle bore	moderate	6	moderate	5	low: relative few failures	3	90							0
Insufficient lubrication	moderate	6	low	6	moderate: seldom there are failures	4	144							0
Excessive temperature	moderate	6	moderate high	4	very low: relative very few failures	2	48							0
Corrosion	moderate	6	high	3	moderate: often there are failures	6	108							0
Impact damage due to debris on the tracks and ballast.	moderate	6	moderate	5	moderate: sometimes there are failures	5	150							0
Uneven braking forces	very high	8	moderate	5	moderate: seldom there are failures	4	160							0
Improper installation and handling	very high	8	moderate high	4	low: relative few failures	3	96	very high	8	nearly certain	1	little - failure is implausible	1	8
Excessive rotating speed exceeding bearings' critical rotating speed causing seizure	very high	8	moderate	5	low: relative few failures	3	120							0
Excessive bending	moderate	6	low	6	low: relative few failures	3	108							0
Improper installation and handling that may have damaged the component	moderate	6	very high	2	low: relative few failures	3	36	very low	4	very high	2	very low: relative very few failures	2	16
Heavy, prolonged load	unsafe without warning	10	very low	7	very low: relative very few failures	2	140	very high	8	moderate	5	little - failure is implausible	1	40
Excessive speed	unsafe without warning	10	very low	7	very low: relative very few failures	2	140	very high	8	moderate	5	little - failure is implausible	1	40
Repeated shock load	unsafe without warning	10	very low	7	very low: relative very few failures	2	140	very high	8	moderate	5	little - failure is implausible	1	40
Loss of lubricant	unsafe without warning	10	very low	7	low: relative few failures	3	210	very high	8	moderate high	4	very low: relative very few failures	2	64

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Noisy or Overheated Bearing	Seizure, surface cracks.	At the limit, leads to derailment
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Noisy or Overheated Bearing	Seizure, surface cracks.	At the limit, leads to derailment
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Noisy or Overheated Bearing	Seizure, surface cracks.	At the limit, leads to derailment
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Excessive Equipment Vibration	Excessive wear and damage to other mechanical components.	Further misalignment of components.
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Excessive Equipment Vibration	Excessive wear and damage to other mechanical components.	Further misalignment of components.
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Excessive Equipment Vibration	Excessive wear and damage to other mechanical components.	Further misalignment of components.
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Excessive Equipment Vibration	Excessive wear and damage to other mechanical components.	Further misalignment of components.
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Excessive Equipment Vibration	Excessive wear and damage to other mechanical components.	Further misalignment of components.
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Bearing seizure	Discoloration and melting of roller rolling surface	Can lead to a broken axle and even derailment
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Bearing seizure	Discoloration and melting of roller rolling surface	Can lead to a broken axle and even derailment
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Bearing seizure	Discoloration and melting of roller rolling surface	Can lead to a broken axle and even derailment
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Bearing seizure	Discoloration and melting of roller rolling surface	Uneven speed of the wheels. Can lead to a broken axle and even derailment
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Surface damage	Surface cracks	Uneven speed of the wheels. Can lead to a broken axle and even derailment
Wheelset	Axle Box	Bearings		BwABB	Support loading. Smooth movement of the train	Insufficient loading	Unexpected noise. Unable to function properly. Increased friction and wear.	Can lead to a broken axle and even derailment. Train should not be operating under this condition.
Wheelset	Axle Box	Body		BwAB	House and enclose the axle bearings, protecting them from contaminants	Excessive wear and damage	Surface is damaged which could impair the function of this component and require intervention	Bearing protection is not assured, which can compromise the safety of operation and promote bearing failure
Wheelset	Axle Box	Body		BwAB	House and enclose the axle bearings, protecting them from contaminants	Excessive wear and damage	Surface is damaged which could impair the function of this component and require intervention	Bearing protection is not assured, which can compromise the safety of operation and promote bearing failure

	Existing System:				Risk - Reduction		New System:					
	Risk Priority Number (RPN) limit for intensive proofings:						Risk Priority Number (RPN) limit for intensive proofings:			0		
Failure Causes	Severity 1: B 2: C	Detectability 1: B 2: C & A	Frequency 1: B 2: A	Risk priority number	Action	Type	Severity B	Detectability B	Frequency B	Risk priority number	Acceptance of improve- ment	
Axle or housing bore out of roundness	unsafe without warning 10	very low 7	very low: relative very few failures 7	2	140	Constant monitoring of the condition of the bearings to ensure functionality	very high 8	high 3	very low: relative very few failures 2	48		
Corrosive agents	unsafe without warning 10	very low 7	moderate: seldom there are failures 4	4	280	Monitor equipment more often to ensure it is still in good operational condition	moderate 6	high 3	very low: relative very few failures 2	36		
Distorted bearing seals	unsafe without warning 10	very low 7	moderate: seldom there are failures 4	4	280	Constant monitoring of the condition of the bearings to ensure functionality	very high 8	moderate high 4	very low: relative very few failures 2	64		
Misalignment	low 5	moderate high 4	low: relative few failures 3	3	60	Verify thoroughly if the component was properly installed and is correctly aligned	low 5	nearly certain 1	little - failure is implausible 1	5		
Axle or housing bore out of round	low 5	moderate high 4	very low: relative very few failures 2	2	40					0		
Unbalanced/ excessive load	low 5	moderate high 4	very low: relative very few failures 2	2	40					0		
Improper primary suspension dampening	low 5	moderate high 4	low: relative few failures 3	3	60					0		
Inadequate housing support	low 5	moderate high 4	very low: relative very few failures 2	2	40					0		
Inadequate heat removal capability	unsafe with warning 9	little 8	very low: relative very few failures 2	2	144	Constantly monitor the condition of the bearings and operating parameters to avoid functional failures	moderate 6	moderate high 4	very low: relative very few failures 2	48		
Loss of lubricant	unsafe with warning 9	little 8	moderate: seldom there are failures 4	4	288	Constantly monitor the state of the lubricant	moderate 6	moderate high 4	low: relative few failures 3	72		
High temperature	unsafe with warning 9	little 8	very low: relative very few failures 2	2	144	Monitor operating parameters, particularly the temperature of the components	high 7	moderate 5	very low: relative very few failures 2	70		
Excessive speed	unsafe with warning 9	little 8	very low: relative very few failures 2	2	144	Better control of operating speeds	low 5	very high 2	very low: relative very few failures 2	20		
Craters due to electric current flow	unsafe with warning 9	very low 7	low: relative few failures 3	3	189	Constantly monitor the condition of the bearings to avoid functional failures, replacing them whenever necessary	high 7	moderate high 4	very low: relative very few failures 2	56		
Loading is inferior to the nominal minimum loading required	unsafe without warning 10	moderate 5	very low: relative very few failures 2	2	100	Monitor operating parameters more often and rigorously	very high 8	very high 2	very low: relative very few failures 2	32		
Inadequate lubrication with increased friction	unsafe with warning 9	low 6	very low: relative very few failures 2	2	108	Constantly monitor the state of the lubricant and if lubrication is being performed as needed	very high 8	very high 2	very low: relative very few failures 2	32		
Improper installation	unsafe with warning 9	low 6	very low: relative very few failures 2	2	108	Verify thoroughly if the component was properly installed and is correctly aligned	very high 8	very high 2	little - failure is implausible 1	16		

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Wheelset	Axle Box	Body		BWAB	House and enclose the axle bearings, protecting them from contaminants	Fatigue Damage	Axle body surface gets fatigue cracks which can propagate over time	Bearing protection is not assured, which can compromise the safety of operation and promote bearing failure
Wheelset	Axle Box	Body		BWAB	House and enclose the axle bearings, protecting them from contaminants	Loosening	Bolts used to support the axle box body are loosened and might	Bearing protection is not assured, which can compromise the safety of operation and promote bearing failure
Wheelset	Axle Box	Bolts		BWABO	Securing to assembly to maintain proper alignment of the components and ensure the stability of the system	Loosening	loss of clamping force, increased stress concentrations, and eventual failure of the bolted joint.	Leads to misalignment and loss of function of the other components of the axle box
Wheelset	Axle Box	Bolts		BWABO	Securing to assembly to maintain proper alignment of the components and ensure the stability of the system	Loosening	loss of clamping force, increased stress concentrations, and eventual failure of the bolted joint.	Leads to misalignment and loss of function of the other components of the axle box
Wheelset	Axle Box	Bolts		BWABO	Securing to assembly to maintain proper alignment of the components and ensure the stability of the system	Material weakening	Worsening of the material properties	Leads to misalignment and loss of function of the other components of the axle box
Wheelset	Axle Box	Bolts		BWABO	Securing to assembly to maintain proper alignment of the components and ensure the stability of the system	Corrosion and Rust	Weakens the bolt material and reduces its load-bearing capacity	Leads to misalignment and loss of function of the other components of the axle box
Wheelset	Axle Box	Bolts		BWABO	Securing to assembly to maintain proper alignment of the components and ensure the stability of the system	Fracture	Bolt is no longer functional and needs to be replaced	Leads to misalignment and loss of function of the other components of the axle box
Wheelset	Axle Box	Bolts		BWABO	Securing to assembly to maintain proper alignment of the components and ensure the stability of the system	Creep	permanent deformation and loss of preload, compromising the integrity of the bolted connection.	Leads to misalignment and loss of function of the other components of the axle box
Wheelset	Axle Box	Bolts		BWABO	Securing to assembly to maintain proper alignment of the components and ensure the stability of the system	Fatigue Damage	Fatigue cracks at a microscopic scale that propagate	Leads to misalignment and loss of function of the other components of the axle box
Wheelset	Axle Box	Bolts		BWABO	Securing to assembly to maintain proper alignment of the components and ensure the stability of the system	Embrittlement	Weakens the bolt material. The absorbed hydrogen reduces the ductility of the metal	Leads to misalignment and loss of function of the other components of the axle box
Wheelset	Axle Box	Bump Stop ("T")		BWABS	Protective component located on a train's axle box by limiting its vertical movement. Ensuring the wheelset doesn't get misaligned when the train is elevated	Material degradation	Weakening of the material	Can lead to misalignment of the wheelset and loss of function of the bogie
Wheelset	Axle Box	Bump Stop ("T")		BWABS	Protective component located on a train's axle box by limiting its vertical movement. Ensuring the wheelset doesn't get misaligned when the train is elevated	Cracking	Surface damage that can result in breaking	Can lead to misalignment of the wheelset and loss of function of the bogie
Wheelset	Axle Box	Bump Stop ("T")		BWABS	Protective component located on a train's axle box by limiting its vertical movement. Ensuring the wheelset doesn't get misaligned when the train is elevated	Contact with the bogie frame	Excessive wear of the components	Can lead to misalignment of the wheelset and loss of function of the bogie
Wheelset	Axle Box	Covers		BWAC	Enclose the axle box, protecting it from external elements such as debris, moisture, and contaminants.	Cracking	Loss of lubricant due to leakage.	Compromises the function of the lubrication system
Wheelset	Axle Box	Covers		BWAC	Enclose the axle box, protecting it from external elements such as debris, moisture, and contaminants.	Excessive vibration	Loosening of the bolts.	Compromises the function of the lubrication system

Existing System:							Risk - Reduction		New System:						
Risk Priority Number (RPN) limit for intensive proofings:									Risk Priority Number (RPN) limit for intensive proofings:						
Failure Causes	Severity 1: B 2: C	Detectability 1: B 2: C 3: A	Frequency 1: B 2: A	Risk priority number			Action	Type	Severity B	Detectability B	Frequency B	Risk priority number	Acceptance of improvement		
Cyclic loading	unsafe with warning	3	very low	7	moderate: seldom there are failures	4	252	Monitor the component more often and replace it if needed to avoid fatigue initiated failures	very high	8	moderate high	4	very low: relative very few failures	2	64
Excessive vibration	unsafe with warning	3	moderate high	4	low: relative few failures	3	108	Monitor vibration rigorously and try to find where it is coming from and if any damage has been done to the vehicle	moderate	6	very high	2	very low: relative very few failures	2	24
Vibrations and dynamic forces experienced during train operation	high	7	moderate high	4	low: relative few failures	3	84								0
Improper installation	high	7	moderate high	4	very low: relative very few failures	2	56	Verify thoroughly if the component was properly installed and is correctly aligned	moderate	6	very high	2	little - failure is implausible	1	12
Material defects from the manufacturing process defects or improper handling and storage	high	7	low	6	very low: relative very few failures	2	84								0
Exposure to moisture, contaminants, and environmental factors	high	7	low	6	moderate: seldom there are failures	4	168								0
Excessive loading	high	7	moderate	5	low: relative few failures	3	105								0
Excessive temperature during harsh operating conditions	high	7	moderate	5	very low: relative very few failures	2	70								0
Excessive cyclic loading far beyond the strength of the bolt	high	7	very low	7	low: relative few failures	3	147								0
Hydrogen Embrittlement	high	7	low	6	very low: relative very few failures	2	84								0
Contamination with moisture or debris	moderate	6	moderate	5	low: relative few failures	3	90								0
Excessive loading	moderate	6	moderate	5	very low: relative very few failures	2	60								0
Misalignment or improper installation	moderate	6	high	3	very low: relative very few failures	2	36	Verify thoroughly if the component was properly installed and is correctly aligned	moderate	6	very high	2	very low: relative very few failures	2	24
Excessive loading or at high velocities	high	7	moderate high	4	low: relative few failures	3	84								0
Improper installation or handling	high	7	moderate high	4	very low: relative very few failures	2	56	Verify thoroughly if the component was properly installed and is correctly aligned	high	7	very high	2	little - failure is implausible	1	14

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure	Failure Causes
Wheelset	Axle Box	Covers		B/WAC	Enclose the axle box, protecting it from external elements such as debris, moisture, and contaminants.	Leakage of lubricant	Decrease in the lubricating film needed for the mechanism to function correctly	Compromises the function of the lubrication system	Improper installation
Wheelset	Axle Box	Covers		B/WAC	Enclose the axle box, protecting it from external elements such as debris, moisture, and contaminants.	Leakage of lubricant	Decrease in the lubricating film needed for the mechanism to function correctly	Compromises the function of the lubrication system	Damage on the covers that allows for the flow of fluid
Wheelset	Axle Box	External Spring Guide		B/WAESG	Support the spring and ensure it is properly aligned	Surface damage	Misalignment of the springs	Loss of damping function	Improper installation or handling, misalignment
Wheelset	Axle Box	External Spring Guide		B/WAESG	Support the spring and ensure it is properly aligned	Surface damage	Misalignment of the springs	Loss of damping function	Excessive loading
Wheelset	Axle Box	Lubrication System	Lubricant	B/WAL	Distribute oil to reduce friction between moving parts	Loss of lubrication capacity	Unwanted alterations to the lubricant properties that impair its function	Increase in wear of mechanical components and rails due to higher friction forces when vehicle is moving	Contamination
Wheelset	Axle Box	Lubrication System	Lubricant	B/WAL	Distribute oil to reduce friction between moving parts	Loss of lubrication capacity	Leakage of lubricant	Increase in wear of mechanical components and rails due to higher friction forces when vehicle is moving	Improper sealing (could be due to failure of the seals)
Wheelset	Axle Box	Lubrication System	Lubricant	B/WAL	Distribute oil to reduce friction between moving parts	Loss of lubrication capacity	Unwanted alterations to the lubricant properties that impair its function	Increase in wear of mechanical components and rails due to higher friction forces when vehicle is moving	Degradation of the lubricant additives
Wheelset	Axle Box	Lubrication System	Lubricant	B/WAL	Distribute oil to reduce friction between moving parts	Loss of lubrication capacity	Unwanted alterations to the lubricant properties that impair its function	Increase in wear of mechanical components and rails due to higher friction forces when vehicle is moving	Improper handling and maintenance leading to contamination
Wheelset	Axle Box	Lubrication System	Plug	B/WAP	Lubricant drainage point, allowing the lubricant to be changed and levelled	Loosening	Component can get misaligned or even fall off	Loss of expected function for the lubrication system	Excessive vibration that leads to misalignment of the component
Wheelset	Axle Box	Lubrication System	Plug	B/WAP	Lubricant drainage point, allowing the lubricant to be changed and levelled	Contamination	Component can deteriorate at an accelerated rate. Possible formation of blockages of accumulated debris	Loss of expected function for the lubrication system	Exposure to moisture or debris
Wheelset	Axle Box	Lubrication System	Plug	B/WAP	Lubricant drainage point, allowing the lubricant to be changed and levelled	Contamination	Component can deteriorate at an accelerated rate. Possible formation of blockages of accumulated debris	Loss of expected function for the lubrication system	Lubricant being drained contains particles or impurities, or is incompatible with the plug
Wheelset	Axle Box	Lubrication System	Plug	B/WAP	Lubricant drainage point, allowing the lubricant to be changed and levelled	Breaking	Component is damaged and can be rendered useless	Loss of expected function for the lubrication system	Exposure to moisture or debris
Wheelset	Axle Box	Lubrication System	Plug	B/WAP	Lubricant drainage point, allowing the lubricant to be changed and levelled	Leakage of lubricant	Loss of function: leakage of lubricant from the intended drainage point	Loss of expected function for the lubrication system	Misalignment or improper installation
Wheelset	Axle Box	Seals		B/WAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.	Misalignment which promotes excessive wear of the component
Wheelset	Axle Box	Seals		B/WAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.	Axle damage and wear

	Existing System:						Risk - Reduction		New System:							
	Risk Priority Number (RPN) limit for intensive provings:					Risk Priority Number (RPN) limit for intensive provings:				0						
Failure Causes	Severity 1.: B 2.: C	Detectability 1.: B 2.: C 3.: A	Frequency 1.: B 2.: A	Risk priority number			Action	Type	Severity B	Detectability B	Frequency B	Risk priority number	Acceptance of improve- ment			
Improper installation	high	7	moderate high	4	very low: relative very few failures	2	56	Verify thoroughly if the component was properly installed and is correctly aligned	high	7	very high	2	little ~ failure is implausible	1	14	
Damage on the covers that allows for the flow of fluid	high	7	moderate high	4	low: relative few failures	3	84							0		
Improper installation or handling, misalignment	high	7	moderate	5	very low: relative very few failures	2	70	Verify thoroughly if the component was properly installed and is correctly aligned	high	7	very high	2	little ~ failure is implausible	1	14	
Excessive loading	high	7	moderate	5	low: relative few failures	3	105							0		
Contamination	very high	8	low	6	moderate: seldom there are failures	4	132							0		
Improper sealing (could be due to failure of the seals)	very high	8	low	6	low: relative few failures	3	144	Constantly assess the condition of the seals to ensure there are no leakages and replace them whenever necessary	moderate	6	nearly certain	1	little ~ failure is implausible	1	6	
Degradation of the lubricant additives	very high	8	low	6	low: relative few failures	3	144							0		
Improper handling and maintenance leading to contamination	very high	8	low	6	very low: relative very few failures	2	36	Verify thoroughly if the component was properly installed and is correctly aligned	moderate	6	nearly certain	1	little ~ failure is implausible	1	6	
Excessive vibration that leads to misalignment of the component	very high	8	moderate high	4	very low: relative very few failures	2	64							0		
Exposure to moisture or debris	very high	8	low	6	moderate: seldom there are failures	4	132							0		
Lubricant being drained contains particles or impurities, or is incompatible with the plug	very high	8	low	6	low: relative few failures	3	144							0		
Exposure to moisture or debris	very high	8	moderate high	4	moderate: seldom there are failures	4	128							0		
Misalignment or improper installation	very high	8	moderate high	4	very low: relative very few failures	2	64	Verify thoroughly if the component was properly installed and is correctly aligned	high	7	nearly certain	1	little ~ failure is implausible	1	7	
Misalignment which promotes excessive wear of the component	very low	4	moderate high	4	moderate: sometimes there are failures	5	80							0		
Axle damage and wear	very low	4	moderate high	4	moderate: sometimes there are failures	5	80							0		

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.

		Existing System:				Risk - Reduction		New System:					
		Risk Priority Number (RPN) limit for intensive proofings:						Risk Priority Number (RPN) limit for intensive proofings:			0		
Failure Causes	Severity 1: B 2: C	Detectability 1: B 2: C 3: A	Frequency 1: B 2: A	Risk priority number	Action	Type	Severity B	Detectability B	Frequency B	Risk priority number	Acceptance of improvement		
Inadequate surface finish that leads to wear	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			
Exposure to contaminants and solid debris	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			
Vibration that can result in seal distortion	very low	4 moderate high	4 moderate: sometimes there are failures	5 80	Monitor vibrations more frequently and assess the condition of the seals		little	3	very high	2	little - failure is implausible		
Inadequate lubrication	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			
Misalignment	very low	4 moderate high	4 moderate: sometimes there are failures	5 80	Verify thoroughly if the component was properly installed and is correctly aligned		very low	4	nearly certain	1	little - failure is implausible		
Fluid and seal incompatibility leading to surface damage	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			
Thermal degradation that damages the seal surface	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			
Insufficient lubrication that accelerates surface damage	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			
Fluid and seal degradation	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			
Exposure to the atmosphere causing damage to the seal surface	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			
Excessive temperature	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			
Excessive squeeze to achieve seal due to compression set	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			
Hardening due to compression set	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			
High temperatures due to compression set	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			
Sharp corners on mating metal parts damaging the	very low	4 moderate high	4 moderate: sometimes there are failures	5 80						0			

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Axle Box	Seals		BWAS	Restrict the flow of fluid from one region to another.	Leakage	Loss of function. Flow is not restricted so fluid can move freely.	The function of the lubrication system is compromised. Loss of lubrication of the mechanical components.
Wheelset	Wheels			BWAW	Ensure contact with railway tracks to allow for running even with freight load	Wear of wheel's flange	Increase in dynamic loads and can exceed maximum allowed wear	Train stops or even derails
Wheelset	Wheels			BWAW	Ensure contact with railway tracks to allow for running even with freight load	Wheelset locked	Wheel flat on the rolling surface	Noisy rolling operation
Wheelset	Wheels			BWAW	Ensure contact with railway tracks to allow for running even with freight load	Cracking of wheel thread	Pitting of the rolling surface	Reduced movement speed. Train unable to meet schedules
Wheelset	Wheels			BWAW	Ensure contact with railway tracks to allow for running even with freight load	Bad contact with wheel and railway tracks	Loud noise and friction of rail and wheel.	Reduced movement speed. Train unable to meet schedules
Wheelset	Wheels			BWAW	Ensure contact with railway tracks to allow for running even with freight load	Bad contact with wheel and railway tracks	Loud noise and friction of rail and wheel.	Reduced movement speed. Train unable to meet schedules
Wheelset	Wheels			BWAW	Ensure contact with railway tracks to allow for running even with freight load	Wheel locking	Loss of function of the wheelset	Accidents
Wheelset	Wheels			BWAW	Ensure contact with railway tracks to allow for running even with freight load	Excessive wear	Thin and fragile flange of wheel	Damage to the train
Wheelset	Wheels			BWAW	Ensure contact with railway tracks to allow for running even with freight load	Excessive wear	Erosion of wheel profile	Accidents, damage to the train or even derailment
Wheelset	Wheels			BWAW	Ensure contact with railway tracks to allow for running even with freight load	Breaking	Loss of function of the wheelset	Deraiment
Wheelset	Wheels			BWAW	Ensure contact with railway tracks to allow for running even with freight load	Breaking	Loss of function of the wheelset	Deraiment
Wheelset	Wheels			BWAW	Ensure contact with railway tracks to allow for running even with freight load	Breaking	Crack of the wheel rim surface	Accidents

		Existing System:									New System:												
		Risk Priority Number (RPN) limit for intensive proofings:									Risk Priority Number (RPN) limit for intensive proofings:					0							
Failure Causes		Severity 1: B 2: C		Detectability 1: B 2: C & A		Frequency 1: B 2: A		Risk priority number		Action		Type		Severity B		Detectability B		Frequency B		Risk priority number		Acceptance of improvement	
Inadequate protection of spares or damage during installation		very low		4 moderate high 4		moderate: sometimes there are failures 5		80												0			
Misalignment due to dynamic instability		very low		4 moderate high 4		moderate: sometimes there are failures 5		80		Verify thoroughly if the component is properly aligned				very low 4		very high 2		little - failure is implausible 1		8			
Rail faults		unsafe without warning		10 low 6		moderate: sometimes there are failures 5		300		Monitor the condition of the railway tracks and plan interventions to minimise possible damage to the vehicle				high 7		moderate high 4		very low: relative very few failures 2		56			
Improper bearing rotation		very low		4 moderate high 4		moderate: sometimes there are failures 5		80												0			
Overheating due to insufficient heat dissipation		moderate		6 moderate high 4		moderate: seldom there are failures 4		96												0			
Rail faults		moderate		6 very high 2		moderate: sometimes there are failures 5		60		Monitor the condition of the railway tracks and plan interventions to minimise possible damage to the vehicle				very low 4		very high 2		low: relative few failures 3		24			
Wheel is out of roundness		moderate		6 very high 2		moderate: seldom there are failures 4		48												0			
Jam on the brakes		unsafe with warning		3 moderate high 4		moderate: sometimes there are failures 5		180		Rigorously monitor operating conditions and always testing functionality of the brakes before initiating movement				high 7		very high 2		very low: relative very few failures 2		28			
Rail faults		unsafe with warning		3 moderate 5		moderate: seldom there are failures 4		180		Monitor the condition of the railway tracks and plan interventions to minimise possible damage to the vehicle				high 7		very high 2		very low: relative very few failures 2		28			
Overuse		unsafe without warning		10 moderate 5		low: relative few failures 3		150		Assess condition of the equipment and replace it more often before the occurrence of dangerous functional failures				moderate 6		high 3		very low: relative very few failures 2		36			
Fatigue Damage over a prolonged time		unsafe without warning		10 moderate high 4		moderate: often there are failures 6		240		Monitor the component more often and replace it if needed to avoid fatigue initiated failures				very high 8		very high 2		very low: relative very few failures 2		32			
Sudden impact while operating		unsafe without warning		10 moderate high 4		very low: relative very few failures 2		80		Rigorously monitor operating conditions				very high 8		very high 2		very low: relative very few failures 2		32			
Excessive increase in dynamic load		unsafe with warning		3 moderate high 4		low: relative few failures 3		108		Rigorously monitor operating conditions				high 7		very high 2		very low: relative very few failures 2		28			

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Guiding System	Spring Cap			BFWG2	Provide support and protection to springs	Cracking	Damage to the component or loss of component material, compromising its function	Misalignment of the springs
Guiding System	Spring Cap			BFWG2	Provide support and protection to springs	Cracking	Damage to the component or loss of component material, compromising its function	Loss of damping
Guiding System	Spring Cap			BFWG2	Provide support and protection to springs	Cracking	Damage to the component or loss of component material, compromising its function	Misalignment of the springs
Guiding System	Spring Cap			BFWG2	Provide support and protection to springs	Cracking	Surface cracks that propagate	Loss of damping
Guiding System	Lenoir	Smaller Pin		BFWG7	Support the link	Fracture	Pin is broken and/or damage on the welding joint	Loss of damping
Guiding System	Lenoir	Bigger Pin		BFWG6	Support the link	Fracture	Pin is broken and/or damage on the welding joint	Loss of damping
Guiding System	Lenoir	Link		BFWG8	Load dependent friction damping between the axle box and bogie frame in both vertical and lateral directions	Fatigue Damage	Surface cracks that propagate	Loss of damping
Guiding System	Lenoir	Link		BFWG8	Load dependent friction damping between the axle box and bogie frame in both vertical and lateral directions	Wear and Tear	Degradation of the component	Loss of damping
Guiding System	Lenoir	Link		BFWG8	Load dependent friction damping between the axle box and bogie frame in both vertical and lateral directions	Wear and Tear	Misalignment which can hamper the suspension	Loss of damping
Guiding System	Lenoir	Link		BFWG8	Load dependent friction damping between the axle box and bogie frame in both vertical and lateral directions	Wear and Tear	Degradation of the component and its loosening	Loss of damping
Guiding System	Lenoir	Link		BFWG8	Load dependent friction damping between the axle box and bogie frame in both vertical and lateral directions	Loosening	Free movement of the link due to a change in the degrees of freedom of the component	Loss of damping
Guiding System	Pedestal	Smaller Wear Plate		BFWG10	Sacrificial plates that help in guiding the moving body	Fracture	Component is damaged, compromising its protection and guiding function	Degrees of freedom of the bogie are compromised: guiding system not working as intended.
Guiding System	Pedestal	Smaller Wear Plate		BFWG10	Sacrificial plates that help in guiding the moving body	Weld joint fracture	Loss of material properties. Fissuration at the welding joint that accelerates the wear of the component.	Degrees of freedom of the bogie are compromised: guiding system not working as intended.
Guiding System	Pedestal	Smaller Wear Plate		BFWG10	Sacrificial plates that help in guiding the moving body	Weld joint fracture	Fatigue related fissuration at the welding joint, ending in fracture.	Degrees of freedom of the bogie are compromised: guiding system not working as intended.
Guiding System	Pedestal	Smaller Wear Plate		BFWG10	Sacrificial plates that help in guiding the moving body	Corrosion	Chemical degradation of the component, eventually resulting in fracture of the joint.	Degrees of freedom of the bogie are compromised: guiding system not working as intended.
Guiding System	Pedestal	Smaller Wear Plate		BFWG10	Sacrificial plates that help in guiding the moving body	Excessive Deformation	Loss of material properties that lead to excessive deformation even under normal operating conditions.	Degrees of freedom of the bogie are compromised: guiding system not working as intended.
Guiding System	Pedestal	Bigger Wear Plate		BFWG9	Sacrificial plates that help in guiding the moving body	Fracture	Component is damaged, compromising its protection and guiding function	Degrees of freedom of the bogie are compromised: guiding system not working as intended.

	Existing System:					Risk - Reduction		New System:					
	Risk Priority Number (RPN) limit for intensive proofings:							0					
Failure Causes	Severity 1.: B 2.: C	Detectability 1.: B 2.: C & A	Frequency 1.: B 2.: A		Risk priority number	Action	Type	Severity B	Detectability B	Frequency B	Risk priority number	Acceptance of improve- ment	
Manufacturing defects	moderate	6	low	6	very low: relative very few failures	2	72				0		
Excessive loading conditions.	moderate	6	low	6	low: relative few failures	3	108				0		
Improper installation	moderate	6	low	6	very low: relative very few failures	2	72						
Fatigue loads	high	7	very low	7	very low: relative very few failures	2	98						
Welding defects	very low	4	high	3	low: relative few failures	3	36						
Welding defects	very low	4	high	3	low: relative few failures	3	36						
(repeated) Cyclic loading over a long period	moderate	6	very low	7	moderate: sometimes there are failures	5	210						
Corrosion / chemical degradation due to contact with moisture or oxidant agents	low	5	low	6	moderate: sometimes there are failures	5	150						
Continuous operation and exposure to vibrations	low	5	low	6	moderate: seldom there are failures	4	120						
Misalignment	low	5	low	6	low: relative few failures	3	90						
Loss of function of the pins - fell to the railway tracks	moderate	6	moderate-high	4	very low: relative very few failures	2	48						
Excessive loading, especially with the presence of welding defects	low	5	high	3	little - failure is implausible	1	15						
Incorrect temperature control during the welding process (excessive or insufficient preheating)	moderate	6	moderate	5	little - failure is implausible	1	30						
Excessive overthickness that promotes stress concentration at the welding joint.	moderate	6	moderate	5	little - failure is implausible	1	30						
Inadequate chemical composition of the material (base and filler), especially under inadequate welding conditions	low	5	low	6	little - failure is implausible	1	30						
Inadequate welding conditions that lead to worse material properties than intended.	low	5	moderate-high	4	very low: relative very few failures	2	40						
Excessive loading, especially with the presence of welding defects	low	5	high	3	little - failure is implausible	1	15						

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Guiding System	Pedestal	Bigger Wear Plate		BFWG9	Sacrificial plates that help in guiding the moving body	Weld joint fracture	Loss of material properties. Fissuration at the welding joint that accelerates the wear of the component.	Degrees of freedom of the bogie are compromised: guiding system not working as intended.
Guiding System	Pedestal	Bigger Wear Plate		BFWG9	Sacrificial plates that help in guiding the moving body	Weld joint fracture	Fatigue related fissuration at the welding joint, ending in fracture.	Degrees of freedom of the bogie are compromised: guiding system not working as intended.
Guiding System	Pedestal	Bigger Wear Plate		BFWG9	Sacrificial plates that help in guiding the moving body	Corrosion	Chemical degradation of the component, eventually resulting in fracture of the joint.	Degrees of freedom of the bogie are compromised: guiding system not working as intended.
Guiding System	Pedestal	Bigger Wear Plate		BFWG9	Sacrificial plates that help in guiding the moving body	Excessive Deformation	Loss of material properties that lead to excessive deformation even under normal operating conditions.	Degrees of freedom of the bogie are compromised: guiding system not working as intended.
Guiding System	Pedestal	Adjustment Trunnion		BFWG5	Structure's longitudinal suspension (stable axis of rotation or oscillation)	Deterioration	Damage to the component	Instability of the vehicle
Guiding System	Pedestal	Adjustment Trunnion		BFWG5	Structure's longitudinal suspension (stable axis of rotation or oscillation)	Fracture	Damage to the component	Instability of the vehicle
Guiding System	Pedestal	Adjustment Trunnion		BFWG5	Structure's longitudinal suspension (stable axis of rotation or oscillation)	Fracture	Damage to the component	Instability of the vehicle
Guiding System	Pedestal	Adjustment Trunnion		BFWG5	Structure's longitudinal suspension (stable axis of rotation or oscillation)	Wear	Damage to the component and weakening of its material	Damage to other components, particularly the axle box which also suffers from wear
Guiding System	Pedestal	Adjustment Trunnion		BFWG5	Structure's longitudinal suspension (stable axis of rotation or oscillation)	Misalignment	Damage to the component	Incorrect contact with the axle box
Guiding System	Pedestal	Adjustment Trunnion		BFWG5	Structure's longitudinal suspension (stable axis of rotation or oscillation)	Misalignment	Damage to the component	Incorrect contact with the axle box
Guiding System	Pedestal	Trunnion Socket		BFWG4	House the trunnion, assuring its stability, protection and proper alignment	Wear	Damage to the component	Trunnion is not properly aligned or protected, potentially leading to failure of other systems
Guiding System	Pedestal	Trunnion Socket		BFWG4	House the trunnion, assuring its stability, protection and proper alignment	Fracture	Damage to the component	Trunnion is not properly aligned or protected, potentially leading to failure of other systems
Guiding System	Pedestal	Trunnion Socket		BFWG4	House the trunnion, assuring its stability, protection and proper alignment	Fissures	Damage to the component	Trunnion is not properly aligned or protected, potentially leading to failure of other systems
Guiding System	Pedestal	Inner Spring Guide		BFWG1	guide and support the spring, providing a controlled path while the spring is operating	Fracture	Surface cracks that propagate with time	Suspension system function is impaired
Guiding System	Pedestal	Inner Spring Guide		BFWG1	guide and support the spring, providing a controlled path while the spring is operating	Distortion and warping	Function is compromised and shape is distorted	Suspension system function is impaired
Guiding System	Pedestal	Inner Spring Guide		BFWG1	guide and support the spring, providing a controlled path while the spring is operating	Distortion and warping	Function is compromised and shape is distorted	Suspension system function is impaired

	Existing System:						Risk - Reduction				New System:						
	Risk Priority Number (RPN) limit for intensive provings:										Risk Priority Number (RPN) limit for intensive provings:				0		
Failure Causes	Severity 1.: B 2.: C	Detectability 1.: B 2.: C & A	Frequency 1.: B 2.: A	Risk priority number			Action	Type	Severity B	Detectability B	Frequency B	Risk priority number	Acceptance of improvement				
Incorrect temperature control during the welding process (excessive or insufficient preheating)	moderate	6	moderate	5	little - failure is implausible	1	30	Strictly comply with welding standards, ensuring the operation is performed by a specialist	very low	4	very high	2	little - failure is implausible	1	8		
Excessive overthickness that promotes stress concentration at the welding joint.	moderate	6	moderate	5	little - failure is implausible	1	30	Strictly comply with welding standards, ensuring the operation is performed by a specialist	very low	4	very high	2	little - failure is implausible	1	8		
Inadequate chemical composition of the material (base and filler), especially under inadequate welding conditions	low	5	low	6	little - failure is implausible	1	30	Strictly comply with welding standards, ensuring the operation is performed by a specialist	little	3	very high	2	little - failure is implausible	1	6		
Inadequate welding conditions that lead to worse material properties than intended.	low	5	moderate high	4	very low: relative very few failures	2	40	Strictly comply with welding standards, ensuring the operation is performed by a specialist	little	3	very high	2	little - failure is implausible	1	6		
Contact with oxidants, moisture or other agents that chemically deteriorate the component	low	5	moderate	5	low: relative few failures	3	75							0			
Excessively harsh operating conditions	low	5	moderate	5	very low: relative very few failures	2	50							0			
Material defects or design flaws	low	5	moderate	5	very low: relative very few failures	2	50							0			
Incorrect contact with the axle box	moderate	6	moderate	5	low: relative few failures	3	30							0			
Sudden heavy impacts or excessive loads	low	5	moderate	5	very low: relative very few failures	2	50							0			
Incorrect design or handling leading to a clearance	low	5	moderate	5	very low: relative very few failures	2	50							0			
Bad surface finish	high	7	moderate high	4	moderate: seldom there are failures	4	112							0			
Improper installation causing damage	high	7	high	3	very low: relative very few failures	2	42	Verify thoroughly if the component was properly installed and is undamaged	low	5	very high	2	little - failure is implausible	1	10		
Presence of inclusions or an overall bad surface finish that lead to fissuration of the surface	high	7	high	3	low: relative few failures	3	63							0			
Fatigue loads	high	7	moderate high	4	low: relative few failures	3	84	Monitor the component more often and replace it if needed to avoid fatigue initiated failures	high	7	very high	2	little - failure is implausible	1	14		
Improper installation	high	7	very high	2	very low: relative very few failures	2	28	Verify thoroughly if the component was properly installed and is correctly aligned	very low	4	very high	2	little - failure is implausible	1	8		
Inadequate handling and maintenance actions	high	7	very high	2	very low: relative very few failures	2	28	Verify thoroughly if the component was properly installed and is correctly aligned	very low	4	very high	2	little - failure is implausible	1	8		

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Primary Suspension	Springs	Inner Springs		BPSI	Damping and Shock Absorption	Load Loss	Uneven weight distribution across the system. Loss of elastic properties.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Inner Springs		BPSI	Damping and Shock Absorption	Load Loss	Reduced load-bearing capacity and uneven weight distribution across the system. Material is more easily susceptible to breaking. Loss of elastic properties.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Inner Springs		BPSI	Damping and Shock Absorption	Fracture	Inadequate material was selected during design phase which can be incompatible with the intended operating context.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Inner Springs		BPSI	Damping and Shock Absorption	Fracture	Reduced load-bearing capacity and uneven weight distribution across the system. Material is more easily susceptible to breaking.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Inner Springs		BPSI	Damping and Shock Absorption	Fracture	Formation of stress concentration points on the surface, where stresses are amplified leading to localized plastic deformation or crack initiation	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Inner Springs		BPSI	Damping and Shock Absorption	Fracture	Weakening of the material of the component, compromising its structural integrity and leading to its damage	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Inner Springs		BPSI	Damping and Shock Absorption	Fracture	Increased wear and reduced efficiency in damping. Misalignment further promotes the occurrence of failures due to other causes.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Inner Springs		BPSI	Damping and Shock Absorption	Fracture	Severe damage to the component resulting in breakage.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Inner Springs		BPSI	Damping and Shock Absorption	Fracture	Additional stresses. Severe damage to the component resulting in breakage.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Inner Springs		BPSI	Damping and Shock Absorption	Fracture	Vibration can induce cyclic loading on the spring, accelerating the propagation of fatigue cracks and reducing the component's useful life	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Inner Springs		BPSI	Damping and Shock Absorption	Fracture	Severe damage to the component resulting in breakage.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Inner Springs		BPSI	Damping and Shock Absorption	Fracture (assuming failure of Outer Springs)	Severe damage to the component resulting in breakage.	Complete loss of damping functionality as inner and outer springs have failed. Suspension system collapses. Unsafe riding, as vehicle can more easily lose control and derail.

		Existing System:						Risk - Reduction		New System:									
		Risk Priority Number (RPN) limit for intensive proofings:								Risk Priority Number (RPN) limit for intensive proofings:				0					
Failure Causes		Severity 1.: B 2.: C		Detectability 1.: B 2.: C & A		Frequency 1.: B 2.: A		Risk priority number				Severity B		Detectability B		Frequency B		Risk priority number	Acceptance of improvement
Operating out of the designed operating parameters		very low	4	high	3	little - failure is implausible		1	12									0	
Hydrogen embrittlement		low	5	moderate high	4	low: relative few failures		3	60									0	
Material or design flaws		very low	4	moderate	5	very low: relative very few failures		2	40									0	
Hydrogen embrittlement		very low	4	moderate high	4	low: relative few failures		3	48									0	
Stress concentration due to tooling marks and rough finishes		low	5	moderate	5	low: relative few failures		3	75									0	
Corrosion		high	7	moderate high	4	very low: relative very few failures		2	56									0	
Misalignment		high	7	very high	2	moderate: seldom there are failures		4	56	Verify thoroughly if the component was properly installed and is correctly aligned		moderate	6	nearly certain	1	very low: relative very few failures	2	12	
Maximum load ratio exceeded		very high	8	high	3	very low: relative very few failures		2	48									0	
Suffer excessive deflection in the direction perpendicular to the axis		very high	8	very high	2	little - failure is implausible		1	16									0	
Excessive vibration		very high	8	moderate high	4	low: relative few failures		3	96									0	
Stresses greater than the nominal shear stresses		high	7	very low	7	low: relative few failures		3	147									0	
Misalignment and harsh operating conditions		unsafe without warning	10	high	3	low: relative few failures		3	90	Immediately replace the springs that have already failed and ensure their proper installation		moderate	6	very high	2	very low: relative very few failures	2	24	

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Component level I	Component level II	Component level III	Component level IV	Codification	Function	Failure Mode	Local Effects of Failure	Global Effects of Failure
Primary Suspension	Springs	Outer Springs		BPSO	Damping and Shock Absorption	Load Loss	Uneven weight distribution across the system	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Outer Springs		BPSO	Damping and Shock Absorption	Load Loss	Reduced load-bearing capacity and uneven weight distribution across the system. Material is more easily susceptible to breaking.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Outer Springs		BPSO	Damping and Shock Absorption	Fracture	Inadequate material was selected during design phase which can be incompatible with the intended operating context.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Outer Springs		BPSO	Damping and Shock Absorption	Fracture	Reduced load-bearing capacity and uneven weight distribution across the system. Material is more easily susceptible to breaking.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Outer Springs		BPSO	Damping and Shock Absorption	Fracture	Formation of stress concentration points on the surface, where stresses are amplified leading to localized plastic deformation or crack initiation	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Outer Springs		BPSO	Damping and Shock Absorption	Fracture	Weakening of the material of the component, compromising its structural integrity and leading to its damage	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Outer Springs		BPSO	Damping and Shock Absorption	Fracture	Increased wear and reduced efficiency in damping. Misalignment further promotes the occurrence of failures due to other causes.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Outer Springs		BPSO	Damping and Shock Absorption	Fracture	Severe damage to the component resulting in breakage.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Outer Springs		BPSO	Damping and Shock Absorption	Fracture	Additional stresses. Severe damage to the component resulting in breakage.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Outer Springs		BPSO	Damping and Shock Absorption	Fracture	Vibration can induce cyclic loading on the spring, accelerating the propagation of fatigue cracks and reducing the component's useful life	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Outer Springs		BPSO	Damping and Shock Absorption	Fracture	Severe damage to the component resulting in breakage.	Reduced damping functionality. Excessive wear on specific wheelset and suspension components, and track sections.
Primary Suspension	Springs	Outer Springs		BPSO	Damping and Shock Absorption	Fracture (assuming failure of Inner Springs)	Severe damage to the component resulting in breakage.	Complete loss of damping functionality as inner and outer springs have failed. Suspension system collapses. Unsafe riding, as vehicle can more easily lose control and derail.

		Existing System:						Risk - Reduction				New System:											
		Risk Priority Number (RPN) limit for intensive proofings:								Risk Priority Number (RPN) limit for intensive proofings:				0									
Failure Causes		Severity 1.: B 2.: C		Detectability 1.: B 2.: C & A		Frequency 1.: B 2.: A		Risk priority number		Action		Type		Severity B		Detectability B		Frequency B		Risk priority number		Acceptance of improvement	
Operating out of the designed operating parameters		very low	4	high	3	little – failure is implausible		1	12											0			
Hydrogen embrittlement		low	5	moderate high	4	low: relative few failures		3	60											0			
Material or design flaw s		very low	4	moderate	5	very low: relative very few failures		2	40											0			
Hydrogen embrittlement		very low	4	moderate high	4	low: relative few failures		3	48											0			
Stress concentration due to tooling marks and rough finishes		low	5	moderate	5	low: relative few failures		3	75											0			
Corrosion		high	7	moderate high	4	very low: relative very few failures		2	56											0			
Misalignment		high	7	very high	2	moderate: seldom there are failures		4	56	Verify thoroughly if the component was properly installed and is correctly aligned				moderate	6	nearly certain	1	very low: relative very few failures	2	12			
Maximum load ratio exceeded		very high	8	high	3	very low: relative very few failures		2	48											0			
Suffer excessive deflection in the direction perpendicular to the axis		very high	8	very high	2	little – failure is implausible		1	16											0			
Excessive vibration		very high	8	moderate high	4	low: relative few failures		3	96											0			
Stresses greater than the nominal shear stresses		high	7	very low	7	low: relative few failures		3	147											0			
Misalignment and harsh operating conditions		unsafe without warning	10	high	3	low: relative few failures		3	90	Immediately replace the springs that have already failed and ensure their proper installation				moderate	6	very high	2	very low: relative very few failures	2	24			