Implementation of the Reliability Centered Maintenance methodology to the door systems of a train carriage

António Pedro Teixeira Pereira

Masters Dissertation

Supervisor at FEUP: Prof. Armando Leitão

FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Masters in Mechanical Engineering

2023-07-10

Resumo

A área da manutenção é atualmente um ponto crucial da atividade de vários setores como o da indústria, serviços e transportes. Com a constante necessidade de melhorar níveis de qualidade de produtos e serviços, existe uma crescente complexidade nos equipamentos, o que aumenta também a complexidade da sua manutenção. É cada vez mais importante realizar a manutenção de equipamentos da forma mais eficaz, cumprindo os objetivos pretendidos e eficiente, utilizando o mínimo de recursos. Para este efeito, é requerido um profundo conhecimento sobre todos os aspetos dos processos, produtos e equipamentos.

A presente dissertação apresenta como principal objetivo a aplicação da metodologia RCM (Reliability Centered Maintenance) aos sistemas de portas das carruagens Arco da CP – Comboios de Portugal, procurando documentar e implementar os planos e atividades de manutenção desenvolvidos. Esta metodologia começa por definir o sistema a analisar, seguindo-se uma análise FMEA (Failure Mode and Effect Analysis), que permite reconhecer e descrever cada função, falhas funcionais e modos de falha associados a cada sistema, de forma a facilitar a tomada de decisões sobre os planos e atividades de manutenção a implementar, assim como a sua periodicidade.

O projeto incide na criação de uma ferramenta que ajude no processo de decisão em contexto operacional. Este trabalho contém uma análise aos sistemas de portas das carruagens Arco da CP, visto que estas foram recentemente adquiridas pela CP e que os sistemas de portas são das maiores fontes de avarias nestas carruagens. Implementando a metodologia RCM, pretende-se aumentar o conhecimento sobre estes sistemas e melhorar a eficiência e eficácia das atividades de manutenção, de forma a aumentar a fiabilidade e disponibilidade das portas das carruagens Arco, melhorando o serviço prestado.

Abstract

The maintenance area is currently a crucial point in the activity of various sectors, such as industrial, services and transportation. With the constant need to improve the quality levels of products and services, there is a growing complexity in equipment, which also increases the complexity of their maintenance. It is increasingly important to perform equipment maintenance in an effective and efficient way, fulfilling all objectives with the minimum amount of resources needed. This requires in-depth knowledge of all aspects of processes, products and equipment.

The main goal of the present dissertation is the application of the RCM (Reliability Centered Maintenance) methodology to the door systems of the Arco carriages of CP – Comboios de Portugal, seeking to document and implement the maintenance plans and activities developed. This methodology begins by defining the system in analysis, followed by a FMEA (Failure Mode and Effect Analysis), which allows to recognize and describe each function and its associated functional failures and failure modes for each system, facilitating the decision making on the maintenance plans and activities to be implemented, as well as their periodicity.

This project focuses on creating a tool which helps the decision making in an operational context. This work contains an analysis of the Arco carriages of CP, as these were recently acquired and the door systems are some of the biggest sources of failures and breakdowns. By implementing the RCM methodology, it is intended to increase the knowledge about these systems and improve the efficiency and effectiveness of maintenance activities, to increase the reliability and availability of the Arco carriages' doors, improving the service provided.

Acknowledgements

Firstly, I would like to thank Prof. Armando Leitão for his insights and effort to always improve this work.

Next, I would also like to thank CP – Comboios de Portugal and Eng. Carlos Machado for the opportunity to be a part of this project, for integrating me seeminglessly with the company and the employees, as well as for the support, availability, pacience and motivation along the entire experience.

I would like to thank the operation/maintenance workers for all the lectures and demonstrations along these months, which helped immensely to keep progressing the project.

To Bruno Soeiro, Joel Couto, Rui Guedes and Vitor Bichança for sharing their work space with me and for making the time I spent at CP a rich experience, not just in terms of the work performed, but for the lessons they taught me beyond the scope of the project as well.

To Eng. Daniel Pereira for his availability and willingness to see it that I had every tool I needed to conclude a successful work.

To my parents, brother, nephews and godsons for the support, availability, patience and most of all motivation not just for this project, but along the entire course of this degree. They are without a doubt the main reason I strive for success.

Last but not least, to my friends and colleagues for their huge presence in all endeavors throughout this degree, work related and otherwise. For their cooperation, solidarity, empathy and most of all, friendship.

Table of Contents

List of Figures

List of Tables

1 Introduction

CP – Comboios de Portugal (Portuguese Trains) is a Portuguese railway company, founded in 1860, which transports about 145 million passengers per year. CP's railroad covers almost the entire region of continental Portugal. The company's mission is to connect people and communities in a sustainable way, based on the railway.

Nowadays, consumers are well informed and have easier access to alternative products and services, regardless of the sector. This means that the demand for quality products and services is higher than ever, as quality is seen as a basic need.

Companies have become more aware that in order to be able to provide the highest quality for their products and services, they need to have a well-defined approach when it comes to their maintenance plans. That is because the failure of equipment leads to defects in products or to not being able to provide a good enough service to the costumer, which means that the high quality standards have a direct impact on how maintenance should be performed. Maintaining equipment will lead to lower amounts of failures occurring, increasing the quality of the products and services provided, while reducing the costs associated with the lack of quality, such as reworks, refunds, loss of clients, among others.

The railway is one of the most used and historically relevant means of transport, of both people and goods. Since it is a fundamental means of transport between big cities and within the urban regions, a failure in a system can cause heavy consequences in other sectors, mainly because delays can cause harm in other activities in these areas. Besides that, equipment breakdowns can cause accidents with disastrous consequences.

Maintenance plays an important role when it comes to preventing these issues from happening, because with the adequate maintenance plans and activities, it is possible to decrease the risk of breakdowns happening to a minimum, besides being able to reduce the consequences of when they do happen.

1.1 Project Framework and Motivation

Thousands of people travel every day by train in Portugal, dozens in every single train and every passenger demands a high-quality, reliable service. CP strives for the fulfillment of their clients' needs. Maintenance helps reduce breakdowns, guaranteeing higher reliability, higher availability, higher customer satisfaction and lower costs.

CP recently acquired Arco carriages from RENFE (Red Nacional de los Ferrocarriles Españoles) and is still adapting its operation to this new equipment. The door systems have been some of the main sources of breakdowns and consequent unavailability, and therefore it was decided to implement the RCM methodology to these systems. Three different door systems were analysed: the access doors, the intercirculation doors and the hall doors.

This project was developed in a business environment, in CP's facilities at Contumil, with occasional visits to CP's workshop in Guifões, between the months of March and June of 2023.

1.2 Project Objetives

The aim of this project is to apply the RCM methodology to the door systems of the newly acquired Arco carriages of CP. It is intended to increase the knowledge about these systems and the reliability and availability of the Arco carriages' doors, through better maintenance practices. The implementation of this methodology implies a deep understanding of these systems and requires contact with people from different sectors of the company, such as operation, maintenance and engineering.

To perform this analysis, several steps need to be followed:

- Clarify the RCM methodology;
- Understand how the systems in analysis function;
- Define a list of relevant components;
- Define the system boundaries;
- Develop a list of functions, functional failures, failure modes and failure effects;
- Define a list of proposed tasks to be implemented for each failure mode;
- Define a new maintenance plan;
- Define new work instructions;
- Implement the new maintenance plan.

After implementing this methodology, there is a need to analyse its effectiveness, in terms of reliability and availability increase, as well as cost decrease, and to iterate the needed steps until the objectives are met.

1.3 Project Methodology

The time needed to conclude each task is detailed as follows:

- From 06/02 to 01/03 – Gain understanding about the RCM methodology and the systems to be analysed, through documents and meetings with staff members;
- From 02/03 to 11/04 – Define the list of relevant components, define the systems' boundaries, write a description of how they function and develop the list of functions, functional failures, failure modes and failure effects, through documents, meetings with staff members and direct interaction and experimentation with the systems;
- From 12/04 to 25/04 – Define the lists of proposed tasks to be implemented for each failure mode, with the information previously gathered;
- From 26/04 to 16/05 – Define the new maintenance plan and new work instructions, using information from the previously created documents;
- From 17/05 to 16/06 – Validation of the created documents, through meetings with staff members and audits.

1.4 Dissertation Structure

This dissertation is divided into seven chapters.

The first chapter has a small introduction to the subject, and goes into the project framework and motivation, project objectives and the methodology followed.

The second chapter presents a contextualization of the project, through a bibliographic review. It goes over important concepts, such as maintenance management, maintenance, asset function, availability, reliability and failure, FMEA, proactive tasks and default actions.

The third chapter introduces the RCM methodology, going over the seven basic questions, the RCM Decision Diagram, the RCM analysis report and other documents.

The fourth chapter contains an analysis of the description and operation of each door system studied.

The fifth chapter details the application of the RCM methodology to the Arco carriages, going in depth about each step taken.

The sixth chapter contains the result analysis.

The seventh and final chapter contains the conclusions.

2 Contextualization of Maintenance

In this chapter, a contextualization of maintenance will be made, starting with the evolution of maintenance throughout the years and going through relevant concepts, needed for the RCM methodology.

2.1 Maintenance Management

Maintenance management includes all management activities that determine the maintenance objectives, strategies and responsibilities, as well as their implementation (BS, 2010).

The main aim of maintenance management is to assure the safety of everyone involved and the quality of the products and services provided, in a way that is economically efficient and helps maximize equipment availability, thus reducing the costs associated with maintenance procedures.

To meet these goals, it is important to establish a maintenance plan, which is a structured and documented set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance (BS, 2010).

2.2 Maintenance

The NP EN 013306:2007 standard defines maintenance has a combination of all technical, administrative and managerial actions during the life cycle of an item intended to restore it to a state in which it can perform the required function (IPQ, 2007).

Throughout the years, maintenance has suffered big changes, due to the increasing complexity and variety of physical assets that must be maintained, the increased awareness of the relationship between equipment failures and safety, and the need to reduce prices associated with maintenance (Moubray, 1997). Since the 1930s, the evolution of maintenance can be divided into four generations (Moubray, 1997; Vicente, 2010).

The first generation covers the period until World War II. At this time, systems were not very highly mechanized, which meant that downtime was not very significant. The systems were also simple and over-designed, making them reliable and easy to repair. Maintenance was purely corrective, with action being taken only after a failure occurred, with the objective of restoring operating conditions. Any preventive maintenance task was not economically viable.

The second generation came with World War II, which led to an increased demand for goods with lower manpower available, which led to a need for mechanization. As machines got more complex and more used, the industry sector was beginning to depend on them. This meant that the downtime of machines was much more relevant to production. The concept of preventive maintenance was implemented to prevent failures, and not just act after they occurred. At this time, maintenance costs started to become an increasing part of operational costs, growing awareness for the need to create ways to plan and program maintenance.

The third generation came in the mid-1970s and was characterized by increased mechanization and automation, meaning that reliability and availability were very important issues. The increased automation meant that failures could cause defects that were replicated in very high quantities, having a negative impact in product and service quality, which were in higher demand than before. In the 1990s, risk-based inspection and maintenance methodologies began emerging. Maintenance efforts were focused on maintaining the initial capability of the assets, which was questionable, because some failures had big safety and environmental consequences.

For this reason, the importance of preventing failure instead of maintaining initial capability of the assets became evident. The fourth generation is characterized by the implementation of risk-based inspection maintenance and RCM (Reliability Centered Maintenance). It also became apparent that an integrated approach of maintenance and safety was the appropriate way for optimizing capacity, given their mutual influence. This generation addresses not only "what is done", but also "how it is done". The objective of the maintenance process is to increase the profitability of the operation and optimize the total life cycle cost without compromising safety or environmental concerns (Vicente, 2010; Arunraj & Maiti, 2006). The referred generations are described in Figure 1.

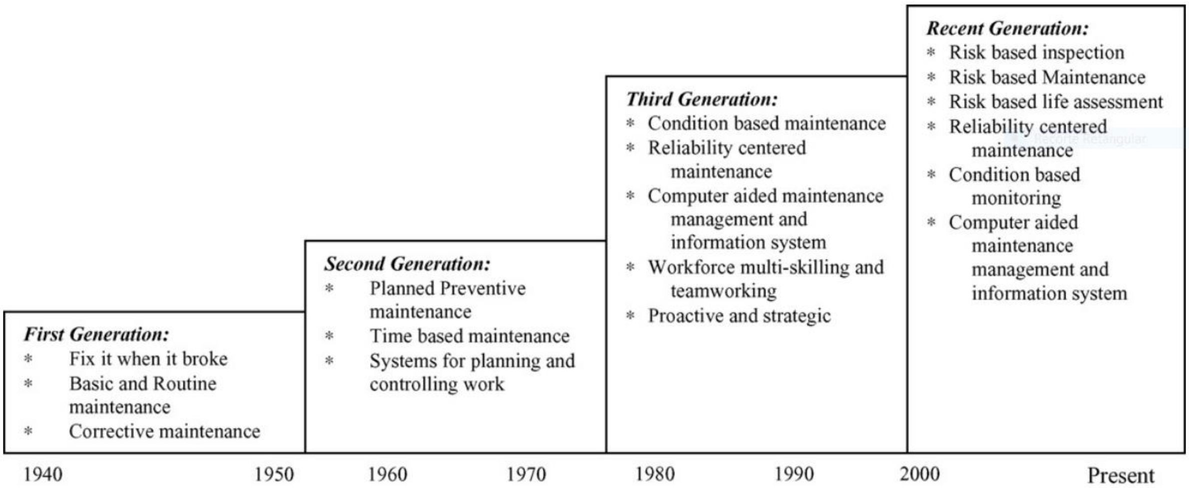


Figure 1 – Maintenance Generations (Arunraj & Maiti, 2006)

2.3 Maintenance Policies

There are several ways to address system failures, depending on the type of maintenance objectives. Maintenance can be planned or unplanned, based on the possible consequences of failure, as well as on the ability to perform certain types of planned maintenance:

- Corrective maintenance is carried out after a failure occurs and it's objective is to return an asset to a state in which it can perform its required functions (BS, 2010). When it is unplanned, it can also be referred to as breakdown maintenance (Mansor, Ohsato, & Sulaiman, 2012).
- Preventive maintenance is carried out at predetermined intervals or according to other criteria and intends to reduce the probability of failure or the degradation of the functioning of an item (BS, 2010).
- Predictive maintenance is a condition-based maintenance carried out following a prediction (BS, 2010). This prediction can be based on continuous monitoring, by continuously measuring the needed indicators such as temperature, vibration levels, sound levels, and other, using sensors. It can also be based on periodic inspections carried out to determine the condition of the asset at predetermined intervals.

Figure 2 summarizes the different types of maintenance.

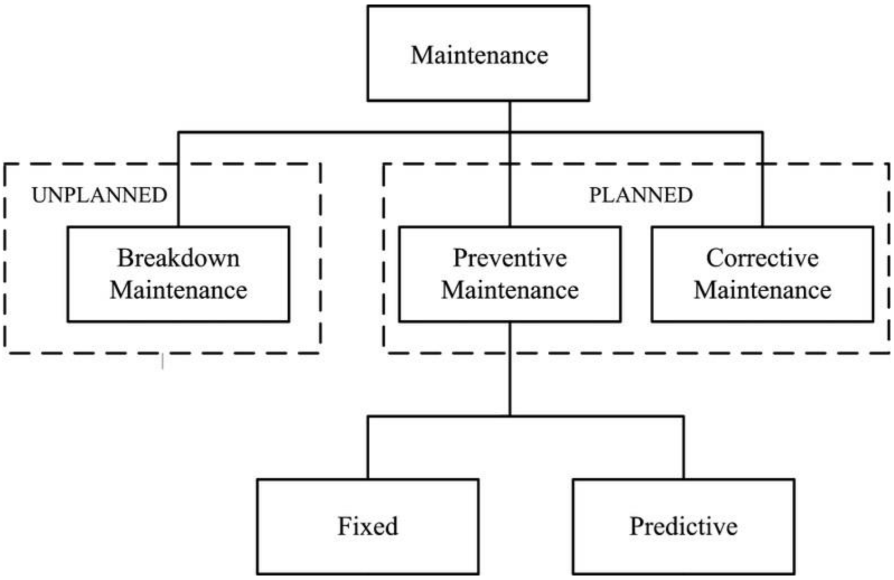


Figure 2 – Types of Maintenance (Mansor, Ohsato, & Sulaiman, 2012)

Regardless of the type of maintenance, it is crucial that the equipment can be repaired. Maintainability is the ability of an asset under given conditions of use, to be restored to a state in which it can perform a required function, when maintenance is performed. (BS, 2010) Mathematically, it is the probability that an asset will be repaired until a specified time when it is needed to.

2.4 Asset Function

Any physical asset is put into service for a purpose, to perform a certain function. When maintaining an asset, the aim is to make sure that it can continue performing the function it is meant to. To define the objectives of maintenance in terms of requirements, there is a need to gain clear understanding of the functions of each asset, as well of the required performance standards (Moubray, 1997).

The main types of functions are (Hoyland & Rausand, 2009):

- Essential functions – Functions required to fulfill the intended purpose of the asset. For example, the essential function of a pump is "to pump fluid";
- Auxiliary functions – Functions required to support the essential functions. For example, the auxiliary function of a pump is "to contain fluid";
- Protective functions – Functions required to protect people, equipment and the environment. These can be classified as:
    - Safety functions, to prevent accidents or reduce their consequences;
    - Environmental functions, usually antipollution measures;
    - Hygiene functions.

2.4.1 Function Definition

According to the BS EN 13306:2010 standard, the required function of an asset can be defined as the function, combination of functions, or a total combination of functions of an item which are considered necessary to provide a given service (BS, 2010).

At the most basic level, a function definition should include a verb and an object ("to pump gas", "to drill a hole", "to open the door"). But in maintenance terms, it is expected that assets perform at a certain acceptable level of performance. So, a function definition is not complete unless it clearly specifies the level of performance needed for that asset to be meeting requirements ("to open the door, within 4 seconds").

It is important to note that the function statement does not include statements about the reliability of the asset (for example, "to open the door, within 4 seconds, 7 days a week"). This is because reliability is not a function itself, but a performance expectation. This is also confirmed by the BS EN 13306:2010 standard, that defines reliability as the ability of an item to perform a required function under given conditions for a given time interval (BS, 2010; Moubray, 1997).

2.4.2 Performance Standards

Any asset should be able to perform at a minimum standard level. If it was possible for the asset to continuously run at that minimum level without deteriorating, there would be no need for maintenance. In practice, that is not the case, which means that when putting an asset into service, it should be able to deliver more than the minimum level required, to have margin for deterioration, has shown in Figure 3 (Moubray, 1997).

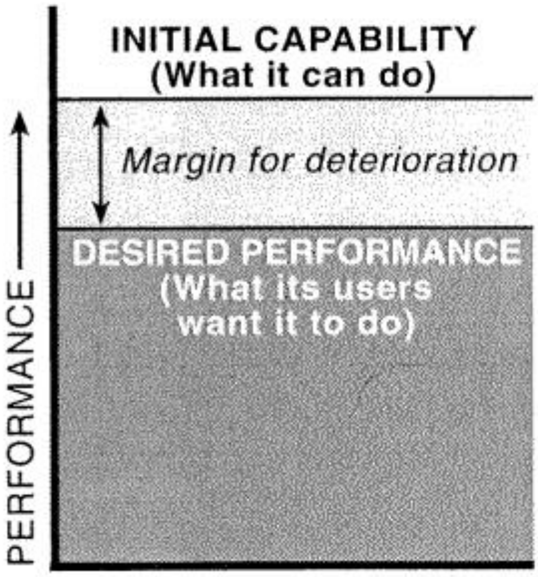


Figure 3 – Margin for Deterioration (Moubray, 1997)

This means that there are two ways to define performance:

- Desired performance – what the asset is meant to do;
- Built-in capacity – what the asset can do.

It is important to keep in mind that, at most, maintenance procedures can only return the asset to its initial capability, and not to a higher level of performance. And for the maintenance procedure to be considered successful, the performance level should be at least as high has the desired performance.

This means that maintenance achieves its objectives by maintaining the capability of the asset between the initial capability and the desired performance, as shown in Figure 4.

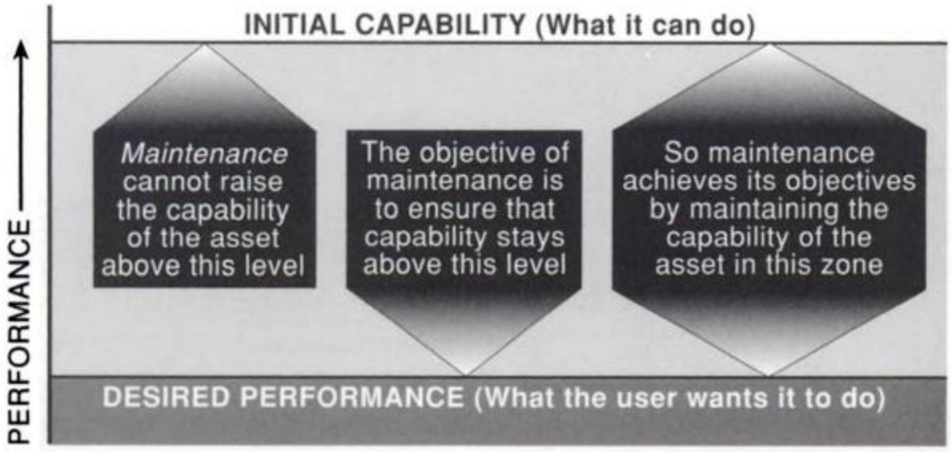


Figure 4 – Maintenance Objectives (Moubray, 1997)

A non-maintainable situation is one where the desired performance is higher than the initial capability, meaning that it is not possible to deliver the desired performance, regardless of the amount of maintenance performed (Moubray, 1997).

2.5 Asset Availability

The BS EN 13306:2010 standard defines availability as the ability to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided (BS, 2010). As previously mentioned, one of the main aims of maintenance is to make sure that the asset can continue performing the function it is meant to. This means that maintenance procedures should focus on maintaining availability levels and should therefore be as short as possible.

With these objectives in mind, there is a need for indicators that can accurately and quantitively measure the success of the maintenance plan being implemented. Availability can be used to conclude about the efficiency of maintenance, making it one of the most relevant indicators. Mathematically, availability is defined as the probability of the equipment being available in a given time period. It can be calculated through different estimators, like the one shown in Equation (2.1) (Leitão et al, 2019).

$$Availability = \frac{up\ time}{up\ time + down\ time} \tag{2.1}$$

Where:

up time – Time interval throughout which an item is in an up state (meaning able to fulfill its functions) (BS, 2010).

down time – Time interval throughout which an item is in a down state (meaning not able to fulfill its functions) (BS, 2010).

Another estimator for availability is shown in Equation (2.2) (Leitão et al, 2019).

$$Availability = \frac{MTBF}{MTBF + MTTR} \tag{2.2}$$

Where:

MTBF – Mean Time Between Failures (average of the times between failures) (BS, 2010).

MTTR – Mean Time To Repair (average of the times to restoration) (BS, 2010).

MTBF can be calculated as shown in Equation (2.3).

$$MTBF = \frac{1}{\lambda(t)} \tag{2.3}$$

Where:

λ(t) – Failure rate, the expected number of failures in a given time interval.

MTBF is a more practical indicator than the failure rate, because it is easier to interpret that an asset fails every 30 days, than it is to interpret that the failure rate is 0.03333 failures per day. Assuming a constant failure rate, MTBF can also be calculated as shown in Equation (2.4). Ideally, failure rates would be decreasing, which would mean that the maintenance policies were having a positive influence on improving reliability.

$$MTBF = \frac{tf}{N\ Failures} \tag{2.4}$$

Where:

tf – Number of working hours.

N Failures – Number of failures.

A system's working history is defined by periods of functioning states alternated with periods of breakdown states. Figure 5 shows the function history of a system.

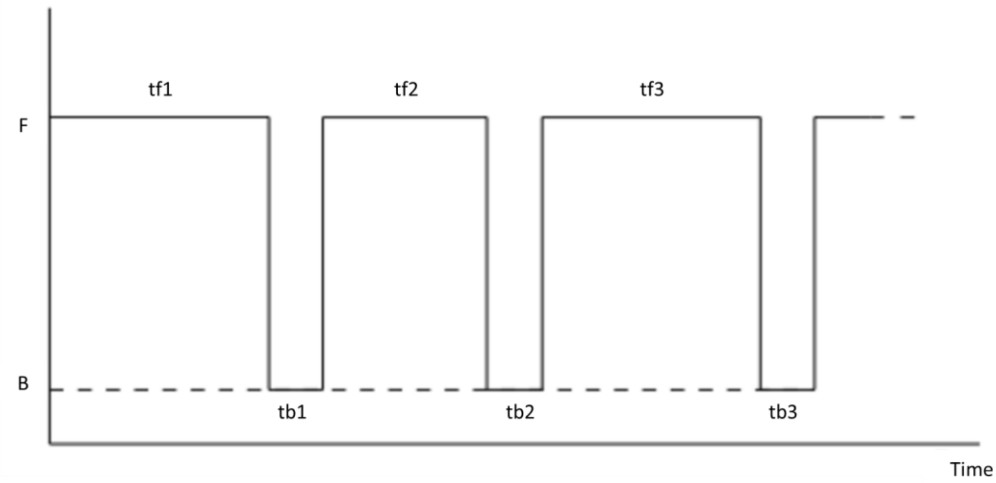


Figure 5 – Function History of a System (Adpated from (Barbosa, 2018))

Where:

F – Functioning state.

B – Breakdown state.

tf – Time that the asset is functioning.

tb – Time that the asset is broken down.

Figure 6 shows a representation of MTBF.

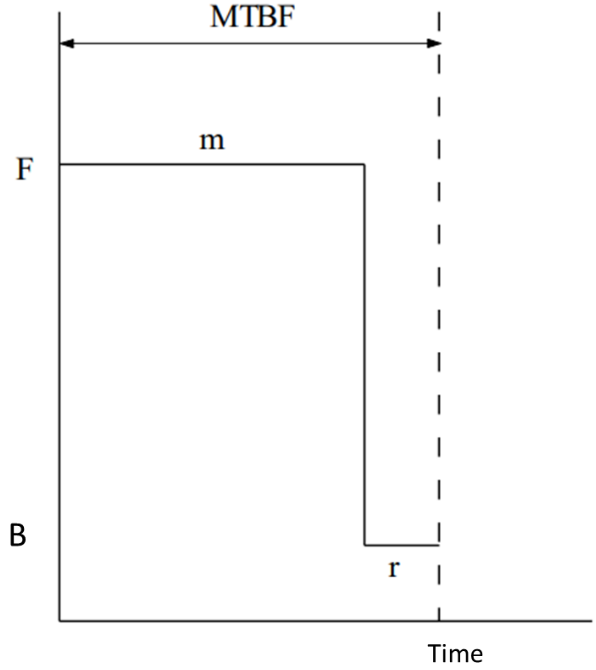


Figure 6 – Representation of MTBF (Barbosa, 2018)

Where:

m – Time that the asset is functioning.

r – Time that the asset is broken down.

One of the main goals of maintenance is to have MTBF be as high as possible and MTTR as low as possible, leading to higher availability levels.

2.6 Asset Reliability

As mentioned before, the BS EN 13306:2010 standard defines reliability as the ability of an item to perform a required function under given conditions for a given time interval (BS, 2010).

An asset is expected to fulfill its functions, and there are expectations regarding those functions and the availability of the asset. Reliability has a direct impact on the ability to meet these expectations. When reliability is low, availability will also be limited, and the asset will not be able to meet requirements. Reliability of assets and equipment is crucial for any business, given the fact that high reliability values are needed to maintain the needed high quality and safety levels, as well as to reduce the costs, both maintenance-based and indirect costs caused by lower availability.

Mathematically, the probability of a failure occurring in a given time interval can be defined as shown in Equation (2.5).

$$F(t) = \int_0^t f(t)\, dt \tag{2.5}$$

Where:

F(t) – Probability of the system failing in the interval [0,t].

f(t) – Probability density function, the failure frequency in the interval [0,t].

Mathematically, reliability is the probability of the system not failing in a given time interval. It can be calculated as shown in Equation (2.6).

$$R(t) = 1 - F(t) = 1 - \int_0^t f(t)\,dt = \int_t^\infty f(t)\,dt \tag{2.6}$$

For maintenance purposes, it is important to know the rate at which systems that have not failed until a specific time will fail. This is represented by the hazard function, that can be calculated as shown in Equation (2.7).

$$h(t) = \frac{f(t)}{R(t)} \tag{2.7}$$

2.7 Asset Failure

Moubray (1997) defines failure as the inability of an asset to do what its users want it to. Similarly, the BS EN 13306:2010 standard defines failure as the termination of the ability of an item to perform a required function (BS, 2010).

Nowlan and Heap (1978) divide failures into functional failures (the inability of an item to meet a specified performance standard) and potential failures (an identifiable physical condition which indicates a functional failure is imminent).

Failures can have serious consequences such as increased costs, decreased efficiency, and potential safety issues. It is important for organizations to implement effective maintenance strategies to minimize the chance of failure and ensure that systems continue to function as intended. One of the main aims of maintenance is to have failures be as short and far in between as possible.

Failures can be classified as (Hoyland & Rausand, 2009):

- Intermittent failures – Failures that result in a lack of some function only for a very short period of time;
- Extended failures – Failures that result in a lack of some function until a part of the system is replaced or repaired. These include:
    - Complete failures – Failures that cause a complete lack of a function;
    - Partial failures – Failures that lead to a lack of some function.

Both can be further classified as:

- Sudden failures – Failures that could not be forecast by prior testing or examination;
- Gradual failures – Failures that could be forecast by prior testing or examination.

A failure that is both complete and sudden is called a catastrophic failure, and a failure that is both partial and gradual (commonly due to wear) is called a degraded failure. In cases of catastrophic failures, it is essential to have contingency plans in place, to minimize the impact of those failures and quickly return the system to its normal state.

Figure 7 summarizes the classification of failures.

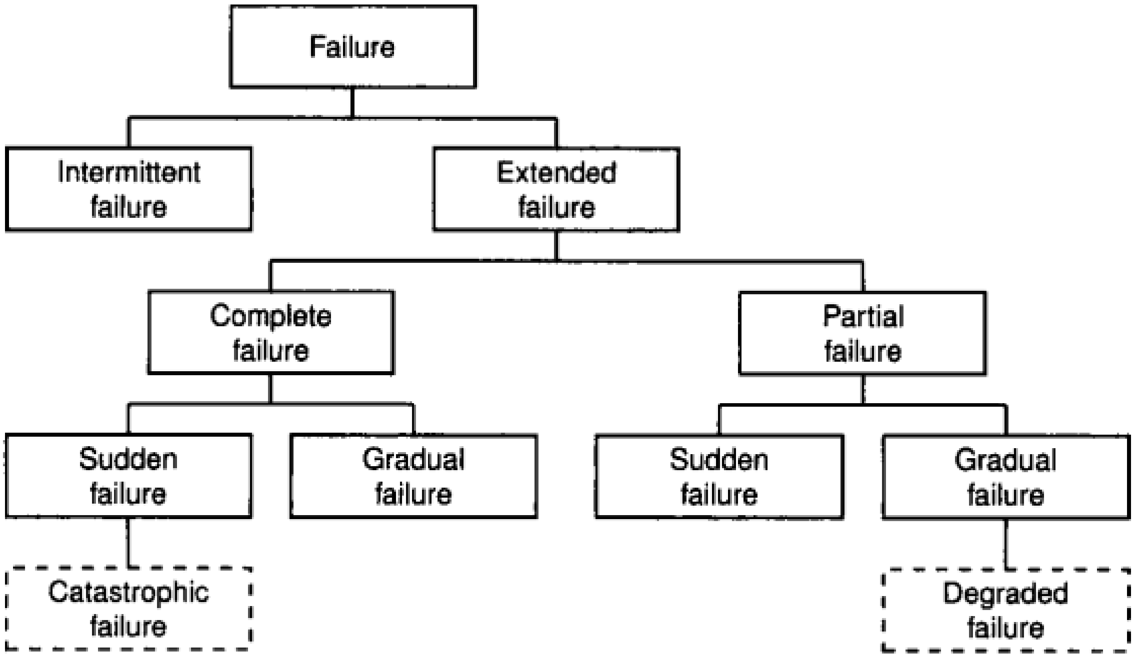


Figure 7 – Failure Classification (Hoyland & Rausand, 2009)

Depending on the literature consulted, the terms “failure” and “breakdown” can have different meanings. The more usual way to distinguish a failure from a breakdown is that a breakdown represents a total lack of a given function of the system, whereas a failure of a component may not represent the total lack of a function (an example of this are redundant systems, where a component failing does not represent a breakdown). In other words, a breakdown is a more extreme situation than a failure. At CP there was not a clear distinction between the two situations, as the term “breakdown” was not used, and both situations were attributed the nomenclature of “failure”.

2.7.1 Failure Mode

Once a failure is detected, it is important to identify why that failure occurred. A failure mode is the way the inability of an item to perform a required function occurs (BS, 2010; Moubray, 1997). In other words, it is the event that caused the failure.

To be able to accurately identify failure modes, maintenance personnel must have a deep understanding of the system and its components, as well as knowing common issues that may arise. Regular inspection and monitoring can help detect potential failure modes and take appropriate action to prevent them from occurring. In addition, proper training and procedures can help reduce the likelihood of human error.

Failure modes can include (Moubray, 1997):

- Mechanical failure – Breaking or malfunction of a physical component, like bearings, valves or other, usually due to wear;
- Electrical failure – Failure of electrical components or circuits, including short circuits, open circuits, and overloading;
- Software failure – Failure of a software system or application to perform as intended;
- Human error – Failures due to mistakes made by operators or maintenance personnel;
- Environmental failure – Failures caused by external factors such as high/low temperatures, moisture and radiation.

2.7.2 Failure Causes

The BS EN 13306:2010 standard defines failure cause as the circumstances during specification, design, manufacture, installation, use or maintenance that result in failure (BS, 2010).

Failure causes can be classified as (Hoyland & Rausand, 2009):

- Design failure – A failure due to inadequate design of a system;
- Weakness failure – A failure due to a weakness in the system itself when subjected to stresses within the stated capabilities of the system;
- Manufacturing failure – A failure due to nonconformity during the manufacturing process of the system;
- Ageing failure – A failure whose probability of occurrence increases with the amount of use the system is subjected to;
- Misuse failure – A failure due to the application of stresses during use that exceed the stated capabilities of the system;
- Mishandling failure – A failure caused by incorrect handling or lack of care of the system.

2.7.3 Failure Effects

Failure effects describe what happens when a failure occurs (Moubray, 1997). To provide a comprehensive failure effects statement, it is necessary to address the following aspects (Vicente, 2010; SAEJA1012, 2002):

- The evidence of the failure occurrence (or what would happen if a multiple failure occurred, in the case of hidden functions);
- The potential harm to human life or the environment resulting from the failure;
- The negative impact the failure could have on production or operations;
- The physical damage that the failure could cause;
- The actions required to restore the system's function;
- The number of hours and workers needed for the restoration.

2.7.4 Failure Consequences

Failure consequences describe why each failure matters, how it impacts the organization. It is important to analyse the consequences of each failure, to better define to which failures should be allocated more resources in terms of maintenance. This means that the focus should be in preventing failures that have highly severe consequences, whereas the failures with little to no consequences can have a corrective maintenance policy, for example.

Failure consequences can be classified in four categories (Moubray, 1997):

- Hidden consequences – Those that do not have a direct impact on the organization. Most of these failures are caused by protective devices not functioning as intended. Risks associated with installed safeguards that are not failsafe under certain conditions should be identified and addressed;
- Safety and environmental consequences – Safety consequences are those that can hurt or even kill someone. Environmental consequences are those that can go against an environmental standard, whether it be corporate, regional or national;
- Operational consequences – Those that can affect production or operations (output, quality, customer service, and other);
- Non-operational consequences – Associated with direct repair costs.

A multiple failure has consequences that would not be caused by any one of the individual failures alone. These consequences are considered in the definition of the failure consequences for the first failure (Heap & Nowlan, 1978).

2.8 FMEA

FMEA (Failure Modes and Effects Analysis) is a systematic method used to identify potential failure modes and assess their impact in a system. It is a proactive approach to risk assessment that helps organizations improve the reliability and safety of their products, processes, and systems. This information can be used to prioritize risk mitigation activities and improve overall system performance. FMECA (Failure Modes, Effects and Criticality Analysis) is a methodology that builds upon FMEA, by ranking the failure modes by their criticality. Some criticality analysis methods will be detailed throughout this chapter.

Some of the objectives of FMEA include (Hoyland & Rausand, 2009):

- To list potential failures and identify the magnitude of their effects;
- To provide a basis for quantitative reliability and availability analyses;
- To provide historical documentation for future reference;
- To provide basis for establishing corrective action priorities.

FMEA should also answer the following questions (Leitão & Guimarães, 2019):

- How can each part conceivably fail?
- What mechanisms might originate these failure modes?
- What could the effects be if the failures did occur?
- Does the failure have a negative impact on safety?
- How is the failure detected?
- What inherent provisions are provided in the design to compensate for the failure?

2.8.1 FMEA Implementation

The implementation of FMEA involves the following steps (Falck, 2010):

- Define the system – Clearly define the boundaries of the system under analysis and determine its components and functions. This means dividing the system into subsystems and identifying each subsystem's LRUs (Line Replacement Unit) and SRUs (Shop Reparable Unit). LRUs can be classified as (Vicente, 2010):
    - LRU without repair, which are replaced when they fail;
    - LRU repairable in maintenance;
    - LRU not repairable in maintenance, due to the lack of capacity, ability, labor, skills, tools or materials needed. In this case, the component is identified as SRU, and is repaired outside of maintenance, either in an internal repair shop or at the component's manufacturer.
- Identify potential failure modes – Analyse each component and function of the system to identify potential failure modes, considering all possible scenarios that could lead to a failure;
- Evaluate the effects and consequences of failure – Determine the effects and consequences of each failure mode, considering the impact on the system itself, the organization, the environment and safety;
- Assess the criticality of failure modes – Evaluate the severity of each failure mode based on its impact and the likelihood of occurrence;
- Identify risk mitigation activities – Based on the criticality of each failure mode, develop risk mitigation activities to minimize the probability of failures occurring and reduce the severity of their impact, when they do occur;
- Implement risk mitigation activities – Put the risk mitigation activities into practice, ensuring that the necessary changes are made to the system and that these changes are verified and validated;
- Monitor and review – Continuously monitor the performance of the system and review the results of the FMEA process to identify areas for improvement and to ensure that the system remains reliable and safe.

2.8.2 Risk Matrix

The risk associated to each failure mode is a function of the frequency of occurrence of the failure mode and its potential end effects (severity). The risk may be illustrated in a risk matrix, like the one in Figure 8 (Leitão & Guimarães, 2019).

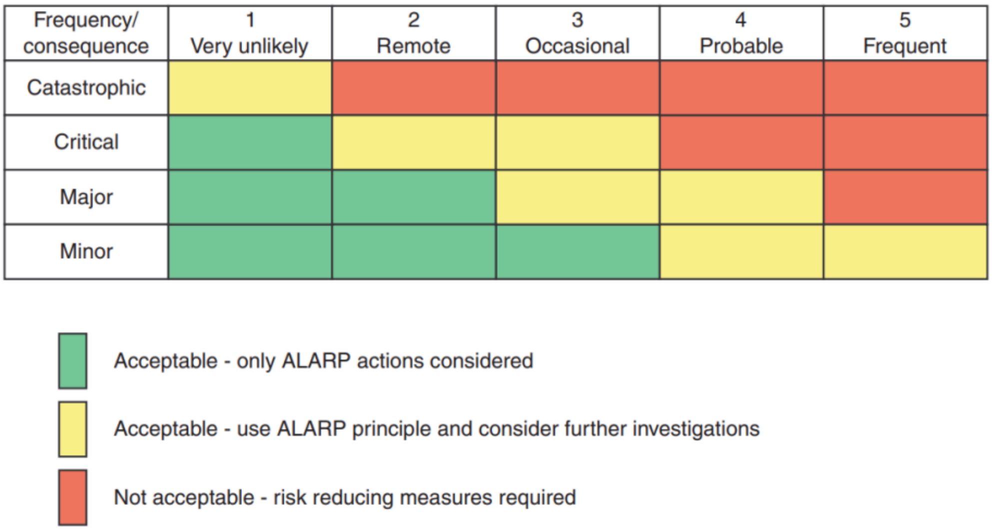


Figure 8 – Risk Matrix (Leitão & Guimarães, 2019)

ALARP is a principle according to which risks should be reduced to levels that are “as low as reasonably practicable”. This principle considers the cost of the risk reduction, which means that there is a point where further risk reduction is increasingly costly to implement, and therefore not worth to do so (Jones-Lee & Aven, 2011).

Analysing the matrix in Figure 8, it makes sense to only consider ALARP actions for situations represented on the bottom left corner of the matrix, where both consequences and frequency have low values. In the top right corner of the matrix, where both consequences and frequency have high values, risk reducing measures must be taken.

Although this matrix is useful in order to determine what actions should be taken regarding each failure mode individually, there are better tools for comparing the risks between different failure modes. For this purpose, there is a need to quantify the risk associated with each failure mode, like the RPN (Chapter 2.8.3).

2.8.3 RPN

Risk Priority Number (RPN) is a method of quantifying the risk rankings (Equation(2.8)). The higher the value of RPN is, the higher the risk associated with a failure mode.

$$RPN = S * O * D \tag{2.8}$$

Where:

S – The rank of severity of the failure mode.

O – The rank of occurrence of the failure mode.

D – The rank of likelihood the failure will be detected before the system reaches the end-user/customer.

These ranks can have different meanings for each FMEA, which makes benchmarking numbers between companies and groups very difficult (Leitão & Guimarães, 2019).

This means that there is a significant degree of subjectivity on the values of these ranks, and that their main purpose is to evaluate the effects of proposed changes on the RPN value itself, to analyse the efficiency of those changes.

Tables 1, 2 and 3 show examples of quantification of the S, O and D ranks, respectively.

Table 1 – Severity (S) Ratings (Adapted from (Dinmohammadi et al, 2016))

Rating	**Criteria**	**Characterization**
1	Insignificant	Failures that do not significantly affect the performance of a system.
2	Moderate	Failures that moderately affect the performance of a system.
3	High	Failures that highly affect the performance of a system.
4	Critical	Failures that highly affect the performance of a system and can cause damages or put in danger someone, if nothing is done to prevent it.
5	Catastrophic	Failures that cause damages and/or injuries/death.

Table 2 – Occurrence (O) Ratings (Adapted from (Dinmohammadi et al, 2016))

Rating	**Criteria**	**Frequency**
1	Remote	1 in 1 500 000
2	Unlikely	1 in 15 000
3	Occasional	1 in 400
4	Probable	1 in 20
5	Frequent	1 in 2

Table 3 – Detectability (D) Ratings (Adapted from (Dinmohammadi et al, 2016))

Rating	**Detectability**
1	Very low
2	Low
3	Moderate
4	High
5	Almost certain

2.8.4 RBD

One of the main aims of maintenance is to maximize reliability levels. The reliability of a system can be further detailed as a function of the reliability of its components. A Reliability Block Diagram (RBD) is a representation of a system's components and how they interact with each other in terms of reliability. Figure 9 shows a RBD.

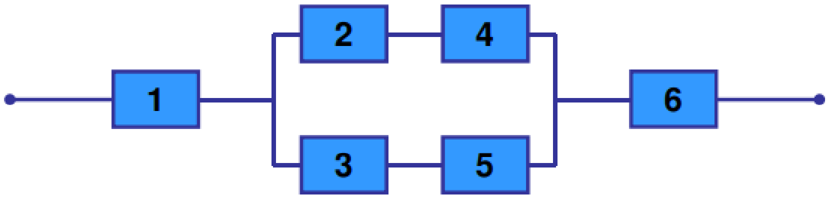


Figure 9 – RBD (Almada-Lobo, 2014)

The logic of RBDs can be explained as follows (Almada-Lobo, 2014):

- Each component can be in one of two operational states: functioning adequately or failed;
- R_i is the reliability of component *i*;
- Q_i is the probability that component *i* fails, such that $R_i + Q_i = 1$.

The components of the system can be displaced in series or in parallel, depending on how they interact with other components and with the system as a whole.

Figure 10 represents a system composed of a series of components. In this system, even if components 1, 2 and 3 are in a functioning state, the system does not function if component *n* is in a failed state. In other words, all components must function for the system to function.

Figure 10 – Series RBD (Almada-Lobo, 2014)

The reliability of the system represented in Figure 10 can be calculated through Equation (2.9).

$$R_s = R_1 . R_2 . R_3 . R_n \tag{2.9}$$

Where:

R_s – Reliability of the system.

R_i – Reliability of component *i*.

The reliability of the system is always lower than the individual reliability of the least reliable component. For example, if a system has 2 components in series with a reliability of 50% and 90%, the reliability of the system will be 45%. The more components are added to a series, the less reliable the system becomes.

Figure 11 represents a system composed of components in parallel. In this system, at least one of the components needs to be in a functioning state for the system to function.

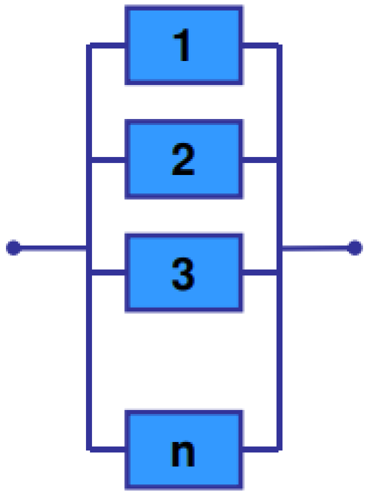


Figure 11 – Parallel RBD (Almada-Lobo, 2014)

The reliability of the system represented in Figure 11 can be calculated through Equation (2.10).

$$R_s = 1 - (1 - R_1)(1 - R_2)(1 - R_3)(1 - R_n) \tag{2.10}$$

The redundancy in the system created by components in parallel is an important tool to increase reliability levels. It is possible to obtain higher reliability for the system then the individual reliability of each component. For example, if a system has 2 components in parallel with a reliability of 50% each, the reliability of the system will be 75%. The more components are added to a parallel system, the more reliable the system becomes.

2.8.5 FTA

A Fault Tree Analysis (FTA) is a technique used for causal analysis in risk and reliability studies. It is a top-down search method, where the analysis looks to determine how the top event can be caused by individual lower level failures or their combination, as can be seen in Figure 12 (Leitão & Guimarães, 2019).

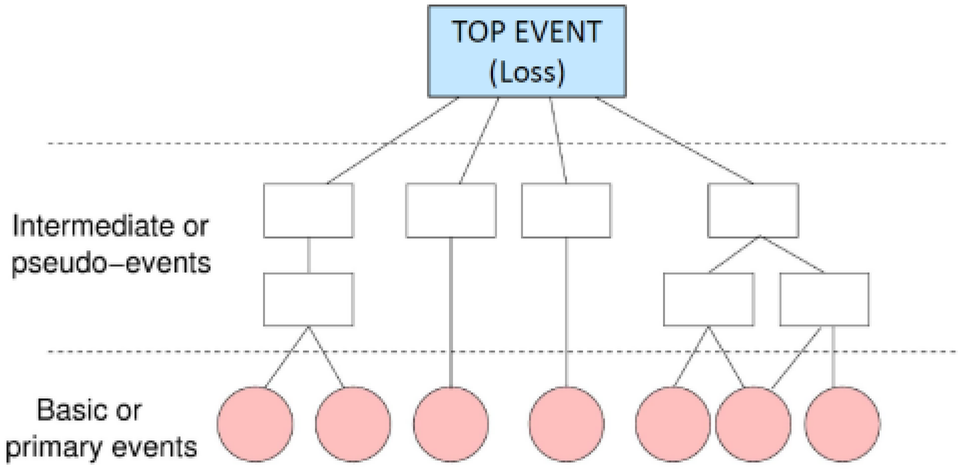


Figure 12 – FTA (Leitão & Guimarães, 2019)

The FTA process follows the following steps (Leitão & Guimarães, Fault Tree Analysis, 2019):

- Definition of the system, the top event and the boundary conditions;
- Construction of the fault tree;
- Identification of the minimal cut sets;
- Qualitative analysis of the fault tree;
- Quantitative analysis of the fault tree.

In order to construct the fault tree, there is a need for clear understanding of the system and how its components interact with each other. This means that often, the starting point of an FTA is an existing FMEA and a system block diagram.

The first step in constructing the fault tree is to clearly define the top event. This definition should answer the following (Leitão & Guimarães, 2019):

- What? – For example, "A fire";
- Where? – For example, "in the main engine";
- When? – For example, "during normal operation"

The next step is defining the events and conditions that cause the top event, connecting them with AND or OR gates (Figure 13). This step should be iterated until an appropriate level is found. At this level are the basic events, which should be independent events for which there is failure data available.

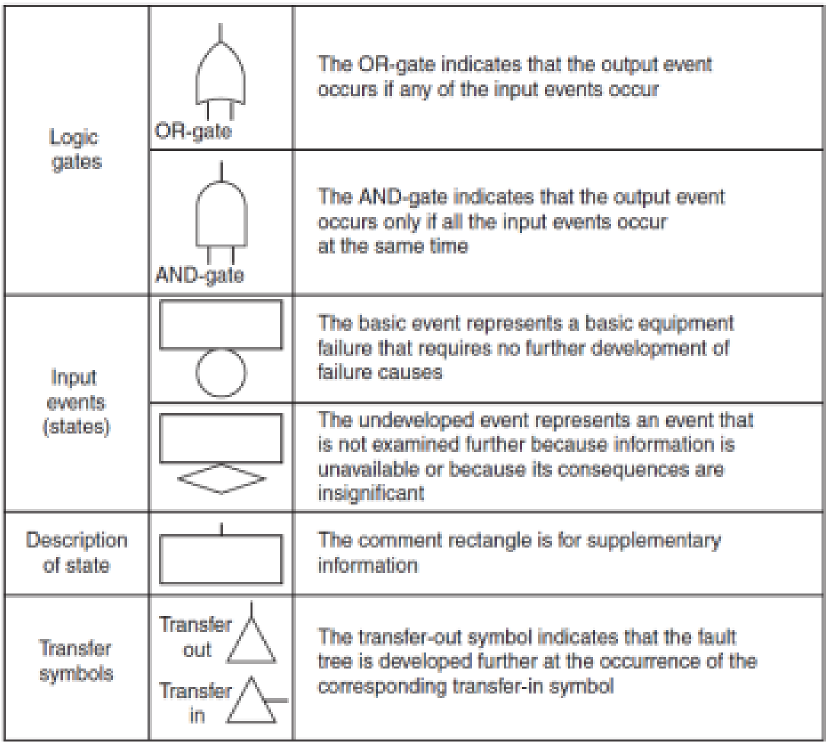


Figure 13 – FTA Symbology (Leitão & Guimarães, 2019)

A qualitative analysis can be performed by defining the cut-sets. A cut-set is a combination of basic events that leads to the top event occurring. In the example in Figure 14, (A and B and C) is a cut set. A minimal cut set is a cut-set that does not contain another cut-set, such as (A and B) and (A and C).

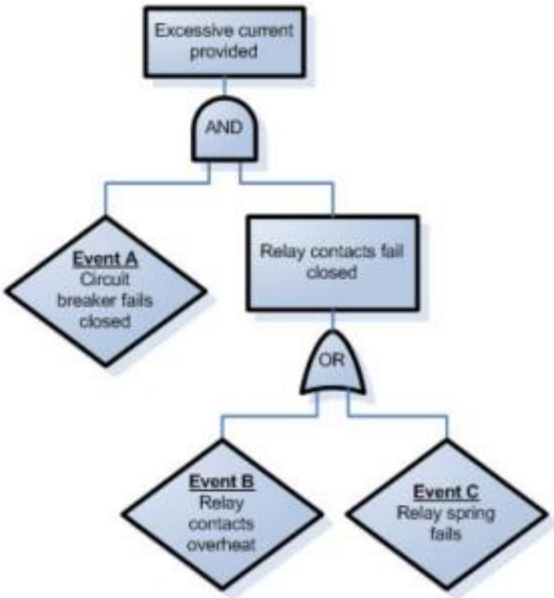


Figure 14 – FTA Cut-sets (Leitão & Guimarães, 2019)

The quantitative analysis looks to find the probability Q_0 of the top event occurring at a given time. This value is a function of all the q_i, the probability that basic event *i* occurs at a given time.

For the example shown in Figure 15 of a top event preceded by 2 events connected by an AND-gate, Q_0 can be calculated as shown in Equation (2.11)

.

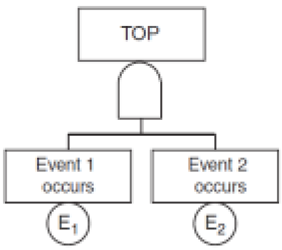


Figure 15 – AND-Gates (Leitão & Guimarães, 2019)

$$Q_0(t) = q_1(t).q_2(t) \quad (2.11)$$

Where:

Q_0 – Probability of the top event occurring.

q_i – Probability of base event *i* occurring.

For the example shown in Figure 16 of a top event preceded by 2 events connected by an OR-gate, Q_0 can be calculated as shown in Equation (2.12).

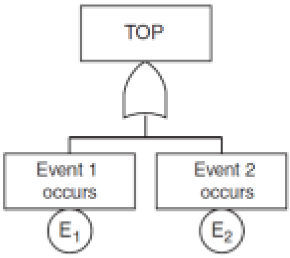


Figure 16 – OR-Gates (Leitão & Guimarães, 2019)

$$Q_0(t) = 1 - [1 - q_1(t)].[1 - q_2(t)]$$

(2.12)

To calculate q_i, the type of event needs to be considered.

When an event is associated with the failure of a non-repairable unit, q_i can be calculated through Equation (2.13).

$$q_i(t) = 1 - e^{-\lambda_i . t} \approx \lambda_i . t$$

(2.13)

Where:

λ_i – Failure rate of the non-repairable unit associated with event *i*.

t – Time.

When an event is associated with the failure of a repairable unit, q_i can be calculated through Equation (2.14).

$$q_i(t) =\approx \lambda_i \, . MTTR_i$$

(2.14)

Where:

$MTTR_i$ –Mean Time to Repair of the repairable unit associated with event *i*.

When dealing with redundant or safety systems, their failure is only detected when they are needed or through periodic testing. Considering a unit that is periodically tested with test interval τ, q_i can be calculated through Equation (2.15).

$$q_i(t) =\approx \frac{\lambda_i . \tau_i}{2}$$

(2.15)

Where:

τ_i – Test interval for the periodic testing of the unit associated with event *i*.

2.8.6 ETA

An Event Tree Analysis (ETA) is based on a diagram that shows the consequences of a specified critical accidental event in a system. An accidental event is a deviation from the normal situation, that can cause unwanted consequences, such as gas leaks, fires, and others. To reduce these consequences, there should be barriers. Barriers are preventive devices that should be triggered in response to the unwanted consequences caused by an accidental event, such as sprinklers to prevent a fire from spreading, circuit breakers to prevent damages to an electrical circuit, and others. Figure 17 shows an example of an ETA, where the accidental event considered is an explosion occurring.

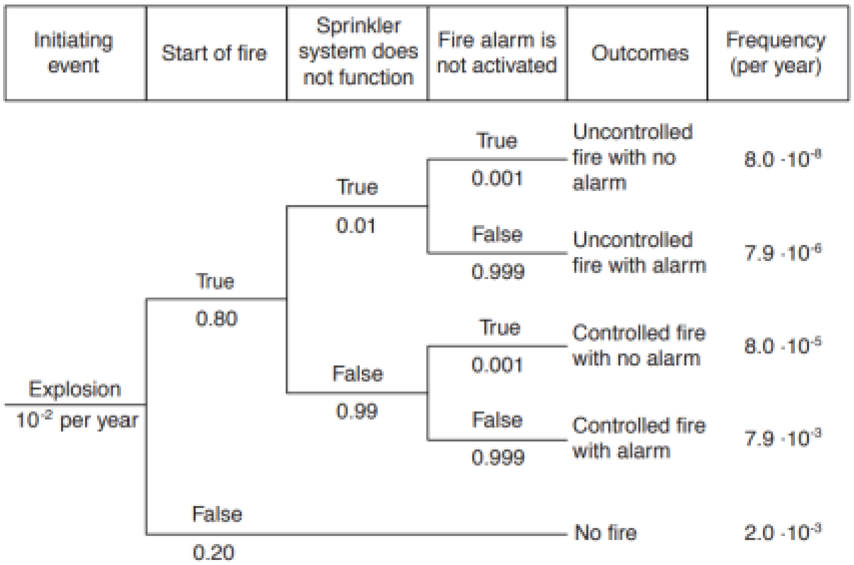


Figure 17 – ETA (Leitão & Guimarães, 2019)

The ETA process follows the following steps (Leitão & Guimarães, 2019):

- Identify the relevant accidental event;
- Identify the barriers that are designed to deal with the accidental event;
- Construct the event tree;
- Describe the possible resulting accidental sequences;
- Determine the frequency of the accidental event and the probabilities of the branches in the event tree;
- Calculate the probabilities/frequencies for the identified consequences.

The definition of the accidental event should answer the following:

- What? – For example, “A fire”;
- Where? – For example, “in the main engine”;
- When? – For example, “during normal operation”.

Then, each additional event as well as the barriers for each of them should be identified, in the order that they occur in, as shown in Figure 18.

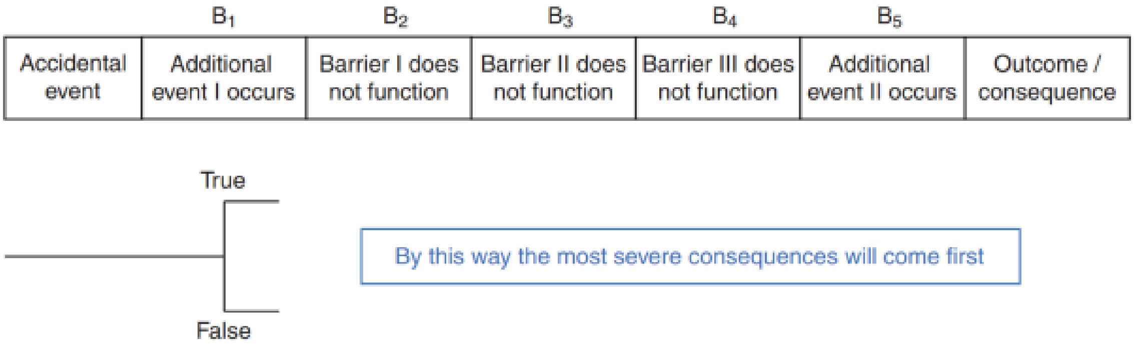


Figure 18 – Event Tree Construction (Leitão & Guimarães, 2019)

The outcomes are the end results for each branch represented in the event tree. A quantitative analysis can be performed regarding the outcomes, as shown in Equation (2.16).

$$F_j = f \prod_{i \in S} p_i \prod_{i \in F} q_i \tag{2.16}$$

Where:

F_j – Frequency of consequence *j*.
f – Frequency of the initial accidental event.
S – Successful barriers.
p_i – Probability that barrier *i* functions as intended.
F – Unsuccessful barriers.
q_i – Probability that barrier *i* fails.

2.9 Proactive Taks and Default Actions

The actions that can be taken to deal with failures can be divided into two categories (Moubray, 1997):

- Proactive tasks – Tasks undertaken before a failure occurs, to prevent a failure in the asset in review (preventive maintenance);
- Default actions – Actions that deal with the failed state (corrective maintenance). These are chosen when it is not possible to identify an effective proactive task, and when failure does not have significant safety and/or environmental consequences.

2.9.1 P-F Curve

The P-F curve (Figure 19) illustrates the evolution of the condition of an asset, leading up to a functional failure. Point P represents the point at which a potential failure can be detected. If it is not detected and action is not taken, it will eventually reach point F, the point of functional failure (Moubray, 1997).

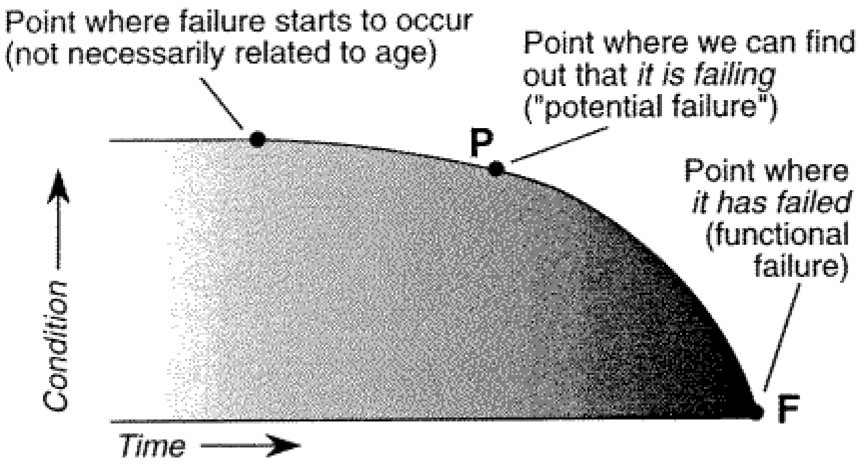


Figure 19 – P-F Curve (Moubray, 1997)

It is important to detect a potential failure as quickly as possible, to increase the P-F interval (amount of time between the P and F points). There are certain tasks that can increase the P-F interval, and in this way, make it less likely that point F is reached. Nevertheless, the usual periodicity for on-condition maintenance tasks (Chapter 2.9.2) is based on Equation (2.17).

$$Periodicity \leq \frac{PF\ Interval}{n} \tag{2.17}$$

Where:

n – Number of needed inspections within the P-F interval. For precaution, this value is usually equal to 2, to ensure that two inspections are made within the P-F interval (Vicente, 2010).

PF – Amount of time between the P and F points.

The nett P-F interval is the amount of time available to take action to reduce or eliminate the consequences of failure, after a potential failure being detected (Vicente, 2010).

In the example in Figure 20, the inspection interval is 6 months, while the P-F interval is 9 months. If an inspection is made immediately before the P point, the potential failure will only be detected 6 months after the P point.

Therefore, the nett P-F interval will be equal to 3 months, which is the difference between the P-F interval and the inspection interval. This highlights the crucial importance of correctly defining these intervals, because if the inspection interval is too close to the P-F interval, there may not be sufficient time to reduce or eliminate the consequences of failure.

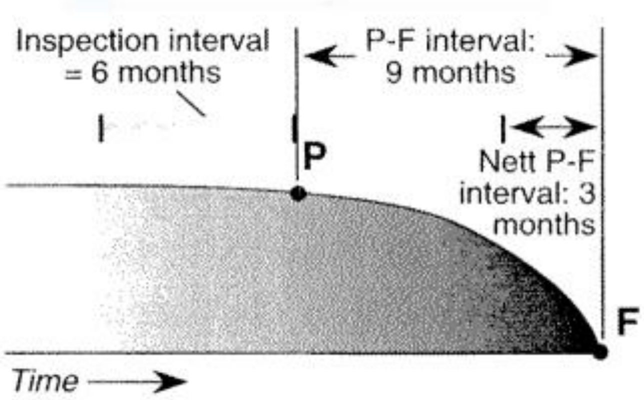


Figure 20 – Nett P-F Interval (Moubray, 1997)

Consistency in the P-F interval is crucial, given the fact that if the variation in these intervals is big enough, it can induce significant errors in maintenance management. In cases of inconsistent intervals, the shortest P-F interval should be considered (Figure 21).

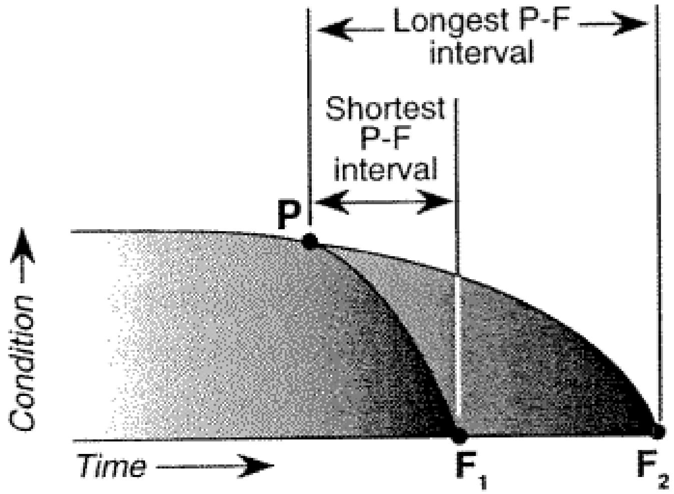


Figure 21 – Inconsistent P-F Intervals (Moubray, 1997)

2.9.2 Proactive Tasks

Proactive tasks are divided into three categories (Moubray, 1997; Aleluia, 2020):

- On-condition maintenance – Entails checking for potential failures, so that action can be taken to prevent the functional failure or to avoid the consequences of the functional failure. These include condition monitoring techniques, techniques based on variations in product quality, primary effects monitoring techniques and inspection techniques. These are only feasible if:
  - It is possible to define a clear potential failure condition;
  - The P-F interval is reasonably consistent;
  - It is practical to monitor the item at intervals less than the P-F interval;
  - The nett P-F interval is long enough for action to be taken to reduce or eliminate the consequences of the functional failure.

- Scheduled restoration – Entails a repair action to restore an asset to its initial condition (right after its manufacturing), regardless of the condition at the time. These are only feasible if:
    - There is an identifiable age at which the item shows a rapid increase in the conditional probability of failure;
    - Most of the items survive to that age (all the items if the failure has safety or environmental consequences);
    - They restore the original resistance to failure of the item (meaning that failure is not more likely to occur in a restored item than in a new one).
- Scheduled discard – Entails discarding an item or component at or before a specified age limit, regardless of its condition at the time. These are only feasible if:
    - There is an identifiable age at which the item shows a rapid increase in the conditional probability of failure;
    - Most of the items survive to that age (all the items if the failure has safety or environmental consequences).

2.9.3 Default Actions

Default actions include (Moubray, 1997; Aleluia, 2020):

- Failure-finding tasks – These are tasks designed to check if an asset is functioning. Used to detect and correct hidden failures;
- Redesign – Changes in hardware, software, methodologies or procedures, which can also include training operators. Redesigns must be made in situations where preventive maintenance tasks are not able to reduce the safety and/or environmental risks to acceptable levels;
- No scheduled maintenance – For cases where the efforts or costs associated with preventing failure is not viable, and therefore assets are left in service until a functional failure occurs. This action is only feasible if the failure has no environmental or safety consequences associated. These can be divided into two categories:
    - "Wait and see" – This policy consists of allowing the failure mode to occur to gain information about its useful life;
    - Life Extension programs (PEV – "Programas de exploração de vida") – This policy consists of a periodic control by sampling of the operating conditions of an asset, to look for potential failures. These allow to gather useful information regarding the periodicity of the failure mode, without the need for it to occur, unlike the "Wait and see" policy. (Vicente)

3 RCM Methodology

Regularly stopping machines for systematic predictive maintenance can decrease their availability, which can be a concern due to the strict quality standards that require rigorous maintenance to prevent failure and subsequent quality loss (Vicente, 2010).

RCM (Reliability-Centered Maintenance) is a process that helps determine the maintenance needs of any physical asset in its operating context, aiming to optimize its inherent reliability capabilities. The RCM approach involves analysing the reliability of each component, the consequences of its failure, and the costs of avoiding that failure, to determine the maintenance requirements. By using RCM principles, it is possible to determine why, when, and how maintenance tasks should be performed, and define a balance between preventive and corrective maintenance tasks based on each asset's unique characteristics (Moubray, 1997; Heap & Nowlan, 1978).

The term RCM was first introduced by Nowlan and Heap (1978), in the maintenance report for the "MSG-2: Airline Manufacturer Maintenance" program, which aimed to enhance reliability and safety while controlling costs. This methodology emerged in the aeronautic industry in the 1960s, where preventive maintenance tasks were effective in improving reliability to meet required levels.

RCM can be divided into the following steps (Aleluia, 2020):

- Assembling a multidisciplinary team;
- Selecting and defining the assets in review;
- Analysing their functions;
- Analysing their failure and breakdown history;
- Performing a FMEA analysis;
- Defining the appropriate maintenance tasks;
- Implementing those tasks;
- Analysing the results;
- Making the necessary changes;
- Iterating the previous two steps.

3.1 Seven Basic Questions

RCM II, studied and developed by Moubray (1997) is an improvement on the original RCM methodology. The RCM II process looks to find answers to seven basic questions about the asset in review (Moubray, 1997):

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

This methodology begins by defining the operational context of the asset in review, its functions and performance standards. Then it is important to determine its failure modes and their causes. The next step is to identify the effects of these failures. An important tool is a FMEA analysis, to help with these steps. The answers to these first five questions should be written in an Information Worksheet, like the one in Figure 22. This example can also be consulted with more clarity in Annex A.

RCM II INFORMATION WORKSHEET © 1996 ALADON LTD	SYSTEM: 5 MW Gas Turbine	SYSTEM Nº 216 - 05	Facilitator: N Smith	Date 07 - 07 - 1996	Sheet Nº 1
	SUB-SYSTEM: Exhaust System	SUB-SYSTEM Nº 216 - 05 - 11	Auditor: P Jones	Date 07 - 08 - 1996	of 3

	FUNCTION		FUNCTIONAL FAILURE (Loss of function)		FAILURE MODE (Cause of failure)	FAILURE EFFECT (What happens when it fails)
1	To channel all the hot turbine gas without restriction to a fixed point 10m above the roof of the turbine hall	A	Unable to channel gas at all	1	Silencer mountings corroded away	Silencer assembly collapses and falls to bottom of stack. Back pressure causes the turbine to surge violently and shut down on high exhaust gas temperature. Downtime to replace silencer up to four weeks
		B	Gas flow restricted	1	Part of silencer falls off due to fatigue	Depending on nature of blockage, exhaust temperature may rise to where it shuts down the turbine. Debris could damage parts of the turbine. Downtime to repair silencer 4 weeks.
		C	Fails to contain the gas	1	Flexible joint holed by corrosion	The joint is inside turbine hood, so leaking exhaust gases would be extracted by the hood extraction system. Fire and gas detection equipment inside hood is unlikely to detect an exhaust gas leak, and temperatures are unlikely to rise enough to trigger the fire wire. A severe leak may cause gas demister to overheat, and may also melt control wires near the leak with unpredictable effects. Pressure balances inside the hood are such that little or no gas is likely to escape from a small leak, so a small leak is unlikely to be detected by smell or hearing. Downtime to replace joint up to 3 days
				2	Gasket in ducting improperly fitted	Gas escapes into turbine hall and ambient temperature rises. Hall ventilation system would expel gases through louvres to atmosphere, so concentration of gases is unlikely to reach noxious levels. A small leak at this point may be audible. Downtime to repair up to 4 days
				3	Upper bellows holed by corrosion	The upper bellows are outside turbine hall, so a leak here discharges to atmosphere. Ambient noise levels may rise. Downtime to repair up to 1 week.
		D	Fails to convey gas to a point 10 m above roof	1	Exhaust stack mounting bolts shear due to rust	Exhaust stack is likely to be held up by the guy ropes for a while before it falls over, but would lean at at an angle. If it did fall over, there is a high probability that it could crush a structure containing people. Downtime to repair a few days to several weeks.
				2	Exhaust stack blown over in gale	The stack structure is designed to withstand winds up to 200 mph, so it is only likely to fall over in a gale if the guy ropes were already weakened, perhaps by corrosion. If it went, it could be blown onto an accommodation module. Downtime to repair up to several weeks.
2	To reduce exhaust noise level to ISO Noise Rating 30 at 50 metres	A	Noise level exceeds ISO Noise Rating 30 at 50 m	1	Silencer material retaining mesh corroded away	Most of the material would be blown out, but some might fall to the bottom of stack and obstruct the turbine outlet, causing high EGT and possible turbine shudown. Noise levels would rise gradually. Downtime to repair about 2 weeks.
				2	Duct leaks outside turbine hall	.... etc

Figure 22 – Information Worksheet (Moubray, 1997)

Regarding the sixth question, one of the most important dilemmas in maintenance is finding the right balance between what can be done and what should be done, usually associated with what makes economic sense. Successive increases in risk reduction come at increasingly higher costs.

Lastly, it is important to know what to do when a suitable proactive task cannot be found, meaning what default actions should be taken.

3.2 RCM Decision Diagram

Once the FMEA analysis is completed and the information is documented in the Information Worksheet, the subsequent step in the RCM methodology is to develop a maintenance plan.

The Decision Diagram (Figure 23) is a flow chart that that guides the selection of the most suitable maintenance tasks. It uses a sequence of Yes/No questions to determine the level of significance of each failure mode and to identify the appropriate action to be taken. This diagram can also be consulted with more clarity in Annex A.

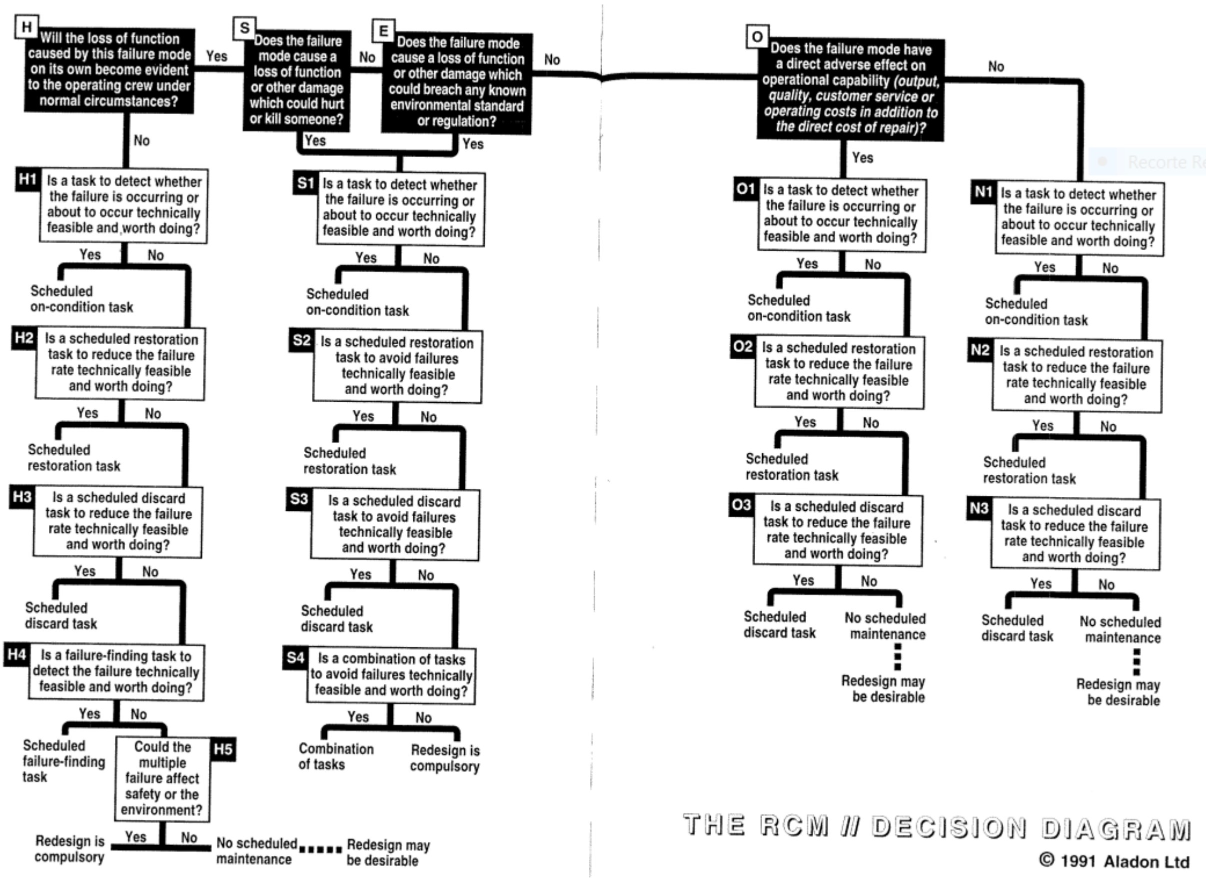


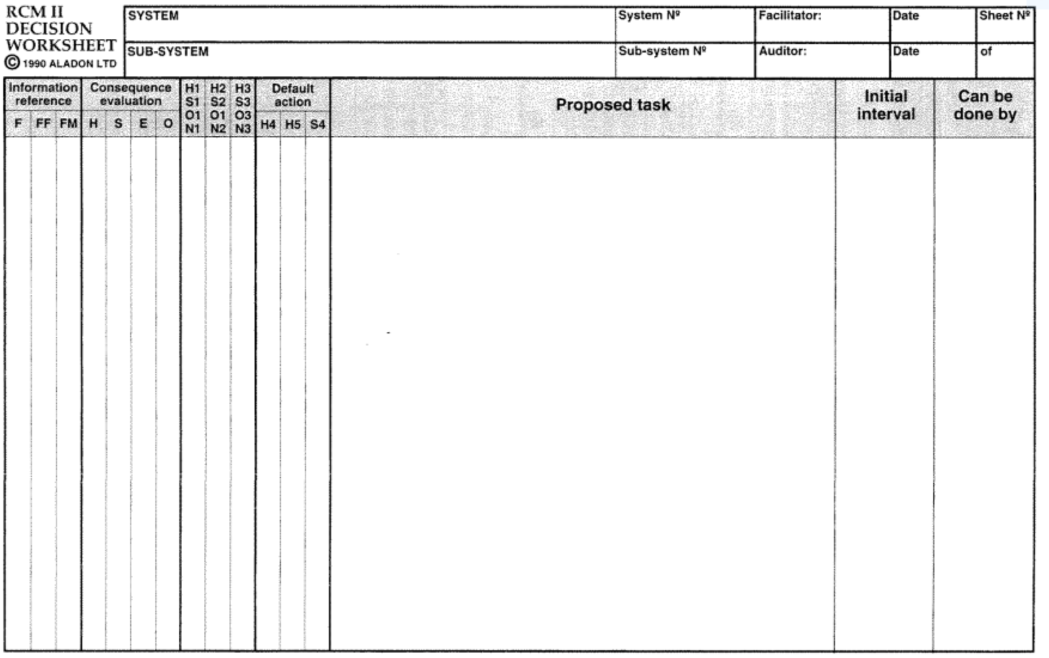
Figure 23 – RCM Decision Diagram (Moubray, 1997)

The decision tree's logic is as follows (Vicente, 2010):

- For hidden failures, a proactive task should be implemented if it reduces the frequency of multiple failure to an acceptable level. If a suitable proactive task cannot be found, then a failure-finding task must be implemented. If a suitable failure-finding task cannot be found and if the multiple failure does not have safety or environmental consequences, a no scheduled maintenance policy can be adopted. Otherwise, a redesign is compulsory;
- For failures with safety or environmental consequences, it is only worth it to implement a proactive task if it can single-handedly reduce the failure risk to an acceptable level. If a suitable proactive task cannot be found, it is mandatory to either redesign the asset, or to make changes in the operation/maintenance activities;

- If a failure has operational consequences, a proactive task is only worth it if its implementation costs for a considered period of time are lower than the sum of the costs of the operational consequences and the repair costs for the same period. In other words, it is based on economic criteria. If the implementation of the proactive task is not economically feasible, a no scheduled maintenance policy can be adopted, and a redesign may be desirable;
- Similarly, if a failure has non-operational consequences, a proactive task is only worth it if its implementation costs for a considered period of time are lower than the repair costs for the same period. If the implementation of the proactive task is not economically feasible, a no scheduled maintenance policy can be adopted. If the repair costs are too high, a redesign may be desirable.

The answers to the questions in the Decision Diagram, as well as proposed tasks and their periodicity are registered in a Decision Worksheet (Figure 24).



RCM II DECISION WORKSHEET © 1990 ALADON LTD	SYSTEM	System Nº	Facilitator:	Date	Sheet Nº
	SUB-SYSTEM	Sub-system Nº	Auditor:	Date	of

Information reference			Consequence evaluation				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default action			Proposed task	Initial interval	Can be done by
F	FF	FM	H	S	E	O				H4	H5	S4			

Figure 24 – Decision Worksheet (Moubray, 1997)

3.3 RCM Analysis Report

After filling in the Information Worksheet and the Decision Worksheet, the facilitator does the RCM analysis report. This document contains all information regarding (Vicente, 2010):

- The definition of the systems in review;
- The members of the RCM review group;
- The identified failure modes;
- The suggested redesigns;
- The Information Worksheet;
- The Decision Worksheet.

This document should be audited by the review group, who will indicate the necessary changes. These changes are then made, and the report is edited.

3.4 Other Documents

After having the RCM report approved, there are five support documents that will help with the implementation of the maintenance tasks that were defined:

- The preventive maintenance requirements;
- The failure diagnosis;
- The list of LRUs;
- The list of redesigns;
- The list of failure modes.

Preventive Maintenance Requirements

Having defined the preventive maintenance tasks and their periodicity, it is necessary to study how these should be organized. There are a limited number of maintenance visits that are made, which means that it is important to accurately and efficiently define which tasks should be performed on each visit.

As different tasks have different periodicity and there is a limited number of visits, it is impossible to have every task be performed exactly at the required periodicity. This means that some tasks are performed more often than needed, and other are performed less often than needed. For each case, a cost-benefit analysis should be performed, to determine if the task should be performed in the nearest visit before or after its needed periodicity (Vicente, 2010).

Failure Diagnosis

The failure diagnosis is a document that contains information about the failure modes whose maintenance policy is “no maintenance planned”. Its main aim is to help identify which failure mode caused a breakdown, as well as being able to contain information on what corrective actions should be put in place and which LRUs should be replaced in order to restore conditions.

List of LRUs

The list of LRUs is an important document for the RCM methodology, because each failure mode is usually associated with a LRU that fails. This means that it is crucial to know every LRU in the system, to be able to detect a potential failure and prevent it, or restore the item’s ability to perform its functions, by accurately repairing or replacing the needed LRUs. This document should also classify each LRU according to the categories identified in Chapter 2.8.1.

List of Redesigns

The list of redesigns is a document that contains all the redesigns to be implemented and serves as a checklist.

List of Failure Modes

The list of failure modes is a document that contains all the failure modes from the RCM analysis.

4 System Analysis

The first step needed in order to implement the RCM methodology was analysing the door systems of the Arco carriages, to understand their operating context. Three different door systems were studied:

- Access doors – The doors used to access the inside of the carriage;
- Intercirculation doors – The doors that connect carriages between each other, located at their ends;
- Hall doors – The doors that separate the vestibule (the area located next to the access doors, as you enter the carriage) from the halls where the seats are located.

4.1 Access Doors

Each carriage is equipped with four access doors, two on each side. These doors have just one sheet and are sliding/fitting doors (they slide to open/close and they fit into the carriage when closed). Figure 25 shows the access doors.

Figure 25 – a) Access Door closed; b) Access Door opened

These doors can be automatically opened by pulsing the opening buttons, located on both the inside and outside of the carriage or through the key lock switch. Figure 26 a) shows the exterior opening button and Figure 26 b) shows the interior opening and closing buttons.

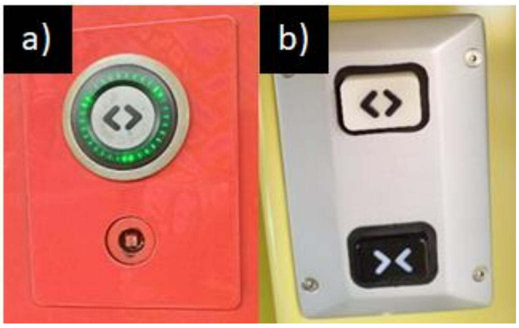


Figure 26 – a) Exterior opening button; b) Interior opening and closing buttons

The door can be automatically closed by pulsing the closing button on the inside, remotely controlled on one of the doors by the ORV ("Operador de Revisão e Vendas" – Review and Sales Operator), or by a signal proportional to speed.

With the key lock switch shown in Figure 27, the ORV is able to close every access door on the train, with the exception of the one where the key lock switch is being actuated, which only closes when the ORV removes the key.

Figure 27 – Key Lock Switch

When the train is moving, the tachymeter shown in Figure 28 sends signals to the door control cards, based on the measured speed. These signals will trigger actions on the door, which will be detailed in Chapter 4.1.2.

Figure 28 – Tachymeter

4.1.1 Access Door Description

Fitted Frame

It contains the sheet, which is made up of 10 mm thick safety glass assembled with a rubber gasket on an aluminum profile, bolted and reinforced with a 1 mm thick stainless-steel panel. The interior is injected with polyurethane foam, to reinforce and soundproof the sheet. The sheet has a "sensitive edge", which allows to trigger the "anti-entrapment" system, in addition to ensuring the sealing of the door. The top part, where the mechanism is attached, is also where the latch is located, as shown in Figure 29.

Figure 29 – Latch

Drive Mechanism

The drive mechanism shown in Figure 30 has an output shaft in the central part. A toothed pulley is mounted on this shaft by a keyway. This pulley gears with a toothed belt. A device with a ball joint attached to the toothed belt allows, by means of the guiding arm, the dragging of the sheet. Inside the two cylinders (one on each side of the central body) are the pistons, which are connected to each other by means of a rack, which passes through the transverse hole of the central body. This central body houses a pinion that gears with the rack and has an output shaft with a keyway to fix the toothed pulley. Two tension rollers, located on both sides of the toothed pulley, allow adjustment of the belt's tension. At each end of the mechanism there is a return pulley, geared with the toothed belt.

Figure 30 – Drive Mechanism

Drag Mechanism

The excitation of the opening electro valve allows it to inflate air in the direction of opening the door. The movement of the piston of one of the cylinders moves the rack, which then gears with the pinion and causes the rotation of the toothed pulley, while the other cylinder allows the escape of air, thus helping to support and balance tensions in the dragging movement. This rotation of the toothed pulley moves the toothed belt, thus allowing the sheet to be dragged and the door to be opened. When the closing electro valve is excited, the door closes.

Pneumatic Set

It consists of two electro valves, two pneumatic cylinders, two exhaust valves, two flow regulators, two pressure switches and piping.

Stabilizer

The stabilizer shown in Figure 31 supports the sheet in a vertical position, through two guides, an upper one and a lower one. It consists of a body with an axle equipped with two pinions and two supports assembled with bearings. These pinions gear in the two racks, an upper one and a lower one.

Figure 31 – Stabilizer

Safety Mechanism

Each platform has a door release handle that depressurizes the pneumatic circuits of the two doors in the platform by turning them 90° clockwise. This handle is connected to an alert buzzer. The door can be reset by turning the handle 180° counterclockwise, followed by a 90° clockwise rotation, thus returning it to the initial position, shown in Figure 32.

Figure 32 – Door Release Handle

Moving Step

The moving step is articulated with the drive mechanism through an endless screw, shown in Figure 33. When the door opens, the rotation of the return pulley causes the screw to rotate, which lowers the screw nut and extends the step. When the door closes, the rotation of the screw raises the screw nut and hides the step.

Figure 33 – Endless Screw

4.1.2 Access Door Operation

Opening

The door can be opened using the interior or exterior opening buttons, with the train stopped or moving at speeds below 7 km/h. Actuation of the key lock switch causes the door on which it was actuated to be opened. The detection of an obstacle during the closing movement via the sensitive edge (Figure 34) also causes the door to open.

When there is a collision between the door and an obstacle, there is a shift in pressure on the sensitive edge, that is detected by the pressure switch, which sends a signal do the control card, that re-opens the door.

Figure 34 – Sensitive Edge

At speeds above 7 km/h, excitation of the electromagnet shown in Figure 35 causes the mechanical blocking of the interior opening button, preventing its use.

Figure 35 – Electromagnet

At speeds above 15km/h, actuating the key lock switch does not cause the door to open, as there is an electrical inhibition of the controls, on the control card.

In the absence of electrical supply, but with the presence of pneumatic pressure, it is possible to open the door, by isolating it through the pneumatic isolation block and forcing the door open. If it is not possible to perform the pneumatic isolation of the door through this block, the pneumatic isolation of the platform can be performed using the pneumatic isolation faucet of the platform doors, located below the door. Figure 36 shows the pneumatic isolation block and the manual isolation block. The manual isolation block is used to manually be able to inhibit the door's electrical controls, while also mechanically blocking it in the closed position, stopping it from being opened.

Figure 36 – Exterior Blocks

Closing

With the train stopped or at speeds below 7km/h, the door can be closed using the interior closing button. Actuation of the key lock switch causes all doors to close, with the exception of the door on which it was actuated, which only closes when the ORV removes the key.

At speeds above 7 km/h, the door closes automatically, unless the key lock switch has been actuated.

At speeds above 15km/h, the door closes automatically, even if the key lock switch has been actuated.

When there is no supply voltage, the electro valves are no longer excited and the door closes. If any of the electro valves short-circuit while the door is closed, the door remains closed.

4.2 Intercirculation Doors

On each end of the carriage, there is an intercirculation door, connecting it to the next carriage. These are sliding doors with two sheets, and their automatic opening is achieved by actuating a movable handle. Closing is also automatic, by timed pneumatic command. Figure 37 shows an intercirculation door.

Figure 37 – Intercirculation Door

These doors can be blocked either in the opened or closed position, from the inside or the outside, using the manual blocks shown in Figure 38.

Figure 38 – Manual Block

4.2.1 Intercirculation Door Description

Suspension Mechanism

The suspension mechanism has a guide on which the attachment points of the mechanism to the carriage's structure are located. On the rail of this guide, the four suspension carts move, two for each sheet. The sheets work suspended from these carts through the respective suspension parts. The suspension carts are equipped with eccentrics, shown in Figure 39, whose rotation raises or lowers the suspension parts. This difference in height allows the adjustment of the parallelism between the sheet and the carriage's structure.

Figure 39 – Eccentric

Drag Mechanism

The drag mechanism shown in Figure 40 is made up of a double-acting pneumatic cylinder, fixed on one side to the guide and on the other to one of the suspension carts. The movement of the cylinder's rod causes the movement of the suspension carts of one of the sheets, which transmit the movement to the carts of the other sheet through the belt.

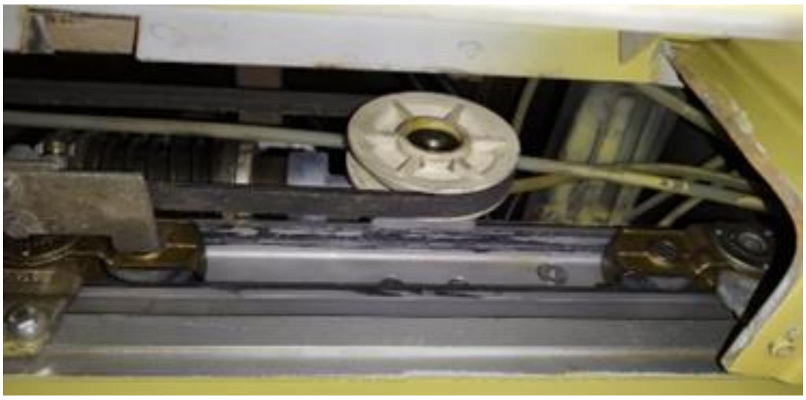


Figure 40 – Drag Mechanism

This allows the door's movement, as it slides on its lower guide, shown in Figure 41.

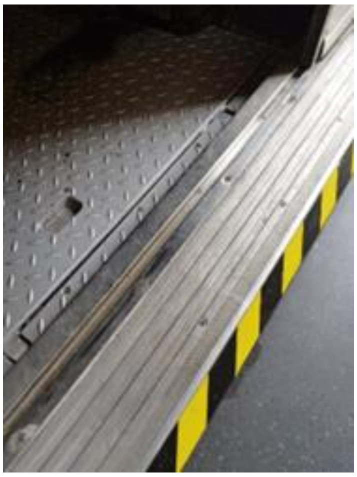


Figure 41 – Lower Guides

Sheets

Each sheet has a rubber gasket and a lower guiding system made up of two soundproof polyethylene tracks fixed to the lower profile. On each side of one of the sheets there is a movable handle that allows the door to be opened.

Safety Mechanism

On one side of the door, a door release handle (Figure 42) is installed at the top, which depressurizes the drive circuit. If it is not possible to perform the pneumatic isolation of the door using this handle, the pneumatic isolation of the platform can be performed using the pneumatic isolation faucet of the platform doors.

Figure 42 – Door Release Handle

When the door is at the front or rear of the train, it must be locked in the closed position, by actuating the manual block (Figure 38). The opening of the door is also limited by a safety mechanism that prevents its opening if the passage flap is raised. Figure 43 shows the passage flap in the raised position. When the flap is raised, a pin is inside the flap's groove, which prevents the door's opening.

Figure 43 – Passage Flap (in raised position)

4.2.2 Intercirculation Door Operation

Opening

The door can be opened by using one of the movable handles located on both sides of one of the sheets. This action causes an actuation strip to rise, which causes the command valve to be actuated. The command valve activates the pneumatic cylinder, causing the door to open. The door can also be manually opened, after pneumatically isolating it.

Closing

The door is closed by timed pneumatic action. The timing is given by the flow regulator. The closing device is designed so that the sheets re-open automatically if:

- They encounter an obstacle. Safety is achieved as follows:
  - As soon as an obstacle interrupts the course of the piston, the cylinder, which is floating, moves because there is an imbalance between the spring and the pneumatic pressure, causing the door to re-open.
- If a passenger presses the movable handle while the door is closing, the actuation strip raises, activating the command valve again, which activates the cylinder and causes the door to re-open.

4.3 Hall Doors

The hall doors are sliding doors, with one sheet. They can be automatically opened by cutting the beam of light projected by the side photocell or through the upper diffused photocell. The door is closed by action of the electric motor, timed by the control card. Figure 44 a) shows the side photocell, Figure 44 b) shows its reflector and Figure 44 c) shows the upper diffused photocell.

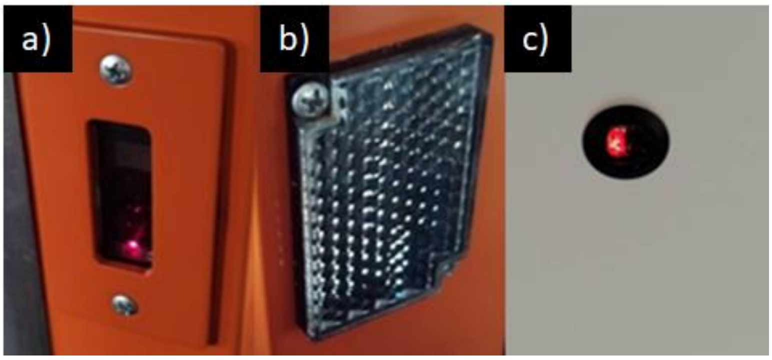


Figure 44 – a) Side Photocell; b) Reflector; c) Upper Diffused Photocell

4.3.1 Hall Door Description

Suspension Mechanism

The suspension mechanism has a guide on which the attachment points of the mechanism to the carriage's structure are located. On the rail of this guide, the two suspension carts move. The sheets work suspended from these carts through the respective suspension parts. The suspension carts are equipped with eccentrics, shown in Figure 45, whose rotation raises or lowers the suspension parts. This difference in height allows the adjustment of the parallelism between the sheet and the carriage's structure.

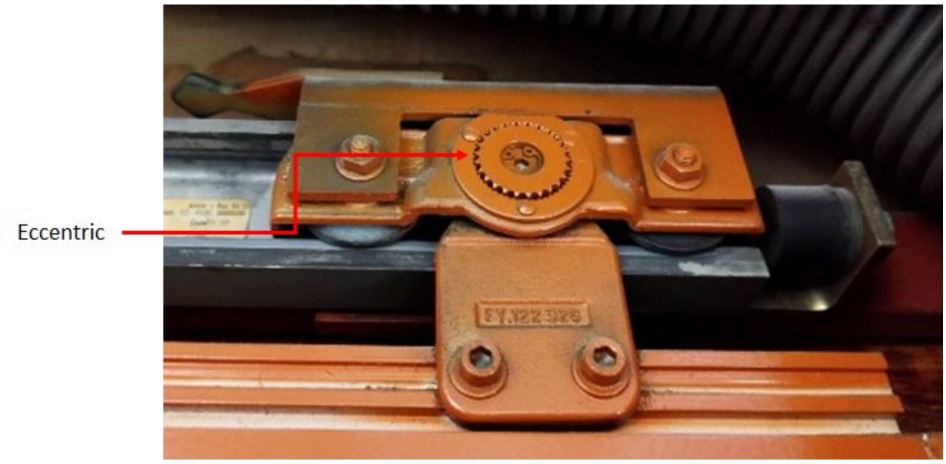


Figure 45 – Eccentric

Drag Mechanism

The drag mechanism consists of an electric motor and a toothed pulley geared with a toothed belt that allows the transmission of movement to the suspension carts. This allows the door's movement. Figure 46 shows the toothed pulley and belt.

Figure 46 – Pulley and Belt

Sheet

The sheet shown in Figure 47 is made up of a glass assembled with a rubber gasket on an aluminum alloy profile. The sheet is equipped with a frontal rubber gasket that ensures the sealing of the door.

Figure 47 – Sheet

Safety Mechanism

On each door is installed a door lock button, shown in Figure 48, which makes it possible to electrically isolate the door.

Figure 48 – Door Lock Button

4.3.2 Hall Door Operation

Opening

The door can be automatically opened by cutting the beam of light projected by the side photocell or through the upper diffused photocell. In this way, the motor starts the movement in the opening direction, transmitting this movement to the toothed pulley and successively to the toothed belt, which in turn causes the movement of the suspension carts, opening the door.

Closing

After eight seconds (four seconds of opening the door plus four seconds of holding the door in the opened position), the door closes. If an object prevents the closing movement, an overcurrent is detected by the control card, which gives the motor an order to re-open the door.

5 Application of the RCM Methodology to the Arco Carriages

Having analysed the systems, the application of RCM to the Arco carriages was divided into several steps, which will be detailed in this chapter. The order that they are presented in is the same order that they should have been fulfilled in, although there was some overlap between some steps, as there was a need for iteration in order to correct and perfect some aspects throughout the course of the work performed.

5.1 RCM Review Group

The seven basic questions cannot be answered by a single person, there is a need for a multidisciplinary team to guarantee that different points of view are considered in each answer (Vicente, 2010; Aleluia, 2020).

At CP, each RCM review group is comprised of:

- A facilitator;
- An operations supervisor;
- An operator;
- A maintenance supervisor;
- A maintenance worker;
- An external specialist.

Figure 49 shows the RCM review group that carried out the RCM analysis of the door systems of the Arco carriages.

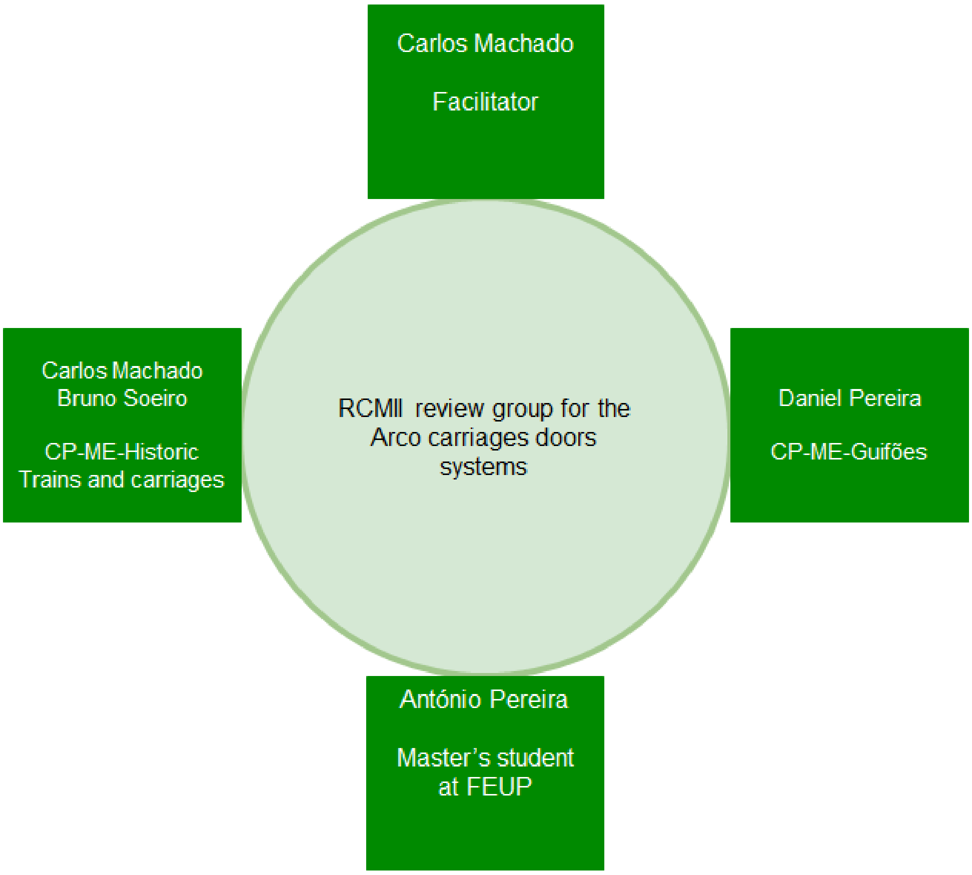


Figure 49 – RCM Review Group

5.2 System Boundaries and List of LRUs

Having assembled the team, the next step was to define the systems' boundaries, in order to know exactly what to include in the analysis, excluding everything that was not relevant for the intended purposes. Figures 50, 51 and 52 show the boundaries that were defined for the access, intercirculation and hall doors, respectively.

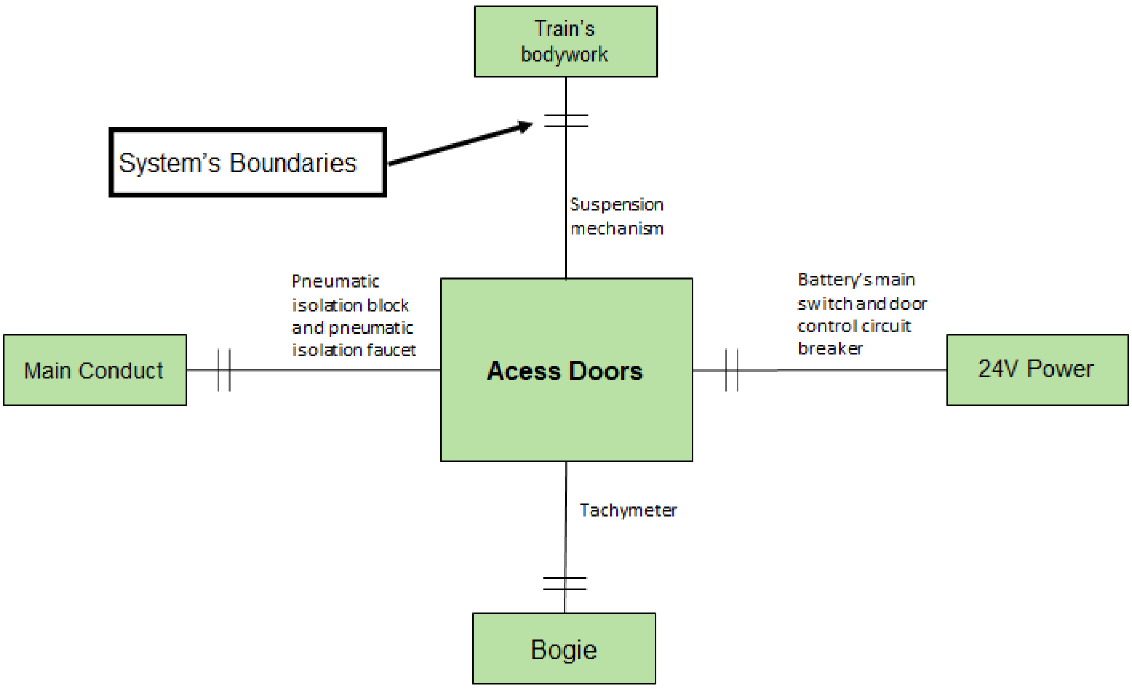


Figure 50 – Acess Door Boundaries

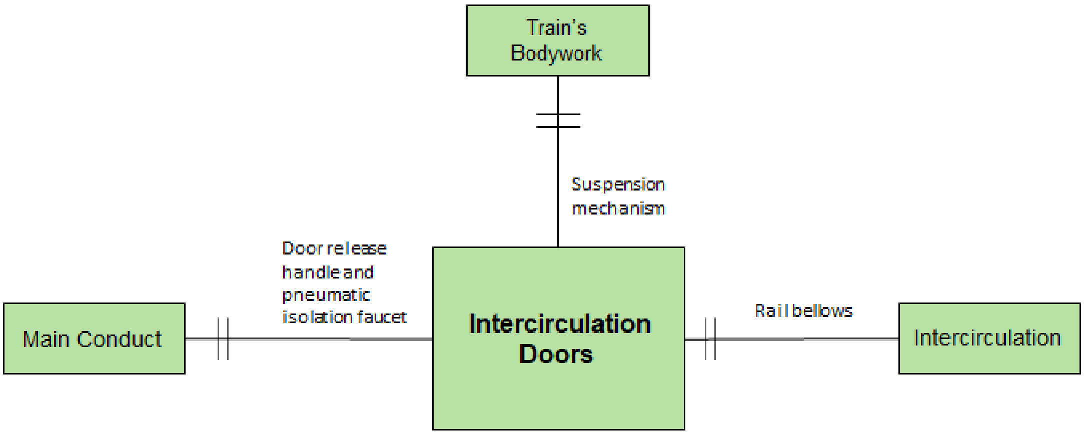


Figure 51 – Intercirculation Door Boundaries

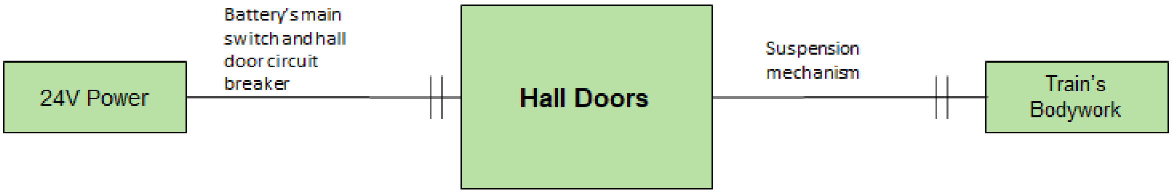


Figure 52 – Hall Door Boundaries

In Figures 50, 51 and 52, if the text describing the boundary is "inside" the boundary, it is included in the RCM Analysis and if it is "outside", it is excluded. For example, in Figure 52 the battery's main switch and the hall door circuit breaker are "outside" of the boundary with the 24V Power supply, meaning they were not included in the analysis, whereas the suspension mechanism is "inside" the boundary with the train's bodywork, meaning it is included in the analysis.

Afterwards, the list of LRUs was made based on documentation about the Arco carriages, meetings with the maintenance/operation staff and on direct interaction and analysis of the door systems. There were identified 141 significant LRUs for the Access doors, 48 for the Intercirculation doors and 26 for the Hall doors, totaling a number of 215 LRUs. These were then attributed references, to facilitate their identification.

In this document, it is also needed to classify each LRU, as mentioned in Chapter 2.8.1. Due to lack of experience with this equipment, some LRU could not be accurately classified, given the fact that their failure did not occur from the time the Arco carriages were put into service under CP until the time where the RCM analysis was completed. In these cases, it was considered that the LRUs were not repairable, and with future experience, it will be possible to change this classification, if it is verified that the LRU in question is repairable.

5.3 FMEA and Information Worksheet

The Arco carriages were only put into service in July of 2022, and most failures were due to human error, given the lack of training and experience there was regarding this equipment. This meant that the failure and breakdown history of the equipment had little use in helping with the FMEA analysis. The FMEA analysis was mostly based on meetings with maintenance/operation staff and on mechanical tests performed on the doors throughout the first months of work, but some information present on documentation was also used. With this information, it was possible to create the Information Worksheets, containing all functions, functional failures, failure modes and failure effects for each door system.

In this analysis, there were identified:

- 27 functions:
    - 14 for the Access doors;
    - 9 for the Intercirculation doors;
    - 4 for the Hall doors.
- 33 functional failures:
    - 18 for the Access doors;
    - 9 for the Intercirculation doors;
    - 6 for the Hall doors.
- 171 failure modes:
    - 97 for the Access doors;
    - 42 for the Intercirculation doors;
    - 32 for the Hall doors.

This information is documented in the Information Worksheets. An excerpt of the Access Door's Information Worksheet can be consulted in Annex B1.

5.4 Decision Worksheet

Using the Information Worksheets and the Decision Diagram, it was possible to create the Decision Worksheets. These documents contain the proposed maintenance strategies to be implemented, as well as their periodicities. An excerpt of the Access Door's Decision Worksheet can be consulted in Annex B2.

The periodicity of each task had to be determined based on the existing maintenance visits already put in place, since there was no possibility to establish maintenance visits exclusively for the door systems. The only historical information regarding the needed maintenance tasks and their periodicity was the maintenance done by RENFE to these carriages, which was not based on the RCM methodology. These facts mean that the periodicity of each maintenance strategy was determined intuitively, based on analogies with similar equipment, as a first approach. With the experience that will be gained throughout time, it is imperative to adapt the periodicities as is seen adequate. Chapter 5.5 goes more in depth about these periodicities.

The results of the analysis of the consequences of each failure mode are shown in Figure 53 and Table 4.

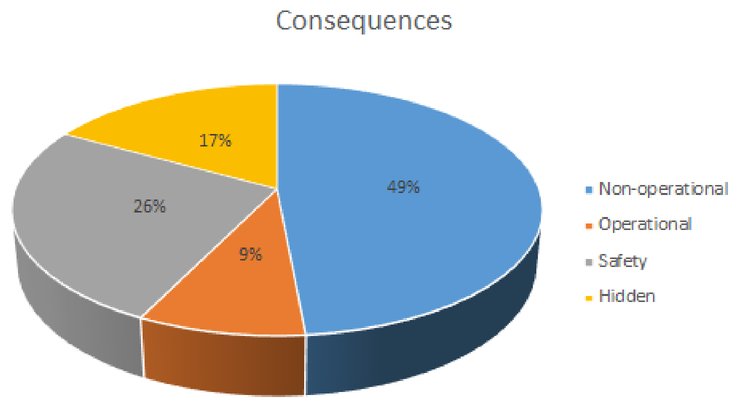


Figure 53 – Consequences

The most common consequence is “Non-operational”, with almost half of the failure modes being identified as such. At CP, consequences are considered operational if the failure mode can cause delays bigger than 5 minutes, which accounts for about 12% of failure modes. There were identified no failure modes with environmental consequences.

Table 4 – Consequences

Consequence	Number of failure modes	Percentage
Non-operational	83	48.54%
Operational	15	8.77%
Safety	44	25.73%
Environmental	0	0%
Hidden	29	16.96%

The maintenance strategies proposed are shown in Figure 54. About one third of failure modes were attributed a “No Maintenance Planned” strategy, as no suitable proactive tasks were found, and there were no safety or environmental consequences associated to each of them.

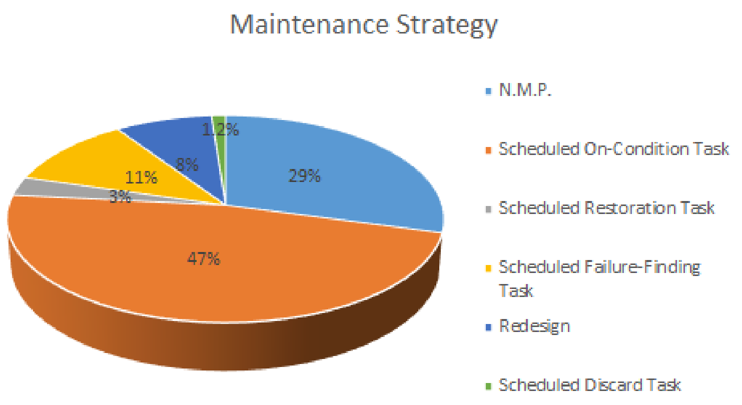


Figure 54 – Maintenance Strategy

Table 5 shows the maintenance strategy proposed, relative to the consequence of the failure modes.

Table 5 – Maintenance Strategy

Consequence	Decision	Number of Tasks	Percentage
Hidden	No maintenance planned	3	1.75%
	Scheduled on-condition	7	4.09%
	Scheduled restoration	0	0%
	Scheduled discard	0	0%
	Scheduled failure-finding	19	11.11%
Safety	Scheduled on-condition	28	16.37%
	Scheduled restoration	0	0%
	Scheduled discard	2	1.17%
	Combination of tasks	0	0%
	Redesign	14	8.19%
Operational	Scheduled on-condition	12	7.02%
	Scheduled restoration	1	0.58%
	Scheduled discard	0	0%
	No maintenance planned	2	1.17%
Non-operational	Scheduled on-condition	34	19.98%
	Scheduled restoration	4	2.34%
	Scheduled discard	0	0%
	No maintenance planned	45	26.32%
Total		171	100%

5.5 RCM Report, Maintenance Plan, Work Instructions and Other Documents

RCM Report

With the information detailed throughout Chapter 5, the RCM report was made. Afterwards it was audited, edited and concluded. This report can be consulted in Annex C.

Maintenance Plan

The maintenance plan was made, with the information from the Decision Worksheets. It contains the maintenance tasks to be performed, as well as the maintenance visit in which they should be performed. There are six maintenance visits:

- ES (“Exame de Segurança” – Safety Exam) – Performed every 12 500 km;
- EI (“Exame Intercalar” – Mid-term Exam) – Performed every 62 500 km;
- V3 (Level 3 Maintenance Visit) – Performed every 125 000 km;
- V2 (Level 2 Maintenance Visit) – Performed every 250 000 km;
- V1 (Level 1 Maintenance Visit) – Performed every 500 000 km;
- R (Revision) – Performed every 1 000 000 km.

Figures 55 and 56 show the timeframe of the maintenance visits.

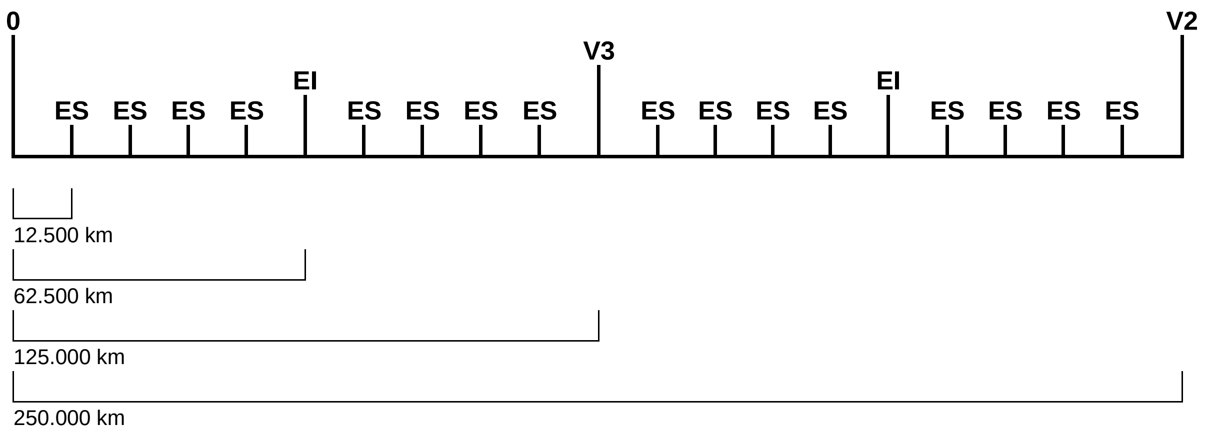


Figure 55 – Visits ES, EI, V3 and V2

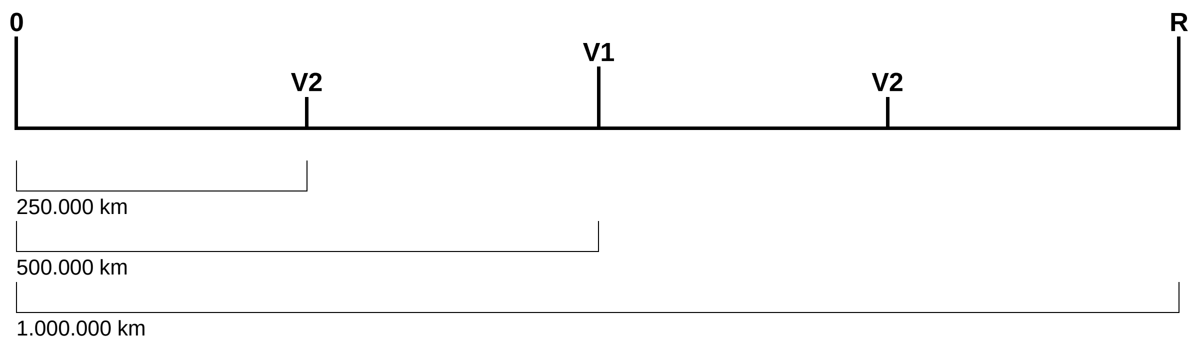


Figure 56 – Visits V2, V1 and R

Table 6 shows the number of tasks performed in each visit. Visit R has the same number of tasks as the previous visit, V1. This is because there were no tasks that were considered to be needed only every 1 000 000 km, and there was not a possibility to do maintenance visits exclusively for the doors systems. This means that in practical terms, there are only 5 maintenance visits for the doors systems, at the point of this first analysis, and that in these systems, every Visit R is the same as a Visit V1. In the future, with the experience gained, it can be possible to attribute certain tasks just to Visit R, every 1 000 000 km.

As mentioned, these periodicities were attributed based on intuition and analogy with similar equipment. Given the fact that these carriages only served for about 83 000 km under CP, only 5 Visit ES and 1 Visit EI were made, and all of these visits were conducted before the RCM analysis was completed. This means that within the timeframe of the work performed, it was not yet possible to start adjusting the periodicity of tasks in order to have the maintenance visits be as efficient as possible.

Table 6 – Maintenance Visits

Visit	Number of Tasks	Percentage
ES	12	11.54%
EI	16	15.38%
V3	49	47.11%
V2	92	88.46%
V1	104	100%
R	104	100%

Work Instructions

The work instructions are documents that go in depth about how to perform each maintenance task. There were developed six work instructions, one for each maintenance visit.

The maintenance plan can be consulted in Annex B3 and the ES visit’s work instructions can be consulted in Annex B4.

Other Documents

The preventive maintenance requirements document was not made. Due to the lack of experience, there was not clear criteria needed to define which tasks should be performed in each maintenance visit. This document should be made in the future, as more experience is gained and criteria begins to be defined.

The list of redesigns document was not made, given the fact that despite 14 failure modes required redesigns, only 2 redesigns were suggested, as they were applicable for all 14 failure modes. The first redesign should improve the signalization to the operating crew about the functioning state of the doors, to eliminate the possibility of the train starting its movement without blocking all the access doors. The second redesign should create a redundant “anti-entrapment” system for the access doors.

6 Result Analysis

At CP there was no concrete quantification of the needed indicators, such as reliability, availability and MTBF. Consequently, there are no quantifiable results to show the impact of the application of the RCM methodology.

There are, however, several anticipated benefits that come from this implementation, such as:

- Reduced frequency of failures and breakdowns;
- Increased equipment availability;
- Increased equipment reliability;
- Decreased downtimes;
- Decreased amount of safety issues;
- Improved service quality.

It is important to begin quantifying and keeping track of the needed indicators, to ensure the effectiveness of future RCM analysis and also to help the decision-making process. As mentioned before, the periodicities of the maintenance tasks can and should be changed, based on the experience that will be gained over time. Having access to these indicators is a way to determine whether the changes made are being effective or not. Besides that, as failures happen, there are more opportunities to analyse each LRU, in order to update their classification, making it more accurate.

It is important to note that in the 10 months that the Arco carriages have been in service under CP, they only travelled about 83 000 km. Assuming this rate is continued in the coming years, this means that it would take about another 9 years of service before reaching the first Visit R. This means that making accurate changes to the established maintenance activities is a long process, and that the documentation of the information gathered from this RCM analysis is crucial. Another important fact is that the Arco carriages are not a new equipment, as they served under RENFE for a number of years, and there is no documentation about the history of the maintenance performed. This means that an LRU that fails at 15 000 km under CP for example, has for certain had a useful life of much more than that, so the process of documenting the useful life of each different LRU and establishing the P-F curves should not start on the first time each LRU fails, but on the first time each new LRU (assembled under CP) fails.

7 Conclusions and Further Work

In this dissertation, the RCM methodology was explored and applied to the analysis of door systems in Arco carriages. The aim was to optimize maintenance procedures and improve the reliability and availability of the door systems.

The analysis of the door systems revealed important insights into their functions, functional failures, failure modes and failure effects. The access doors, intercirculation doors, and hall doors were studied separately to understand their unique characteristics and maintenance requirements. The Information Worksheet facilitated the documentation of this information.

The RCM Decision Diagram served as a valuable tool in selecting the most suitable maintenance tasks for each failure mode. The Decision Worksheet facilitated the documentation of the proposed maintenance tasks.

Additionally, the other support documents provided guidance and information for organizing and executing the maintenance tasks that were defined.

In conclusion, the application of the RCM methodology to the door systems in Arco carriages has provided valuable insights regarding both the operational context of this equipment and for optimizing maintenance practices. By implementing the proposed maintenance strategies, it is expected that the reliability and availability of the door systems will improve. It is important to continue analysing the maintenance strategies as more experience is gained, in order to continuously improve them. It is also important to begin quantifying and keeping track of the needed indicators, both for the improvement of the RCM analysis performed and for future RCM analysis.

This dissertation can serve as a base for further enhancements upon the maintenance procedures of the Arco carriages' door systems, as well as a reference on how to perform future RCM analyses. A future RCM analysis that was proposed was to the Bogie system of the Arco carriages.

References

Aleluia, J. M. (2020). *Aplicação da metodologia RCM II aos sistemas de portas e freio do veículo EuroTram.*

Almada-Lobo, B. (2014). *Reliability Block Diagrams.*

Arunraj, N., & Maiti, J. (2006). *Risk-based maintenance—Techniques and applications.*

Barbosa, F. M. (2018). *Introdução à fiabilidade de sistemas.*

BS. (2010). *BS EN 13306:2010 - Maintenance terminology.*

Dinmohammadi, F., Alkali, B., Shafiee, M., Bérenguer, C., & Labib, A. (2016). *Risk Evaluation of Railway Rolling Stock Failures Using FMECA Technique: A Case Study of Passenger Door System.*

Falck, A. (2010). *Guideline Execution of FMEA/FMECA.*

Heap, H. F., & Nowlan, F. S. (1978). *Reliability-Centered Maintenance.*

Hoyland, A., & Rausand, M. (2009). *System reliability theory: models and statistical methods.*

IPQ. (2007). *NP EN 13306:2007. Terminologia da manutenção.*

Jones-Lee, M., & Aven, T. (2011). *ALARP—What does it really mean?*

Leitão, A., & Guimarães, L. (2019). *Event Tree Analysis.*

Leitão, A., & Guimarães, L. (2019). *Fault Tree Analysis.*

Leitão, A., & Guimarães, L. (2019). *FMECA Failure modes, effects and criticality analysis.*

Leitão, A., Almada-Lobo, B., & Guimarães, L. (2019). *TPM - Total Productive Maintenance.*

Mansor, M., Ohsato, A., & Sulaiman, S. (2012). *Knowledge Management For Maintenance Activities in the Manufacturing Sector.*

Moubray, J. (1997). *Reliability Centered Maintenance.*

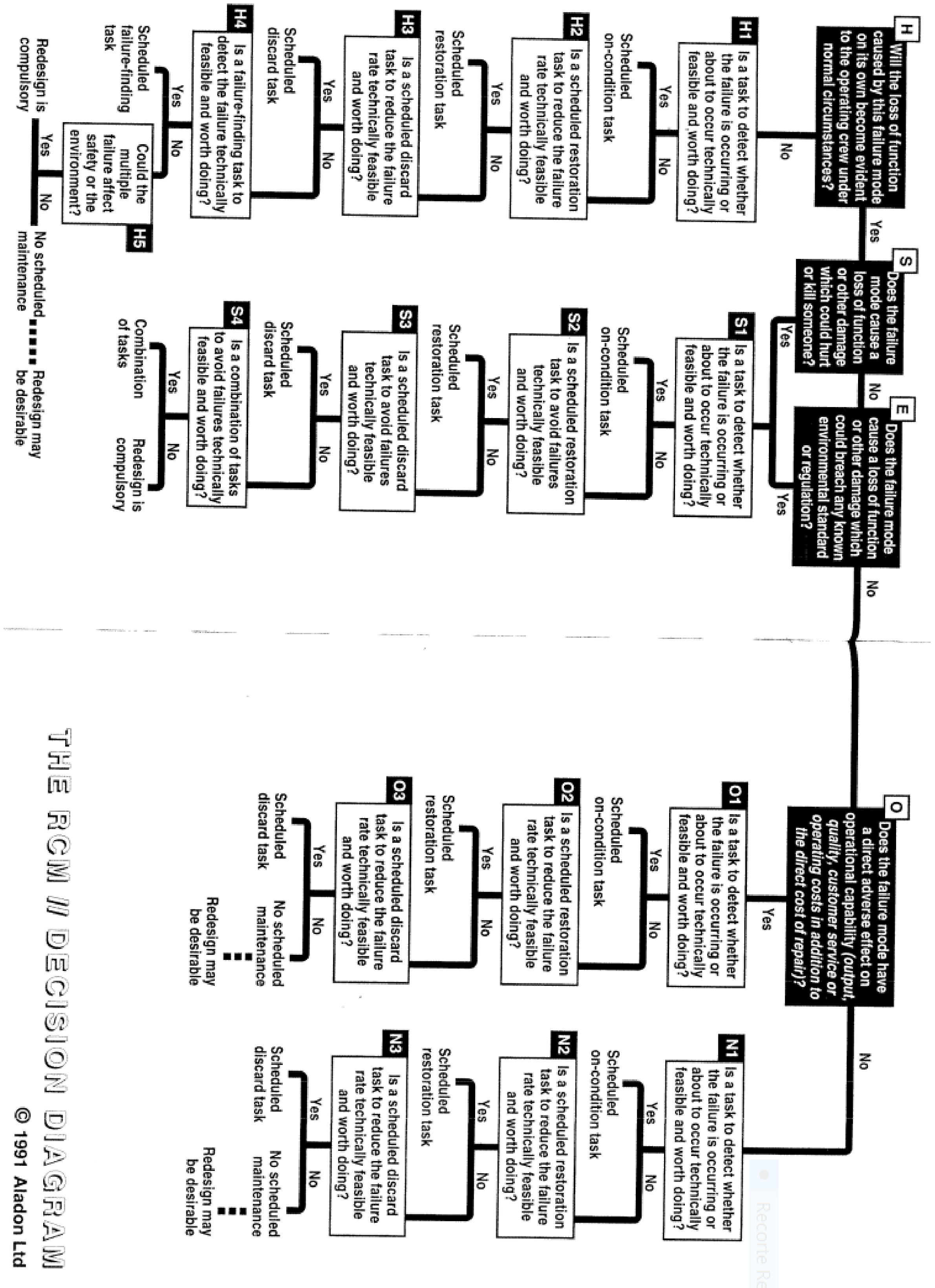
SAEJA1012. (2002). *A Guide to the Reliability-Centered Maintenance (RCM).*

Vicente, R. (2010). *Implementação da metodologia RCM II na CP e na EMEF.*

ANNEX A: FIGURES WITH ENHANCED CLARITY

RCM II INFORMATION WORKSHEET © 1996 ALADON LTD	SYSTEM: 5 MW Gas Turbine	SYSTEM Nº 216 - 05	Facilitator: N Smith	Date 07 - 07 - 1996	Sheet Nº 1
	SUB-SYSTEM: Exhaust System	SUB-SYSTEM Nº 216 - 05 - 11	Auditor: P Jones	Date 07 - 08 - 1996	of 3

	FUNCTION		FUNCTIONAL FAILURE (Loss of function)		FAILURE MODE (Cause of failure)	FAILURE EFFECT (What happens when it fails)
1	To channel all the hot turbine gas without restriction to a fixed point 10m above the roof of the turbine hall	A	Unable to channel gas at all	1	Silencer mountings corroded away	Silencer assembly collapses and falls to bottom of stack. Back pressure causes the turbine to surge violently and shut down on high exhaust gas temperature. Downtime to replace silencer up to four weeks
		B	Gas flow restricted	1	Part of silencer falls off due to fatigue	Depending on nature of blockage, exhaust temperature may rise to where it shuts down the turbine. Debris could damage parts of the turbine. Downtime to repair silencer 4 weeks.
		C	Fails to contain the gas	1	Flexible joint holed by corrosion	The joint is inside turbine hood, so leaking exhaust gases would be extracted by the hood extraction system. Fire and gas detection equipment inside hood is unlikely to detect an exhaust gas leak, and temperatures are unlikely to rise enough to trigger the fire wire. A severe leak may cause gas demister to overheat, and may also melt control wires near the leak with unpredictable effects. Pressure balances inside the hood are such that little or no gas is likely to escape from a small leak, so a small leak is unlikely to be detected by smell or hearing. Downtime to replace joint up to 3 days
				2	Gasket in ducting improperly fitted	Gas escapes into turbine hall and ambient temperature rises. Hall ventilation system would expel gases through louvres to atmosphere, so concentration of gases is unlikely to reach noxious levels. A small leak at this point may be audible. Downtime to repair up to 4 days
				3	Upper bellows holed by corrosion	The upper bellows are outside turbine hall, so a leak here discharges to atmosphere. Ambient noise levels may rise. Downtime to repair up to 1 week.
		D	Fails to convey gas to a point 10 m above roof	1	Exhaust stack mounting bolts shear due to rust	Exhaust stack is likely to be held up by the guy ropes for a while before it falls over, but would lean at at an angle. If it did fall over, there is a high probability that it could crush a structure containing people. Downtime to repair a few days to several weeks.
				2	Exhaust stack blown over in gale	The stack structure is designed to withstand winds up to 200 mph, so it is only likely to fall over in a gale if the guy ropes were already weakened, perhaps by corrosion. If it went, it could be blown onto an accommodation module. Downtime to repair up to several weeks.
2	To reduce exhaust noise level to ISO Noise Rating 30 at 50 metres	A	Noise level exceeds ISO Noise Rating 30 at 50 m	1	Silencer material retaining mesh corroded away	Most of the material would be blown out, but some might fall to the bottom of stack and obstruct the turbine outlet, causing high EGT and possible turbine shudown. Noise levels would rise gradually. Downtime to repair about 2 weeks.
				2	Duct leaks outside turbine hall	.... etc


H
Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?
No
Yes
H1
Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?
Scheduled on-condition task
H2
Is a scheduled restoration task to reduce the failure rate technically feasible and worth doing?
Scheduled restoration task
H3
Is a scheduled discard task to reduce the failure rate technically feasible and worth doing?
Scheduled discard task
H4
Is a failure-finding task to detect the failure technically feasible and worth doing?
Scheduled failure-finding task
H5
Could the multiple failure affect safety or the environment?
Redesign is compulsory
No scheduled maintenance
Redesign may be desirable
S
Does the failure mode cause a loss of function or other damage which could hurt or kill someone?
S1
Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?
Scheduled on-condition task
S2
Is a scheduled restoration task to avoid failures technically feasible and worth doing?
Scheduled restoration task
S3
Is a scheduled discard task to avoid failures technically feasible and worth doing?
Scheduled discard task
S4
Is a combination of tasks to avoid failures technically feasible and worth doing?
Combination of tasks
Redesign is compulsory
E
Does the failure mode cause a loss of function or other damage which could breach any known environmental standard or regulation?
O
Does the failure mode have a direct adverse effect on operational capability (output, quality, customer service or operating costs in addition to the direct cost of repair)?
O1
Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?
Scheduled on-condition task
O2
Is a scheduled restoration task to reduce the failure rate technically feasible and worth doing?
Scheduled restoration task
O3
Is a scheduled discard task to reduce the failure rate technically feasible and worth doing?
Scheduled discard task
No scheduled maintenance
Redesign may be desirable
N1
Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?
Scheduled on-condition task
N2
Is a scheduled restoration task to reduce the failure rate technically feasible and worth doing?
Scheduled restoration task
N3
Is a scheduled discard task to reduce the failure rate technically feasible and worth doing?
Scheduled discard task
No scheduled maintenance
Redesign may be desirable
THE RCM II DECISION DIAGRAM
© 1991 Aladon Ltd

ANNEX B: RELEVANT DOCUMENTATION

ANNEX B1 – ACCESS DOOR INFORMATION WORKSHEET EXCERPT

Função	Falha Funcional	Modo de Falha	Efeito de Falha
1 – Permitir a abertura ou fecho automático da porta em 4 segundos (± 1 segundo) mediante atuação dos botões interiores (abertura e fecho) ou exterior (abertura), emitindo sinal acústico durante o movimento de fecho da porta.	A – Incapaz de permitir a abertura ou fecho automático da porta em 4 segundos (± 1 segundo) mediante atuação dos botões interiores (abertura e fecho) ou exterior (abertura).	1 – Bobine da eletroválvula EAP/ECP em falha por interrupção.	O funcionamento da eletroválvula induz ciclos de fadiga térmica na sua bobine, o que pode originar a interrupção da mesma. A falha por interrupção da bobine da eletroválvula impede a abertura automática da porta. O ORV deve isolar eletricamente a porta na quadra de isolamento manual. Caso seja necessária a abertura da porta, o ORV deve isolar pneumaticamente a porta na quadra de isolamento pneumático, permitindo a sua abertura manual. A reposição de condições implica a substituição da eletroválvula, podendo demorar 0,75h/1H.

ANNEX B2 – ACCESS DOOR DECISION WORKSHEET EXCERPT

Informações Referência			Consequência Avaliação				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default Tarefas			Tarefa Proposta	Intervalo Inicial	Pode ser feito por
F	de	MF	H	S	E	O				H4	H5	S4			
1	A	1	S	N	N	N	N	N	N				N.M.P.		
1	A	2	S	N	N	N	N	N	N				N.M.P.		
1	A	3	S	N	N	N	S						Inspeção auditiva em busca de fugas de ar.	12 500	EM
1	A	4	S	S			S						Inspeção auditiva em busca de fugas de ar.	12 500	EM
1	A	5	S	S			S						Inspeção visual ao estado da fixação dos cilindros.	250 000	EM
1	A	6	S	S			N	N	S				Lubrificar dos cilindros.	250 000	EM
1	A	7	S	S			S						Inspeção auditiva em busca de fugas de ar.	12 500	EM
1	A	8	S	S			S						Inspeção auditiva em busca de fugas de ar.	12 500	EM
1	A	9	S	S			S						Inspeção auditiva em busca de fugas de ar.	12 500	EM
1	A	10	S	S			S						Verificar temporização da abertura/fecho da porta.	125 000	EM
1	A	11	S	S			S						Verificar temporização da abertura/fecho da porta.	125 000	EM
1	A	12	S	S			S						Verificar temporização da abertura/fecho da porta.	125 000	EM
1	A	13	S	S			N	N	N			N	Deverá ser efetuado um reprojeto que evidencie mais rapidamente à tripulação o estado do funcionamento das portas para diminuir a probabilidade de seguimento da marcha sem o bloqueio de todas as portas.		
1	A	14	S	S			N	N	N			N	Deverá ser efetuado um reprojeto que evidencie mais rapidamente à tripulação o estado do funcionamento das portas para diminuir a probabilidade de seguimento da marcha sem o bloqueio de todas as portas.		

ANNEX B3 – MAINTENANCE PLAN

	Portas interiores ► Portas de Intercomunicação	**ES**	**EI**	**V3**	**V2**	**V1**	**R**
082_001	Verificar o funcionamento das portas de intercomunicação, nomeadamente: • a abertura e o fecho sem atritos; • o funcionamento ergonómico do manípulo; [SCI03-05_1A2; SCI03-05_1A6] • a reabertura após deteção de obstáculo; [SCI03-05_3A1; SCI03-05_3A2; SCI03-05_3A3; SCI03-05_3A4]	X	X	X	X	X	X
082_002	Verificar os tempos de abertura, de retenção e de fecho. [SCI03-05_1A20; SCI03-05_1A21]			X	X	X	X
082_003	Inspecionar visualmente o estado de aperto do parafuso de fixação do manípulo de comando da porta. [SCI03-05_1A1]	X	X	X	X	X	X
082_004	Inspeção auditiva verificando a ausência de fugas de ar no circuito pneumático das portas. [SCI03-05_1A26]	X	X	X	X	X	X
082_005	Inspecionar visualmente o estado do cilindro e da sua fixação.				X	X	X
082_006	Lubrificar cilindros e guias das portas.				X	X	X
082_007	Inspecionar visualmente o estado da régua de acionamento. [SCI03-05_1A5]				X	X	X
082_008	Inspecionar visualmente o estado da correia e das suas fixações. [SCI03-05_1A7; SCI03-05_1A8]				X	X	X
082_009	Verificar o desgaste dos roletes dos carrinhos de suspensão. [SCI03-05_1A10]				X	X	X
082_010	Verificar o desgaste da guia dos carrinhos de suspensão. [SCI03-05_1A11]				X	X	X
082_011	Inspecionar visualmente o estado de aperto dos parafusos de fixação das folhas da porta aos carrinhos de suspensão. [SCI03-05_1A12]				X	X	X
082_012	Inspecionar visualmente o estado da fixação da guia dos carrinhos de suspensão da porta. [SCI03-05_1A13]				X	X	X
082_013	Inspecionar visualmente o estado de aperto do parafuso do excêntrico de regulação das folhas da porta. [SCI03-05_1A14]				X	X	X
082_014	Inspecionar visualmente o estado da válvula de acionamento e do braço articulado.				X	X	X
082_015	Inspecionar visualmente a existência e o estado dos batentes da porta. [SCI03-05_7A1]				X	X	X
082_016	Verificar estado do oculo (janela) da porta de intercomunicação, substituir em caso danificado.	X	X	X	X	X	X
082_017	Verificar o estado das folhas das portas de intercomunicação (pintura, juntas, escovas de vedação e bourrelets). [SCI03-05_2A1; SCI03-05_2A2; SCI03-05_6A1]					X	X

ANNEX B3 – MAINTENANCE PLAN

082_018	Inspecionar visualmente o desgaste e estado da fixação das guias inferiores. [SCI03-05_1A23; SCI03-05_1A24]				X	X	X
082_019	Limpar as guias das portas. [SCI03-05_1A25]				X	X	X
082_020	Inspecionar visualmente o estado do limitador de abertura. [SCI03-05_8A2]				X	X	X
082_021	Verificar o funcionamento da quadra de bloqueio mecânico da porta. [SCI03-05_9A1; SCI03-05_9A2]			X	X	X	X
082_022	Verificar o funcionamento do manípulo de isolamento pneumático. [SCI03-05_4A1; SCI03-05_4A2]			X	X	X	X
082_023	Verificar o funcionamento da torneira de isolamento pneumático das portas da plataforma. [SCI03-05_4A3]			X	X	X	X
082_024	Verificar o funcionamento manual da porta.			X	X	X	X
	Portas interiores ► Portas de acesso ao salão	**ES**	**EI**	**V3**	**V2**	**V1**	**R**
084_001	Verificar o funcionamento das portas de acesso ao salão, nomeadamente: • o funcionamento de ambas as fotocélulas; • a abertura e o fecho sem atritos; • a reabertura após deteção de obstáculo; [CAI0401-003_3A1; CAI0401-003_3A2]	X	X	X	X	X	X
084_002	Verificar os tempos de abertura, de retenção e de fecho. [CAI0401-003_1A9; CAI0401-003_1A10; CAI0401-003_1C1]			X	X	X	X
084_003	Verificar desgaste, fixação e tensão da correia. [CAI0401-003_1A17; CAI0401-003_1A18]				X	X	X
084_004	Inspecionar visualmente o estado de desgaste e fixação das polias. [CAI0401-003_1A19]				X	X	X
084_005	Verificar o estado e funcionamento do mecanismo de retenção e fim de curso. [CAI0401-003_1B6]			X	X	X	X
084_006	Verificar o aperto dos parafusos de fixação das folhas aos carrinhos de suspensão. [CAI0401-003_1A14]				X	X	X
084_007	Verificar o desgaste dos roletes dos carrinhos de suspensão da folha da porta. [CAI0401-003_1A12]				X	X	X
084_008	Verificar o desgaste da guia dos carrinhos de suspensão. [CAI0401-003_1A13]				X	X	X
084_009	Inspecionar visualmente o estado da fixação da guia dos carrinhos de suspensão da porta. [CAI0401-003_1A15]				X	X	X
084_010	Inspecionar visualmente o estado de aperto do parafuso do excêntrico de regulação da folha da porta. [CAI0401-003_1A16]				X	X	X
084_011	Verificar estado do vidro da porta de salão, substituir em caso danificado.	X	X	X	X	X	X

ANNEX B3 – MAINTENANCE PLAN

084_012	Verificar visualmente o estado da folha da porta (pintura, juntas, grelha e tirantes).					X	X
084_013	Verificar o estado das células fotoelétricas, espelhos retrorrefletores e das suas fixações. [CAI0401-003_1B2; CAI0401-003_1B3]			X	X	X	X
084_014	Limpar as fotocélulas. [CAI0401-003_1B5]			X	X	X	X
084_015	Verificar a verticalidade e o paralelismo da folha da porta.			X	X	X	X
084_016	Limpar guia superior.				X	X	X
084_017	Verificar o funcionamento do botão de isolamento elétrico da porta; [CAI0401-003_4A1; CAI0401-003_4A2]			X	X	X	X
	Portas de acesso aos passageiros ► Geral	**ES**	**EI**	**V3**	**V2**	**V1**	**R**
103_001	Verificar a abertura e o fecho das portas.	X	X	X	X	X	X
103_002	Verificar o funcionamento dos botões de abertura e de fecho.	X	X	X	X	X	X
103_003	Inspeção auditiva verificando a ausência de fugas de ar no circuito pneumático. [SCI02-07_1A3; SCI02-07_1A4; SCI02-07_1A7; SCI02-07_1A8; SCI02-07_1A9]	X	X	X	X	X	X
103_004	Verificar a temporização de abertura e fecho das portas. [SCI02-07_1A10; SCI02-07_1A11; SCI02-07_1A12]			X	X	X	X
103_005	Verificar a sinalização acústica do fecho de portas.			X	X	X	X
103_006	Verificar a pressão de alimentação das portas.			X	X	X	X
103_007	Verificar o funcionamento do taco-gerador.			X	X	X	X
103_008	Verificar o estado e fixação do conector e do cabo do taco-gerador. [SCI02-07_1A33]			X	X	X	X
103_009	Verificar a existência e estado da sinalética da porta. [SCI02-07_12A1]	X	X	X	X	X	X
103_010	Verificar o funcionamento do anti-entalamento.	X	X	X	X	X	X
103_011	Verificar o funcionamento da ordem de repetição de tentativa de fecho.			X	X	X	X
103_012	Verificar nas botoneiras interiores e exteriores de abertura da porta que existe uma folga de 0,5mm entre o parafuso de atuação e o micro-interruptor. Limpar e lubrificar os microinterruptores. [SCI02-07_1A18; SCI02-07_1A21]				X	X	X
103_013	Verificar a estanquidade das botoneiras. Em caso de entrada de água substituir as juntas do *racord* e/ou a botoneira.				X	X	X

ANNEX B3 – MAINTENANCE PLAN

103_014	Inspecionar visualmente o estado de aperto da fixação dos corrimões. [SCI02-07_13A1]				X	X	X
103_015	Verificar o funcionamento do degrau escamoteável. [SCI02-07_13A2; SCI02-07_13A3; SCI02-07_13A4; SCI02-07_13A5]		X	X	X	X	X
103_016	Verificar o estado das borrachas de vedação dos degraus. [SCI02-07_13A6]				X	X	X
103_017	Limpar e lubrificar o parafuso de comando do degrau escamoteável.				X	X	X
103_018	Verificar o estado da mola de comando do degrau escamoteável.				X	X	X
103_019	Verificar o funcionamento das molas, manobrando o degrau escamoteável com a porta fechada e aberta.			X	X	X	X
103_020	Lubrificar o interior do tubo telescópico e a mola do degrau escamoteável.				X	X	X
103_021	Verificar o funcionamento do trinco. [SCI02-07_1A24; SCI02-07_1A25]		X	X	X	X	X
103_022	Inspecionar visualmente o estado de aperto da fixação do mecanismo do trinco. [SCI02-07_1A23]				X	X	X
103_023	Verificar o funcionamento do cilindro de encravamento.		X	X	X	X	X
103_024	Lubrificar a mola do trinco e da placa de encravamento.					X	X
103_025	Inspecionar visualmente o estado da fixação dos cilindros. [SCI02-07_1A5]				X	X	X
103_026	Lubrificar os cilindros. [SCI02-07_1A6]				X	X	X
103_027	Verificar a estanquidade do motor rotativo.					X	X
103_028	Verificar manualmente o funcionamento da polia central e o acoplamento com o eixo do motor. [SCI02-07_11A2; SCI02-07_11A3]					X	X
103_029	Verificar o estado da correia dentada. [SCI02-07_1A22]				X	X	X
103_030	Verificar a rotação da polia dentada, das polias de retorno e dos rolos tensores, assim como o estado de aperto das suas fixações. Lubrificar. [SCI02-07_11A1]				X	X	X
103_031	Verificar a tensão e o correto enrolamento da correia nas polias e nos rolos tensores. [SCI02-07_11A6]				X	X	X
103_032	Limpar e lubrificar os rolamentos do dispositivo de acionamento.					X	X
103_033	Limpar e lubrificar o eixo e a rótula do dispositivo de acionamento.					X	X

ANNEX B3 – MAINTENANCE PLAN

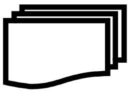
103_034	Verificar a existência e a montagem correta do rolete de posicionamento do braço de suspensão superior.			X	X	X	X
103_035	Verificar o funcionamento e regulação do micro de fim-de-curso.					X	X
103_036	Limpar e lubrificar as articulações das portas. [SCI02-07_1A26]			X	X	X	X
103_037	Verificar a articulação da forquilha de arraste sobre o braço de guiamento, assim como a aperto da sua fixação. [SCI02-07_9A4]			X	X	X	X
103_038	Inspecionar visualmente o estado de aperto das fixações dos braços de suspensão superiores e inferiores. [SCI02-07_9A1]				X	X	X
103_039	Inspecionar visualmente o estado de aperto da fixação do braço de guiamento. [SCI02-07_9A3]				X	X	X
103_040	Verificar a posição da porta em altura.			X	X	X	X
103_041	Verificar o paralelismo da folha da porta relativamente ao montante da caixa.			X	X	X	X
103_042	Verificar o paralelismo entre a guia superior e inferior. [SCI02-07_1A27; SCI02-07_1A28; SCI02-07_1A29; SCI02-07_1A30]				X	X	X
103_043	Verificar o paralelismo da guia exterior, assim como o estado de aperto da sua fixação.				X	X	X
103_044	Inspecionar visualmente o estado de aperto das fixações das guias. [SCI02-07_1A27]				X	X	X
103_045	Limpar o interior das guias.				X	X	X
103_046	Verificar estado do vidro da porta de acesso, substituir em caso danificado.	X	X	X	X	X	X
103_047	Verificar o estado da folha da porta (pintura, juntas de estanquidade). [SCI02-07_8A1; SCI02-07_10A1]					X	X
103_048	Limpar e lubrificar, de forma moderada, a articulação da alavanca (nunca o rolete de plástico) da placa de encravamento.					X	X
103_049	Verificar o posicionamento do estabilizador montado sobre a folha da porta.			X	X	X	X
103_050	Verificar o estado e limpeza do estabilizador.					X	X
103_051	Inspecionar o estado dos pinhões e cremalheiras da folha da porta, verificando que não existem dentes fissurados ou fraturados. [SCI02-07_11A4; SCI02-07_11A5]				X	X	X
103_052	Limpar as cremalheiras com petróleo e secar.					X	X

ANNEX B3 – MAINTENANCE PLAN

103_053	Verificar o funcionamento do comutador de fecho de chave/fecho de quadra. [SCI02-07_2A1]		X	X	X	X	X
103_054	Limpar o comutador de fecho de chave. [SCI02-07_2A2]			X	X	X	X
103_055	Verificar o funcionamento do manípulo de emergência.			X	X	X	X
103_056	Verificar o funcionamento da quadra de isolamento pneumático da porta. [SCI02-07_5A1; SCI02-07_5A2]			X	X	X	X
103_057	Verificar o funcionamento da torneira de isolamento pneumático das portas da plataforma. [SCI02-07_5A3]			X	X	X	X
103_058	Verificar o funcionamento do sinal acústico aquando do isolamento pneumático da porta. [SCI02-07_5B1; SCI02-07_5B2; SCI02-07_5B3]			X	X	X	X
103_059	Verificar o funcionamento da quadra de isolamento manual da porta. [SCI02-07_6A1; SCI02-07_6A2; SCI02-07_6A4]			X	X	X	X
103_060	Efetuar o bloqueio manual da porta, verificando a existência de oposição por parte da mola. [SCI02-07_6A3]			X	X	X	X
103_061	Verificar o funcionamento da anulação do botão de abertura aquando do acionamento da quadra de isolamento manual da porta.			X	X	X	X
103_062	Verificar o funcionamento do sinal luminoso exterior. [SCI02-07_6B1; SCI02-07_6B2]			X	X	X	X
103_063	Verificar o funcionamento do sistema de fecho de portas por velocidade.			X	X	X	X

ANNEX B4 – ES VISIT WORK INSTRUCTIONS

<table>
<tr><th>SISTEMA

EQUIPAMENTO, ÓRGÃO</th><th>TRABALHOS A EFETUAR</th><th>Tempo: 2:00 h</th></tr>
<tr><td></td><td colspan="2">Consultar do Diário Técnico de Bordo (DTB):
• As anomalias registadas deverão ser reparadas oportunamente.
• Preencher e destacar a folha “A” do DTB, garantindo que as respostas são sempre assinadas.
• Anomalias graves ou com reparação demorada deverão ser comunicadas de imediato ao Técnico Oficinal.</td></tr>
<tr><td></td><td colspan="2">Procedimentos de higiene e segurança nas operações de manutenção:
• Alinhar os escadotes da Oficina com as portas da unidade e nunca saltar abaixo das unidades.
• Não movimentar a unidade sem o comunicar aos restantes Agentes.</td></tr>
<tr><td>PORTAS INTERIORES</td><td colspan="2">1. Portas interiores – Portas de intercomunicação
36.1 Verificar o funcionamento das portas de intercomunicação, nomeadamente:
- a abertura e o fecho sem atritos;
- o funcionamento ergonómico do manípulo;
- a reabertura após deteção de obstáculo;
36.2 Inspeção visual ao estado de aperto do parafuso de fixação do manípulo de comando da porta.
36.3 Inspeção auditiva verificando a ausência de fugas de ar no circuito pneumático das portas.
36.4 Verificar estado do óculo (janela) da porta de intercomunicação, substituir em caso danificado.
2. Portas interiores – Portas de acesso ao salão
38.1 Verificar o funcionamento das portas de acesso ao salão, nomeadamente:
- o funcionamento de ambas as fotocélulas;
- a abertura e o fecho sem atritos;
- a reabertura após deteção de obstáculo;
38.2 Verificar estado do vidro da porta de salão, substituir em caso danificado.</td></tr>
<tr><td>PORTAS DE ACESSO AOS PASSAGEIROS</td><td colspan="2">3. Portas de acesso aos passageiros – Geral
3.1 Verificar a abertura e o fecho das portas.
3.2 Verificar o funcionamento dos botões de abertura e de fecho.
3.3 Inspeção auditiva verificando a ausência de fugas de ar no circuito pneumático.
3.4 Verificar a existência e o estado da sinalética da porta.
3.5 Verificar o funcionamento do anti-entalamento da porta.
3.6 Verificar estado do vidro da porta de acesso, substituir em caso danificado.</td></tr>
</table>

ANNEX C: RCM ANALYSIS REPORT

Relatório Análise RCM II

(Pós Auditoria)

Sistemas de Portas - Carruagens Arco

1. Âmbito do relatório

O presente documento serve de suporte à apresentação dos resultados da aplicação da metodologia RCM II aos Sistemas de Portas de Acesso, Portas de Salão e Portas de Intercomunicação das carruagens Arco. A análise decorreu nas instalações oficinais da CP entre 27 de fevereiro e 21 de abril de 2023, ocupando o total de 312 horas.

Ao longo da realização do estudo, foram observados os seguintes princípios:

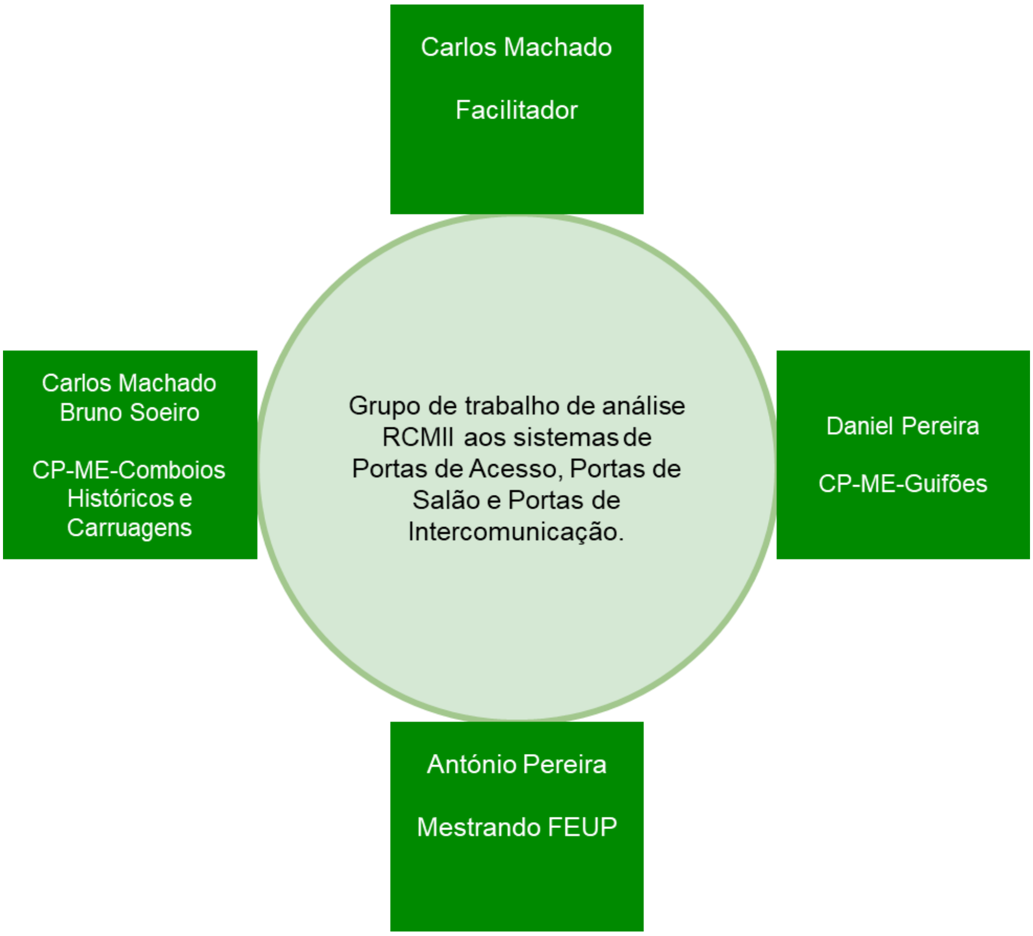
- Na descrição dos efeitos de falha foram descritas todas as evidências diretas para a operação, permitindo caracterizar o tipo de consequência e a tomada de decisão, relativamente a cada modo de falha descrito;

- Os tempos estimados para a reposição de condições comportam para além do tempo de reposição da condição, o tempo de diagnóstico e localização dos componentes em falha. Estes tempos são definidos prossupondo a existência em armazém de todos os materiais necessários. Como exceção a este princípio encontram-se todos os modos de falha com impacto para a segurança, cuja reposição de condições não é considerada. Esta circunstância deriva do facto de não ser admissível a ocorrência de modos de falha com impacto para a segurança. Neste grupo estão inseridos 32 modos de falha;

- Perante a ausência de valores de custo que permitam a determinação dos impactos originados pelos modos de falha identificados como pertencentes ao tipo “operacional”, a sua avaliação foi relativizada através do tempo de indisponibilidade ou operacionalidade deficiente originada na automotora, bem como dos custos de reposição de condições dos componentes em falha;

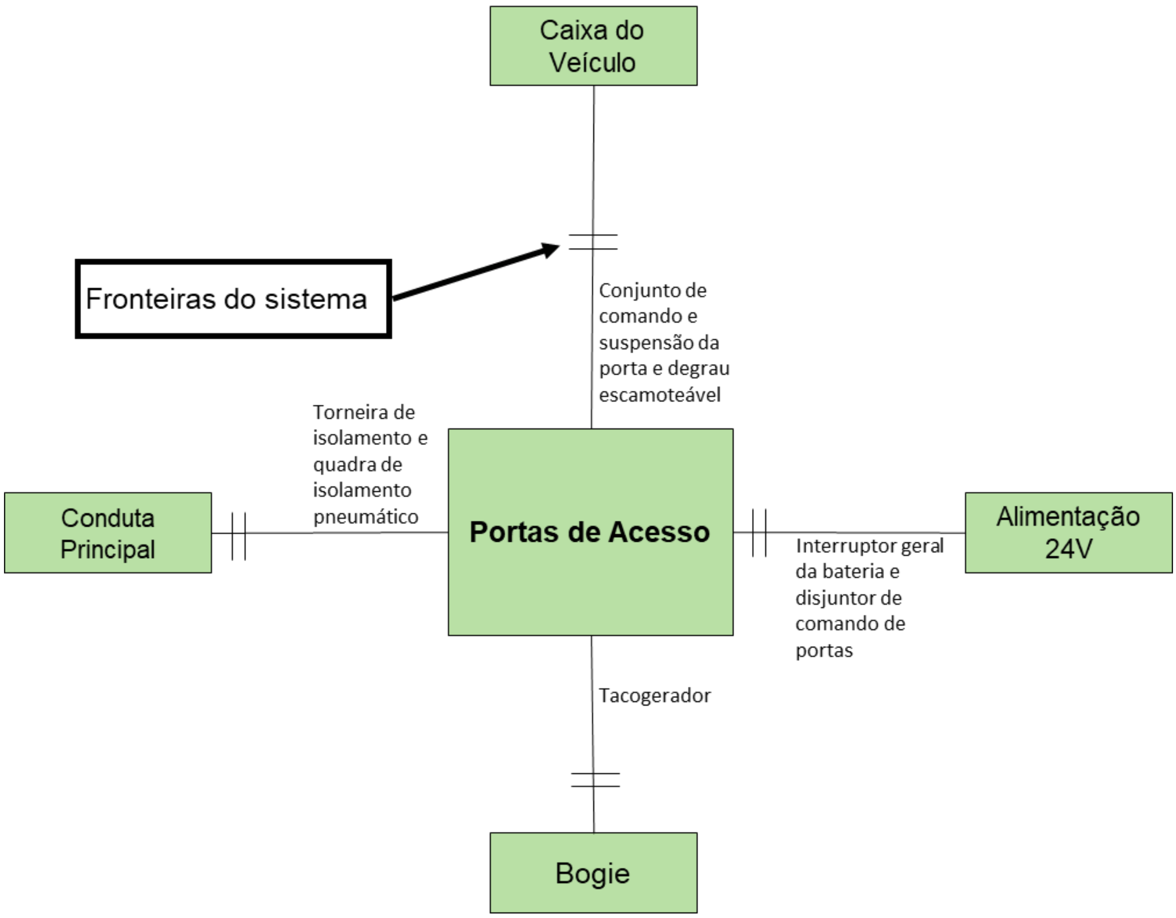
2. Grupo de trabalho

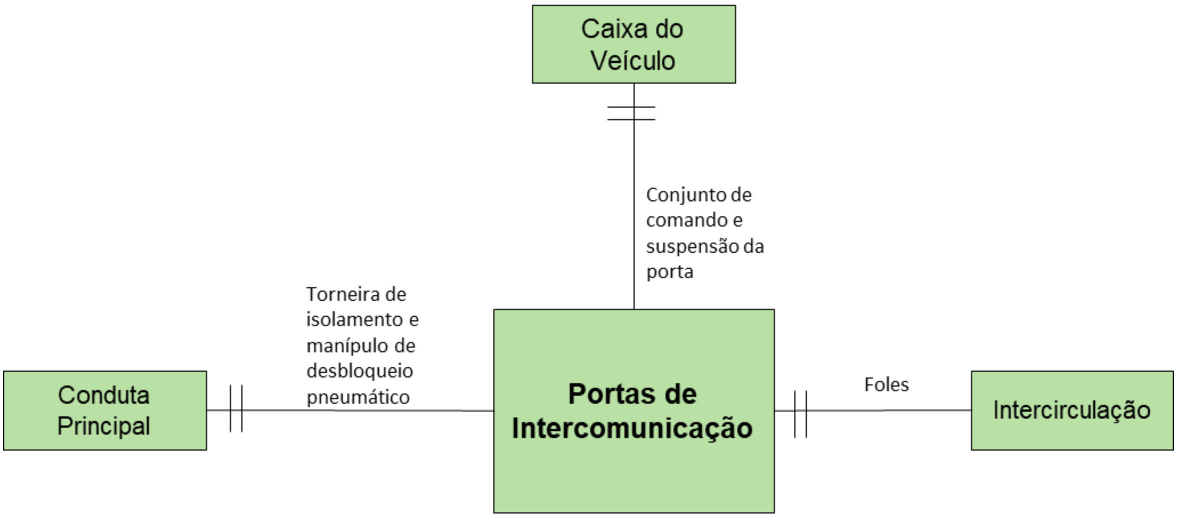
O grupo de trabalho foi constituído por colaboradores da CP-Comboios de Portugal pertencentes à Manutenção e Engenharia, nomeadamente Comboios Históricos e Carruagens e Manutenção Guifões, assim como por um mestrando da FEUP, tendo sido observadas composições do grupo variáveis ao longo do período de análise, condicionadas pela disponibilidade operacional dos respetivos elementos.

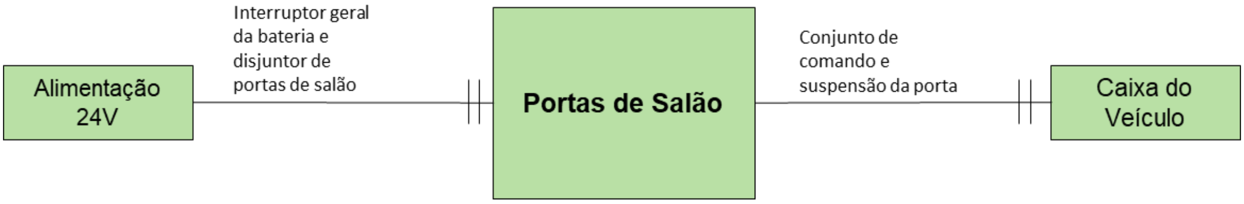


3. Sistemas analisados

Para delimitar de forma rigorosa os sistemas em estudo, elaboraram-se esquemas representativos, onde se encontram perfeitamente identificadas as fronteiras com os sistemas envolventes:



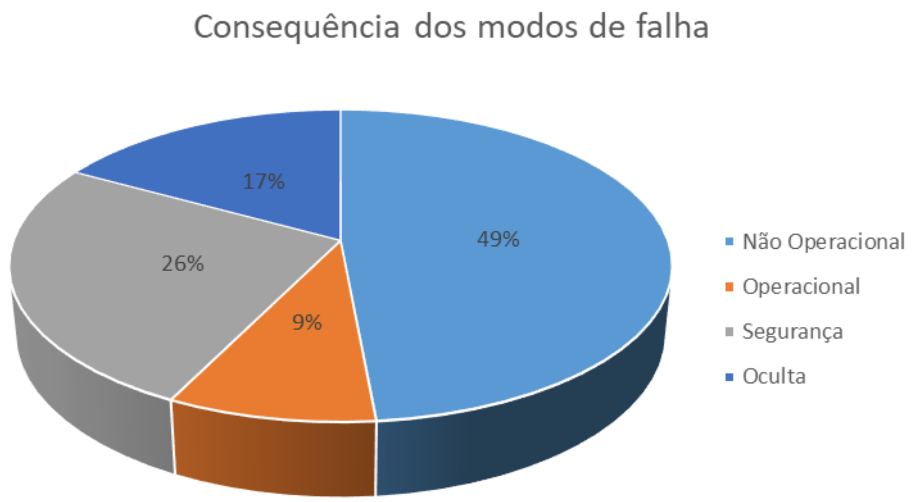




A presente análise incidiu sobre todas as funções identificadas como requeridas aos sistemas de portas, no atual contexto operacional das carruagens Arco.

4. Programa de gestão de falhas

Os sistemas de Portas de Acesso, Portas de Salão e Portas de Intercomunicação apresentam-se vulneráveis a 97, 32 e 42 modos de falha, respetivamente. O total de modos de falha para o conjunto dos 3 sistemas é de 171. No quadro seguinte, é exibida a distribuição dos resultados da presente análise RCMII, sendo que existe uma maior incidência no impacto "Não Operacional".



Consequência	Nº de falhas	Percentagem
Não Operacional	83	48,54%
Operacional	15	8,77%
Segurança	44	25,73%
Ambiental	0	0%
Oculta	29	16,96%

4.1. Tarefas de manutenção proativa

Com a realização da presente análise RCMII aos sistemas de portas das carruagens Arco foram identificadas, como forma de preservação das funções do sistema, as seguintes tarefas:

Tarefa	Nº de Tarefas	Percentagem
Sob condição	81	47,37%
Restauro Programado	5	2,92%
Descarte Programado	2	1,17%

Nota: Para mais detalhe consultar quadro do ponto 5.3.

4.2. Tarefas *Default*

4.2.1. Tarefas de busca de falha oculta

Da totalidade dos modos de falha analisados resultaram 29 cuja consequência se verifica como “Falha Oculta”. Para a presente consequência, foram identificadas 19 tarefas de “Busca de Falha” como sendo as mais viáveis para a minimização de impactos.

4.2.2. Nenhuma Manutenção Programada (N.M.P.)

Relativamente aos modos de falha cujo impacto é caracterizado como “Operacional” e “Não Operacional” foram ponderados os riscos e identificados 47 modos de falha em que a intervenção será “Nenhuma Manutenção Programada”, ou seja, manutenção corretiva, onde a tarefa apenas é realizada quando ocorre a falha. Este tipo de tarefa prossupõe uma organização e disponibilidade do material em armazém, para que seja possível realizar a mesma de imediato, quando necessário (para mais detalhe consultar o ponto 5.3).

4.2.3. Reprojetos

Aquando da análise foram identificados e propostos 2 reprojetos, relativos a 14 modos de falha das Portas de Acesso, com o objetivo de melhorar o desempenho e aumentar a fiabilidade da unidade. A ausência de comando de fecho de portas das carruagens Arco através da cabine de condução permite atualmente que o comboio inicie a marcha com as portas abertas, sendo dadas ordens de fecho distintas a velocidades superiores a 7km/h e a 15km/h. Para além disso, o sistema de anti-entalamento não é redundante, o que significa que a falha deste sistema permite o entalamento de pessoas e bens.

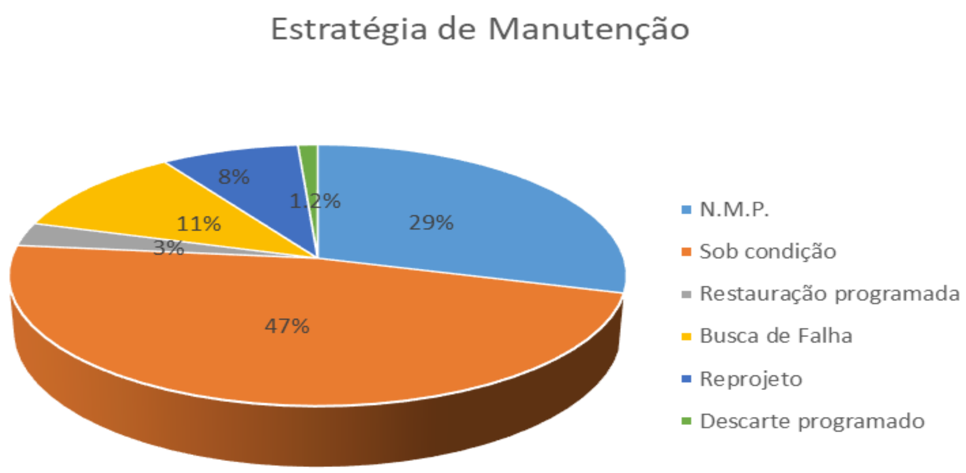
- **Modos de falha** →1A13; 1A14; 3A1; 3A2; 3A3; 3A4; 3A5; 14A1; 14A2
- **Reprojeto** → Deverá ser efetuado um reprojeto que evidencie mais rapidamente à tripulação o estado do funcionamento das portas para diminuir a probabilidade de seguimento da marcha sem o bloqueio de todas as portas.

- **Modos de falha** →4A1; 4A2; 4A3; 4A4; 4A5
- **Reprojeto** → Deverá ser efetuado um reprojeto que crie um sistema redundante de anti-entalamento.

Nota: Para mais detalhe consultar quadro do ponto 5.3.

4.3. Estratégias de manutenção

A análise RCM contempla várias estratégias na decisão, as quais são representadas no seguinte gráfico, tendo em conta a frequência com que se apresentam na presente análise aos sistemas de portas.



O quadro seguinte detalha a estratégia de manutenção adotada relativamente às consequências das falhas:

Consequência	Decisão	Número de tarefas	Percentagem
Oculta	Nenhuma manutenção programada	3	1,75%
	Tarefa sob condição	7	4,09%
	Tarefa de restauro programado	0	0%
	Tarefa de descarte programado	0	0%
	Tarefa de busca de falha	19	11,11%
Segurança	Tarefa sob condição	28	16,37%
	Tarefa de restauro programado	0	0%
	Tarefa de descarte programado	2	1,17%
	Combinação de tarefas	0	0%
	Reprojeto	14	8,19%
Operacional	Tarefa sob condição	12	7,02%
	Tarefa de restauro programado	1	0,58%
	Tarefa de descarte programado	0	0%
	Nenhuma manutenção programada	2	1,17%
Não operacional	Tarefa sob condição	34	19,98%
	Tarefa de restauro programado	4	2,34%
	Nenhuma manutenção programada	45	26,32%
	Totais	171	100%

5. Componentes dos sistemas de portas

Para uma melhor perceção dos sistemas analisados, seguem-se imagens de alguns dos componentes que os constituem.

Figura 1- Comutador de Fecho de Chave (Portas de Acesso).

Figura 2- Eletroíman (Portas de Acesso).

Figura 3- Trinco (Portas de Aces

Figura 4- Carrinho de suspensão (Portas de Salão).

Figura 5 – Motor elétrico (Portas de Salão).

Figura 6 – Correia Trapezoidal e
(Portas de Intercomunicação)

6. Contexto Operacional

6.1. Contexto operacional da unidade

O objetivo do presente ponto é a contextualização da atividade das carruagens Arco. Existem de momento 15 carruagens Arco (5 lotes de 3 carruagens cada). Estas carruagens estão afetas ao serviço regional e inter-regional de passageiros, tendo percorrido cada unidade, em média 83 000 km (cerca de 8 300 km por mês) desde que foi colocado ao serviço o 1º lote, em julho de 2022 até maio de 2023. Estas unidades, à data do presente estudo RCM, estão a prestar serviço no norte de Portugal, nomeadamente:

- Linha do Norte
- Linha do Minho
- Linha do Oeste

Nota: Para avaliação do impacto Operacional dos modos de falha deverá ter-se em consideração o disposto no Contrato de Serviço Público, que estabelece como incidente toda e qualquer ocorrência que origine atraso superior a 5 minutos a comboio ou marcha associada à circulação de passageiros.

Trata-se de composições constituídas por três carruagens, ligadas entre si por tensores de acoplamento e ganchos de tração. Estas carruagens são reboques, pelo que requerem uma unidade motora para as rebocar. Como principais características técnicas das unidades, tem-se:

- Número de unidades ao serviço → 15 carruagens (5 lotes de 3 carruagens cada)
- Velocidade máxima → 200 km/h
- Lotação:

Arco do Serviço Inter-regional
Número de lugares em 1ª classe → 56
Número de lugares em 2ª classe → 80
Número de lugares em mista → 54
Número de suportes para bicicletas em mista→ 8

- Peso em ordem de marcha (1 Carruagem) → 45 t
- Comprimento (1 Carruagem) → 26,4 m
- Possuem ABS
- Possui freio EP

6.2. Descrição e funcionamento – Portas de Acesso

6.2.1. Generalidades e características

Cada carruagem está equipada com quatro portas de acesso, duas por cada lateral. Esta porta é de apenas uma folha, do tipo encaixável-deslizante.

Na posição fechada a porta fica alinhada com o plano exterior da carruagem e na posição aberta posiciona-se paralelamente à face da carruagem, pelo exterior.

Figura 7- Portas de Acesso.

A abertura é automática após atuação dos botões de abertura interior ou exterior ou através do comutador de fecho de chave.

Figura 8- Botão exterior e botões interiores.

O fecho pode ser automático após atuação do botão de fecho interior, comandado à distância pelo ORV a partir de uma das portas, ou a partir de sinal proporcional à velocidade.

Figura 9- Comutador de fecho de chave e tacogerador.

Cada conjunto da porta é formado por um caixilho no qual estão montados:

- 1 Folha
- 1 Mecanismo
- 1 Degrau móvel

Figura 10- Degrau móvel

Vão livre:

- Largura da passagem: 800 mm
- Altura da passagem: 1900 mm

Parâmetros elétricos:

1. Alimentação elétrica: 24 Vcc (18 a 28 V, dependendo do estado da bateria)
2. Velocidade ascendente para tentativa de fecho com anti-entalamento: 7 km/h
3. Velocidade ascendente para fecho sem anti-entalamento e bloqueio pneumático: 15 km/h
4. Velocidade descendente para desbloqueio pneumático: 7km/h

Parâmetros mecânicos:

1. Pressão de alimentação da porta: 7 bar ± 1 bar
2. Consumo de ar para um ciclo de abertura/fecho (excluindo tubagem): 11 l à pressão atmosférica
3. Temporização para a abertura da porta: 4 segundos ± 1 segundo
4. Temporização para o fecho da porta: 4 segundos ± 1 segundo
5. Temporização entre tentativas de fecho pelo pressostato de anti-entalamento: 5 segundos
6. Força efectiva exercida pela folha da porta para atuação do anti-entalamento: 30 N
7. Distância de atuação do micro de fim-de-curso: 10-20 mm

6.2.2. Descrição

Caixilho equipado

Contém a folha, que é constituída por um vidro de segurança de 10mm de espessura montado com junta de borracha em perfis de alumínio, aparafusado e revestido por um painel de aço inoxidável de 1mm de espessura. O interior é injetado com espuma de poliuretano para reforçar e insonorizar a folha. A folha está equipada com um “bordo sensível” que permite o acionamento do anti-entalamento, para além de assegurar a vedação da porta.

A travessa superior, à qual é fixado o mecanismo, compreende também o trinco que permite o fecho da porta.

Figura 11- Trinco.

Mecanismo de acionamento

O mecanismo de acionamento possui um eixo de saída na parte central. Uma polia dentada está montada neste eixo por intermédio de uma chaveta e engrena numa correia dentada. Um dispositivo com rótula fixado na correia dentada permite por meio do braço de guiamento, o arraste da folha. No interior dos dois cilindros (um de cada lado do corpo central) encontram-se os pistões, que estão unidos entre si por intermédio de uma cremalheira, que passa no orifício transversal do corpo central. Neste corpo central encontra-se alojado um pinhão que engrena com a cremalheira e tem um eixo de saída com um rasgo de chaveta, para fixar a polia dentada. Dois rolos tensores, localizados em ambos os lados da polia dentada, permitem o ajuste da tensão da correia. Em cada extremidade existe uma polia de retorno, engrenada na correia dentada.

Figura 12- Mecanismo de acionamento.

Dispositivo de arraste

A excitação das eletroválvulas permite que estas insuflem ar no sentido de abertura das portas. O movimento do pistão de um dos cilindros faz mover a cremalheira, que ao engrenar no pinhão provoca a rotação da polia dentada, enquanto o outro cilindro permite o escape do ar, auxiliando desta forma no suporte e equilíbrio de tensões no movimento de arraste. Esta rotação da polia dentada movimenta a correia dentada, permitindo assim o arraste da folha e abertura da porta. Quando as eletroválvulas deixam de estar excitadas, ocorre o fecho da porta.

Conjunto pneumático

Este conjunto é fixado na travessa superior e é constituído por 2 eletroválvulas, 2 cilindros pneumáticos, 2 válvulas de escape, 2 reguladores de caudal, 2 pressostatos e pela tubagem.

Estabilizador

O estabilizador suporta a folha da porta na posição vertical, através de 2 guias, uma superior e uma inferior. É constituído por um corpo com um eixo equipado com dois pinhões e dois suportes montados com rolamentos. Estes pinhões engrenam nas duas cremalheiras da folha, uma superior e uma inferior.

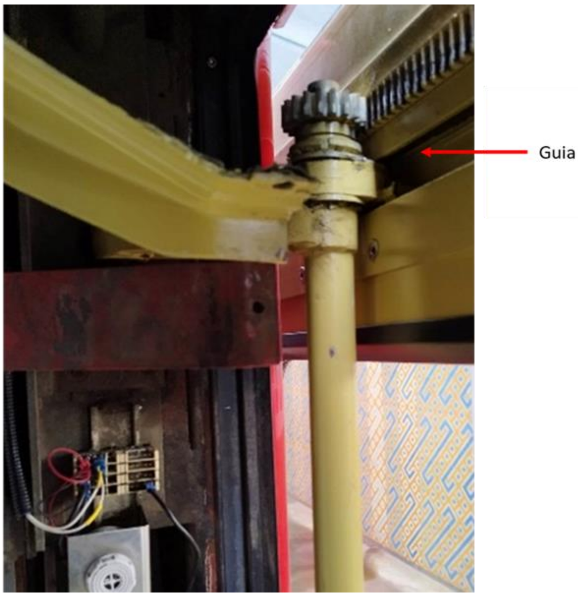


Figura 13- Estabilizador.

Mecanismo de segurança

Em cada plataforma encontra-se instalado um manípulo de desbloqueio das portas que despressuriza os circuitos pneumáticos das duas portas da plataforma, mediante a sua rotação de 90° nos sentidos do ponteiro do relógio. Este manípulo encontra-se ligado a um besouro de alerta. O rearme da porta pode ser efetuado rodando o manípulo 180° no sentido contrário ao dos ponteiros do relógio, seguido de uma rotação de 90° no sentido dos ponteiros do relógio, retornando-o desta forma para a posição inicial, como na figura seguinte.

Figura 14- Manípulo de desbloqueio das duas portas da plataforma.

Degrau móvel

O degrau móvel está articulado com o mecanismo de acionamento da porta através de um parafuso sem fim. Quando a porta abre, a rotação da polia de retorno provoca a rotação do parafuso, que faz descer a porca e provoca a extensão do degrau. Quando a porta fecha, a rotação do fuso faz subir a porca e ocultar o degrau.

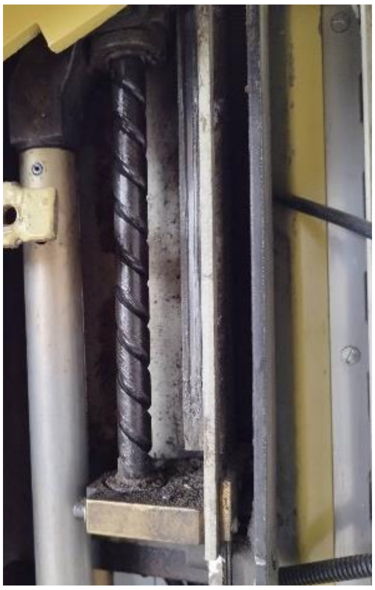


Figura 15- Parafuso sem fim.

6.2.3. Funcionamento

Abertura

A abertura da porta pode ser feita através dos botões de abertura interior ou exterior, com o comboio parado ou com velocidade abaixo dos 7km/h. A atuação do comutador de fecho de chave provoca a abertura da porta na qual este foi atuado. A deteção de um obstáculo durante o fecho da porta através do bordo sensível ou do temporizador provoca a reabertura da porta.

Figura 16- Bordo sensível.

Com velocidade acima dos 7km/h, a excitação do eletroíman provoca o bloqueio mecânico do botão interior de abertura da porta, impedindo a sua atuação.

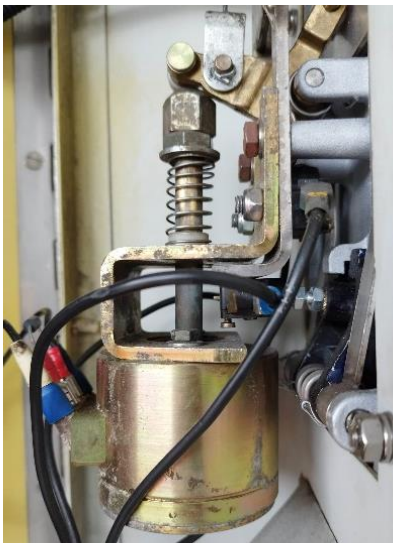


Figura 17- Eletroíman.

Com velocidade acima dos 15km/h, a atuação do comutador de fecho de chave não provoca a abertura da porta, existindo uma inibição elétrica nos comandos da placa de controlo da porta. O anti-entalamento fica também desativado.

Na ausência de alimentação elétrica, mas com existência de pressão pneumática, é possível fazer a abertura da porta, fazendo o seu isolamento pneumático através da quadra de isolamento pneumático da porta e forçando a porta no sentido de abertura. Caso não seja possível fazer o isolamento pneumático da porta através desta quadra, poderá fazer-se o isolamento pneumático da plataforma através da torneira de isolamento pneumático das portas da plataforma, situada no leito na zona superior do bogie.

Figura 18- Quadras exteriores.

Fecho

Com o comboio parado ou com velocidade abaixo dos 7km/h, o fecho da porta pode ser feito através do botão de fecho interior. A atuação do comutador de fecho de chave provoca o fecho de todas as portas com a exceção da porta na qual este foi atuado, que apenas fecha quando o ORV retirar a chave.

Com velocidade acima dos 7km/h a porta fecha automaticamente, exceto se o comutador de fecho de chave da própria porta tiver sido atuado.

Com velocidade acima dos 15km/h a porta fecha automaticamente, mesmo que o comutador de fecho de chave da própria porta tenha sido atuado.

Quando não existe tensão de alimentação, as eletrovávulas da porta deixam de estar excitadas e a porta fecha-se. Se alguma das eletroválvulas entrar em curtocircuito enquanto a porta está fechada, a porta mantém-se fechada.

O bloqueio e isolamento elétrico da porta pode ser feito de forma manual, na ausência de pressão pneumática, através da quadra de isolamento manual da porta.

Guiamento da porta

A porta possui 4 guias, que ajudam a prevenir desnivelamentos ou desalinhamentos da mesma:

- Guia superior

Figura 19- Guia superior.

- Guia inferior angulada

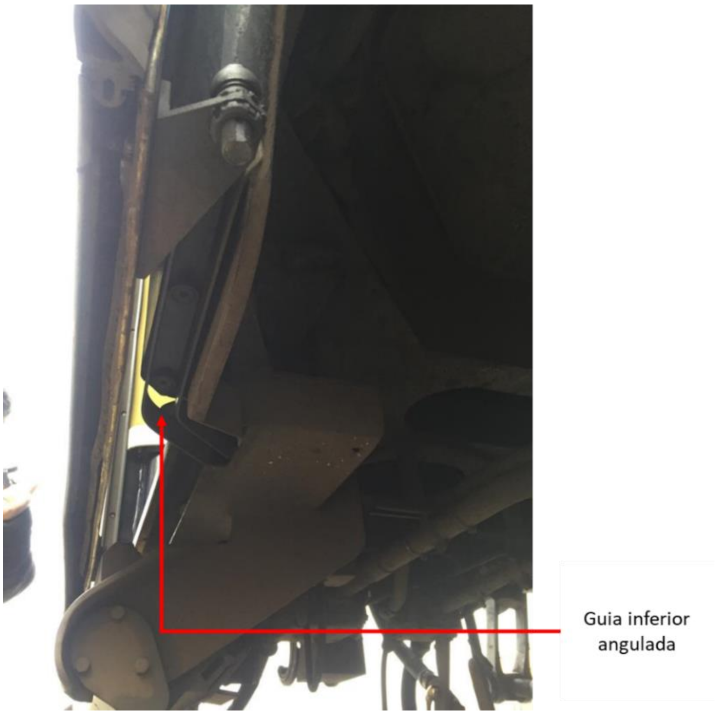


Figura 20- Guia inferior angulada.

- Guia inferior
- Guia exterior

Figura 21 – Guia inferior e guia exterior.

6.3. Descrição e funcionamento – Portas de Salão

6.3.1. Generalidades e características

Esta porta é do tipo deslizante, de apenas uma folha. A abertura da porta é automática mediante o corte do feixe de luz projetado pela fotocélula lateral ou através da fotocélula difusa superior. O fecho da porta é feito por ação do motor elétrico temporizado pela placa de controlo do motor elétrico.

Figura 22- Fotocélula lateral (esquerda), refletor (centro) e fotocélula difusa (direita).

Cada conjunto da porta é constituído por:

- 1 Caixilho equipado
- 1 Mecanismo

Figura 23- Mecanismo de suspensão.

Vão livre:

- Largura da passagem: 650 mm ± 5 mm
- Altura da passagem: 2000 mm

Pesos:

- Do mecanismo: 10 kg
- Da folha: 35,6 kg

Parâmetros elétricos:

1. Alimentação elétrica: 24Vcc
2. Temporização para a abertura da porta: 4 segundos ± 1 segundo
3. Temporização para a retenção da porta aberta: 4 segundos ± 1 segundo
4. Temporização para o fecho da porta: 4 segundos ± 1 segundo

6.3.2. Descrição

Mecanismo de suspensão

O mecanismo de suspensão possui uma guia na qual se encontram os pontos de fixação do mecanismo à caixa. No carril desta guia movem-se os carrinhos de suspensão equipados com excêntricos, cuja rotação faz subir ou descer as peças de suspensão. Esta diferença de altura permite o ajuste do paralelismo da folha relativamente à caixa.

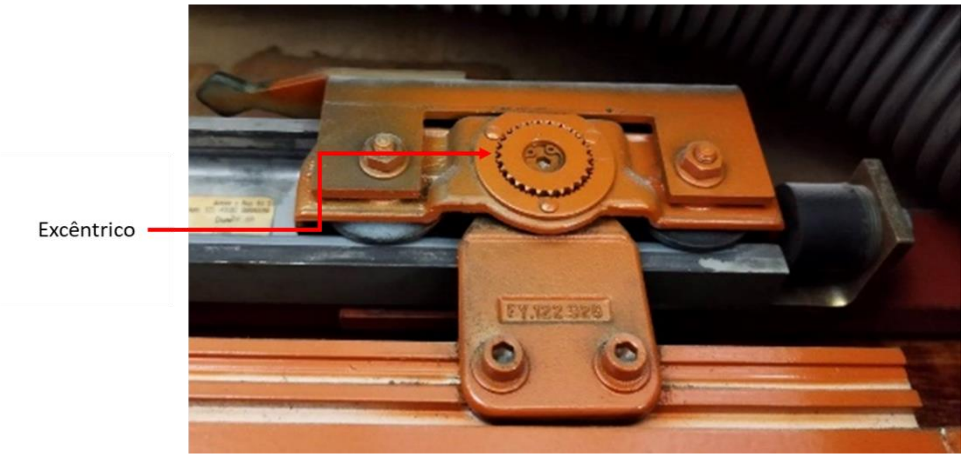


Figura 24- Excêntrico do carrinho de suspensão.

Dispositivo de arraste

O dispositivo de arraste é composto por um motor elétrico e uma polia dentada em que é montada uma correia dentada que permite a transmissão de movimento aos carrinhos de suspensão. A atuação deste dispositivo permite a movimentação da porta.

Figura 25- Polia e correia.

Folha

A folha é constituída por um vidro montado num perfil de liga de alumínio, com uma junta de borracha entre os dois. A folha está equipada com uma junta de borracha frontal que assegura a vedação da porta.

Figura 26- Folha da porta.

Mecanismo de segurança

Em cada porta encontra-se instalado um botão de bloqueio da porta, que permite isolar eletricamente a porta.

Figura 27- Botão de bloqueio da porta.

6.3.3. Funcionamento

Abertura

A abertura da porta é automática mediante o corte do feixe de luz projetado pela fotocélula lateral ou através da fotocélula difusa superior. Desta forma, o motor inicia o movimento no sentido de abertura, transmitindo esse movimento à polia dentada e sucessivamente à correia dentada, que por sua vez provoca a movimentação dos carrinhos de suspensão.

Fecho

Após 8 segundos (4 segundos do movimento de abertura da porta + 4 segundos de retenção da porta na posição aberta), inicia-se o movimento de fecho da porta. Se durante o movimento de fecho um objeto impede o movimento, é detetada uma sobreintensidade que dá ao motor uma ordem de reabertura da porta.

6.4. Descrição e funcionamento – Portas de Intercomunicação

6.4.1. Generalidades e características

Esta porta é do tipo deslizante, de duas folhas. A abertura da porta é automática mediante atuação do punho móvel. O fecho é também automático por comando pneumático temporizado.

Figura 28- Punho móvel.

A porta pode ser bloqueada pelo interior e pelo exterior através da quadra de bloqueio manual, quer na posição de aberta quer na posição de fechada.

Figura 29- Quadra de bloqueio manual.

Cada conjunto da porta é constituído por:

- Um mecanismo de suspensão

Figura 30- Mecanismo de suspensão.

- Um dispositivo de arraste
- Duas folhas

Vão livre:

- Largura da passagem: 900 mm

Pesos:

- Do mecanismo: 15 kg
- Das folhas: 90 kg

Parâmetros mecânicos:

1. Temporização de abertura das folhas da porta: 3 segundos ± 1 segundo
2. Temporização de manutenção das folhas da porta na posição de aberta: 8 segundos ± 1 segundo
3. Temporização de fecho das folhas da porta: 4 segundos ± 1 segundo
4. Pressão de alimentação da porta: 6 bar (+2,-1) bar
5. Esforço sobre o punho móvel para abrir: 25N

6.4.2. Descrição

Mecanismo de suspensão

O mecanismo de suspensão é composto por uma guia na qual se encontram os pontos de fixação do mecanismo à caixa. No carril desta guia movem-se os quatro carrinhos de suspensão, dois por cada folha. As folhas trabalham suspensas destes carrinhos por intermédio das respetivas peças de suspensão. Os carrinhos de suspensão estão equipados com excêntricos, cuja rotação faz subir ou descer as peças de suspensão. Esta diferença de altura permite o ajuste do paralelismo das folhas relativamente à caixa.

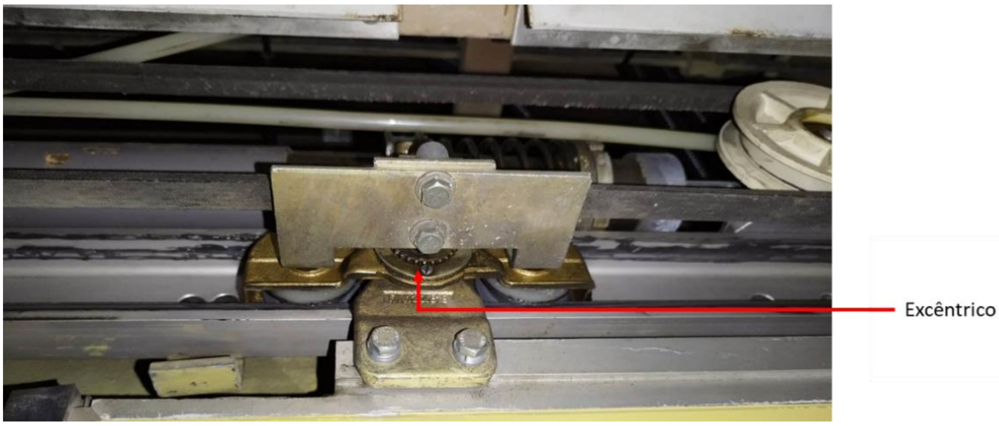


Figura 31- Excêntrico do carrinho de suspensão.

Dispositivo de arraste

O dispositivo de arraste é composto por um cilindro pneumático de duplo efeito, fixado de um lado à guia e do outro a um dos carrinhos de suspensão. O movimento da haste do cilindro provoca o movimento dos carrinhos de suspensão de uma das folhas, que através da correia trapezoidal transmitem o movimento aos carrinhos da outra folha.

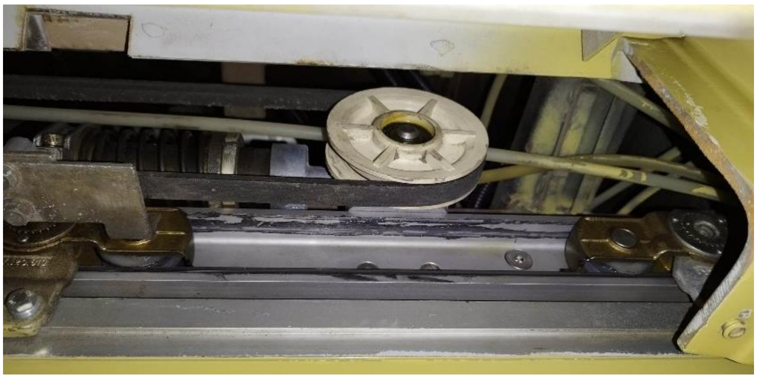


Figura 32- Polia, correia e carrinhos de suspensão.

A atuação deste dispositivo permite a movimentação da porta, que desliza sobre uma guia inferior.

Figura 33- Guia inferior.

Folhas

Cada folha tem uma junta em borracha e um sistema de guias inferior formado por duas calhas insonorizadas de polietileno fixadas no perfil inferior. Em cada lado de uma das folhas da porta existe um punho móvel que permite a abertura da porta.

Figura 34- Folhas da Porta.

Mecanismo de desbloqueio pneumático

Num dos lados da porta, encontra-se instalado na parte superior um manípulo de desbloqueio das portas, que despressuriza o circuito de acionamento. Caso não seja possível fazer o isolamento pneumático da porta através deste manípulo, poderá fazer-se o isolamento pneumático da plataforma através da torneira de isolamento pneumático das portas da plataforma, situada no leito na zona superior do bogie.

Figura 35- Manípulo de desbloqueio pneumático.

Mecanismo de segurança

Quando a porta circula à frente ou à retaguarda da composição deve encontrar-se bloqueada na posição de fechada, mediante atuação da quadra de bloqueio manual. Contudo, em caso de falha deste dispositivo, a abertura da porta encontra-se limitada por um mecanismo de segurança que impede a sua abertura se a pala de passagem se encontrar levantada.

Figura 36- Pala de passagem na posição levantada.

Quando a pala se encontra levantada, o limitador de abertura fica alojado na ranhura, impedindo a abertura da porta.

Figura 37 - Limitador de abertura

6.4.3. Funcionamento

Abertura

A abertura faz-se atuando um dos punhos móveis situados em ambos os lados de uma das folhas. Esta ação provoca a subida de uma varinha de acionamento que faz subir uma régua de acionamento, que aciona a válvula de comando. A válvula de comando aciona o cilindro pneumático, provocando a abertura da porta.

A abertura pode ser feita de forma manual, depois de se isolar pneumaticamente a porta.

Fecho

O fecho faz-se por atuação pneumática temporizada. A temporização é dada pelo regulador de caudal. O dispositivo de fecho está concebido para que as folhas reabram automaticamente:

- se encontrarem um obstáculo. A segurança é obtida do seguinte modo:
    - logo que o obstáculo interrompe o deslocamento do êmbolo, o cilindro, que é flutuante, desloca-se porque passa a haver desequilíbrio entre a mola e a pressão pneumática, provocando a reabertura da porta
- se um passageiro acionar o punho durante o fecho da porta, a varinha de acionamento levanta a régua, acionando novamente a válvula de comando, que aciona o cilindro e provoca a reabertura da porta.