

Failure Mode Analysis and Development for Supporting Hydropower Asset Management

Ricardo Gonçalves Alves

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Orientador na FEUP: Prof. Doutor Armando Luís Ferreira Leitão

Orientador na EDP: Eng. Fábio Oliveira



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Abstract

The increasing strategic importance of hydropower in Portugal’s renewable energy mix places strong demands on the reliability and availability of its critical assets. In this context, the limited availability of structured operational data constrains the development of more rigorous approaches to failure analysis and asset management decision-making.

This dissertation proposes a two-stage methodological approach developed in collaboration with EDP Production’s Exploration and Reliability department , addressing two interconnected challenges: the structured representation of failure modes for critical hydropower assets and the systematic association of historical maintenance records with those failure modes.

In the first stage, Failure Modes, Effects and Criticality Analysis (FMECA) and a Fault Tree Analysis (FTA) were developed for four critical hydropower subsystems: the turbine, generator, power transformer and circuit breakers. A total of 94 failure modes were identified, together with their associated causes and effects, and evaluated through a criticality analysis based on Severity, Occurrence and Detectability parameters. The FTA was then used as a qualitative synthesis of the FMECA, providing a hierarchical representation of how individual failure modes may contribute to broader functional failures.

The second stage develops an NLP-based methodology to associate historical corrective maintenance records with the failure modes defined in the FMECA. A preprocessing pipeline was implemented to normalise and tokenise the maintenance records, resulting in a final dataset of 1,885 usable records out of 5,650 initially available. Three association models were developed and evaluated: a lexical model, a semantic model and a hybrid model integrating both approaches. Validated against a manually reviewed sample of 80 maintenance records, the hybrid model achieved the highest Top-1 accuracy (61.25%), while the lexical model achieved the highest Top-4 hit rate (88.75%).

The proposed methodology supports the systematic interpretation of large volumes of maintenance data by linking historical records to technically compatible failure modes. This association contributes to transforming unstructured operational descriptions into failure mode information that can be used in reliability analysis and maintenance decision support. Furthermore, the work provides a technical basis for more data-driven asset management practices in hydropower generation, while remaining sufficiently flexible to be refined and extended to other asset classes.

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"A pessimist sees the difficulty in every opportunity; an optimist sees the opportunity in every difficulty."

Winston Churchill

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Acronyms and Symbols

ISO	International Organization for Standardization
PAS	Publicly Available Specification
RTF	Run-to-Failure
CBM	Condition Based Maintenance
RCM	Reliability Centered Maintenance
FMECA	Failure Modes, Effects and Criticality Analysis
FTA	Fault Tree Analysis
DFMECA	Design FMECA
PFMECA	Process FMECA
SFMECA	System FMECA
FMEA	Failure Modes and Effects Analysis
NLP	Natural Language Processing
TF-IDF	Term Frequency-Inverse Document Frequency
BM25	Best Matching 25
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
MWO	Maintenance Work Order
RPN	Risk Priority Number
IEC	International Electrotechnical Commission
O	Occurrence
S	Severity
D	Detectability
SAI	Safety and Asset Integrity
EI	Environmental Impact
OPFI	Operational Performance and Financial Impact
OLTC	On-Load Tap Changer
DETC	De-energised Tap Changer
AVR	Automatic Voltage Regulator

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Chapter 1

Introduction

1.1 Project context and Motivation

The global energy sector is undergoing a structural transformation driven by the imperative to decarbonise electricity generation and align economic activity with long-term sustainability objectives. Companies with large renewable energy portfolios occupy a strategically significant position, as their operational performance directly influences both the pace of the energy transition and the reliability of clean electricity supply to end consumers.

EDP is one of the leading corporate groups in the European energy sector, with a consolidated presence in electricity generation, distribution and retail. In Portugal, it holds a leading position across all three of these segments (EDP, 2026b).

Beyond its prominence in the national context, EDP's strategic orientation toward the energy transition is also particularly noteworthy. The company's 2023–2026 Strategic Plan established targets to become coal-free by 2025, achieve a 100% renewable generation mix by 2030 and reach net-zero carbon emissions by 2040. In turn, the subsequent 2026–2028 Business Plan marks a new phase of sustainable growth, supported by strengthened investment in renewable energy sources (EDP, 2026a).

Within EDP's generation portfolio, hydropower occupies a particularly important role, both for its contribution to electricity production from renewable sources and for its capacity to provide flexibility and resilience to the power system. EDP currently have an installed capacity of approximately 6.7 GW (EDP – Energias de Portugal, 2026).

Beyond their contribution to electricity generation, hydroelectric facilities constitute critical infrastructures whose unavailability carries significant operational, economic and strategic consequences. Unplanned failures or extended maintenance interventions in critical hydropower equipment reduce the availability of generating units with direct implications for electricity production volumes, revenue and the continuity of renewable energy supply. In scenarios where hydropower generation is curtailed, alternative generation sources with higher environmental impact may be required to compensate for the shortfall, thereby undermining the very sustainability objectives that the energy transition seeks to advance.

The high technical complexity of these assets, combined with the substantial initial investment they require, makes the definition of effective and appropriately tailored maintenance policies particularly challenging.

It is precisely within this context that the present project is situated. The work was developed within EDP Production division, in close collaboration with the Exploration and Reliability department, which holds responsibility for assessing the condition and failure risk of critical assets and for supporting maintenance planning and investment decisions. The research addresses two interconnected challenges: the need for a structured and technically grounded representation of the failure modes associated with critical hydropower equipment and the need for a systematic and scalable methodology to associate historical maintenance records with failure modes. In doing so, the project transforms unstructured operational data into structured reliability information, establishing a foundation for more data-driven asset management decisions.

1.2 Objectives

The main objective of this dissertation is to develop a structured framework that connects reliability-oriented failure mode analysis with the operational evidence available in historical maintenance records, in the context of critical hydropower assets. The purpose is to support a more systematic interpretation of corrective maintenance events and to contribute to the use of maintenance data in failure mode analysis and asset management.

This objective is developed through two complementary dimensions. The first concerns the identification, organisation and assessment of failure modes, providing the technical reference required for the analysis. The second concerns the use of historical maintenance records as operational evidence, by exploring how these records can be associated with the failure modes previously defined.

To achieve this objective, the following specific objectives were defined:

- Identify and structure the main failure modes, causes and effects associated with the selected hydropower plant subsystems;
- Apply reliability-oriented methodologies to organise failure mode knowledge and support the interpretation of functional failures;
- Explore historical corrective maintenance records as a source of operational evidence for failure mode analysis;
- Develop a methodology for associating maintenance records with failure modes;
- Evaluate the ability of the proposed methodology to identify plausible failure modes.

1.3 Methodological Overview

The methodological design of this dissertation follows a sequential structure. In the first stage, a FMECA was developed for the selected hydropower subsystems and complemented by a FTA. The FMECA provided the detailed catalogue of failure modes, causes, effects and criticality, whereas the FTA offered a system-level representation of how individual failure modes may contribute to broader functional failures. This stage was supported by technical literature and verified with EDP specialists.

In the second stage, historical corrective maintenance records were prepared and compared with the failure modes defined in the FMECA. The association procedure combined the technical context provided by the asset hierarchy with the textual information contained in the maintenance records, enabling the failure modes to be prioritised according to both functional relevance and textual evidence.

1.4 Dissertation Structure

This dissertation is organised into six chapters:

- Chapter 2 presents the theoretical background supporting the project;
- Chapter 3 describes the first methodological part of the dissertation;
- Chapter 4 presents the second methodological part of the dissertation;
- Chapter 5 reports and analyses the results obtained;
- Chapter 6 discusses the main findings and presents the overall conclusions of the dissertation.

Chapter 2

Theoretical Background

2.1 Asset Management: Overview

2.1.1 What is an asset?

An asset may be defined as any item, resource, or entity that has actual or potential value to an organization. This broad definition reflects the diversity of resources on which organizations depend to achieve their objectives. Accordingly, the concept of an asset extends beyond physical equipment and infrastructure to include human, financial, intangible, and information assets, all of which may contribute, directly or indirectly, to organizational performance and value creation. Nevertheless, the scope of this work is restricted to tangible assets, that is, physical items capable of generating and sustaining value during their operational life (British Standards Institution, 2008).

Assets can be classified according to their level of complexity and dependence on other assets. A simple asset performs its function independently, whereas a complex asset depends on the interaction of multiple assets. This distinction is especially relevant in asset-intensive sectors, where the performance of one asset can influence the functioning of the system as a whole.

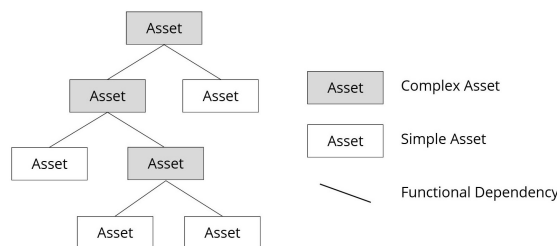


Figure 2.1: Dependency between complex and simple assets. Adapted from: Fecha (2012).

2.1.2 Asset Management Definition

For Schneider et al. (2006), asset management can be understood as the coordinated management of assets throughout their life cycle in order to ensure adequate performance, acceptable

returns and compliance with established service and safety standards. In this context, asset management plays a central role in supporting decisions that influence long-term economic sustainability and organizational performance. Hastings (2010) further emphasizes that asset management includes activities such as identifying asset needs and the associated financial resources, acquiring assets, the provision of logistical and maintenance support, and the management of asset renewal or decommissioning. Collectively, these activities aim to ensure that organizational objectives are achieved in an effective and efficient manner. However, asset management also faces important challenges, including the alignment of strategic and operational priorities with stakeholder expectations, the balancing of reliability, safety and financial performance, and the need to operate effectively within regulatory environments characterized by performance-based incentives and output-based penalties (Alquraiddi and Awad, 2024).

Asset management adopts a whole-of-life perspective, covering assets from the identification of a need to their final disposal. As shown in Figure 2.2, this perspective includes not only operation and maintenance, but also planning, evaluation, implementation, monitoring, renewal and end-of-life decisions. This approach is fundamental because choices made in the early stages of the asset life cycle have a significant effect on later performance, reliability, and total life-cycle cost (Hastings, 2010).

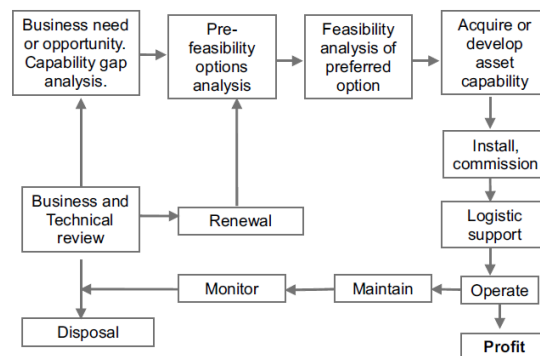


Figure 2.2: Life-cycle Asset Management. Adapted from: Hastings (2010).

Asset management plays a critical role in the success of most organizations, especially those whose activities depend on capital-intensive physical assets. In these contexts, asset management extends beyond an operational requirement and becomes a strategic capability that underpins long-term performance (Flinders, 2026).

Given this importance, it is necessary to consider the main international framework that formalizes the principles and requirements of asset management, namely the ISO 55000 series of standards.

2.1.3 ISO 55000 Series

The ISO 55000 series of standards was introduced in response to the need for a more consistent and internationally accepted approach to asset management. Before these standards were published, practices in this field had developed in a relatively fragmented way across industries and

professional areas. At that stage, PAS 55 was widely recognized as the main reference for good practice in physical asset management (Konstantakos et al., 2019).

According to Konstantakos et al. (2019), the introduction of the ISO 55000 series represented a significant milestone in the development of asset management as a formal management discipline. Like other international management system standards, ISO 55000 offers a recognized set of principles and practices that can support organizations in improving their management processes.

A key strength of this framework lies in its foundation on internationally recognized asset management experience and practices, having been developed by ISO Project Committee 251 and published in 2014 with the participation of 31 countries, which contributed to its broad international acceptance and legitimacy.

Rather than replacing existing organizational systems, the ISO 55000 series is intended to provide a framework that enables organizations to align their asset management practices with internationally established requirements and principles. In its development, particular attention was given to identifying practices that had already proven effective across different organizational and cultural contexts, thereby making the standard applicable to a wide range of asset types and sectors (Ma et al., 2014).

Although ISO 55000 was developed based on PAS 55, the scope of the new standard is considerably broader. PAS 55 was mainly focused on physical assets, whereas ISO 55000 adopts a more comprehensive and generic perspective. It is applicable to any organization and to any type of asset, whether tangible or intangible, as long as such assets contribute to the fulfillment of organizational objectives. Nevertheless, the standard is particularly relevant for asset-intensive organizations, especially those whose operational effectiveness and long-term performance depend heavily on the availability, reliability and management of physical assets (Soares, 2017).

The ISO 55000 series is composed of three complementary standards:

- ISO 55000 presents the overview, principles, and terminology of asset management.
- ISO 55001 specifies the requirements for establishing, implementing, maintaining, and improving an asset management system.
- ISO 55002 provides guidance on how to interpret and apply the requirements of ISO 55001.

In practical terms, ISO 55001 defines what an organization is expected to establish, while ISO 55002 supports the implementation process by clarifying how those requirements may be addressed. This distinction is particularly important because ISO 55001 is the certifiable standard within the series (WSP | Parsons Brinckerhoff, 2016).

2.2 Maintenance

Maintenance constitutes a fundamental function in organizations that rely on physical assets, as it supports the reliability, performance, and operational continuity of equipment and systems over time.

Although assets are generally commissioned under conditions consistent with high levels of performance and efficiency, its condition inevitably degrades throughout service life as a result of wear, ageing and operational stress. Consequently, organizations must be able to detect such deterioration and implement appropriate actions, including the replacement of worn components, in order to preserve or restore the required operating condition of their assets (Kobbacy and Murthy, 2008).

Maintenance can be defined as the “combination of all technical, administrative, and management actions carried out during the life cycle of an item, product, or service, intended to retain it in, or restore it to, a state in which it can perform the required function” (Instituto Português da Qualidade, 2021). In this sense, maintenance is not limited to the repair of failed components, but has evolved into a broader and more structured function encompassing both corrective and proactive practices ensuring that they continue to fulfill their intended purpose (Sharma and Rai, 2023; Kobbacy and Murthy, 2008).

Maintenance actions are generally guided by key objectives such as safety, quality, economic efficiency, and availability. However, balancing these objectives is not always straightforward, since improvements in one dimension may lead to trade-offs in another (Kobbacy and Murthy, 2008).

The maintenance policies adopted by an organization depend on several factors, including the characteristics of the equipment, legally required safety inspections and asset criticality (Instituto Português da Qualidade, 2021). On this basis, maintenance policies can be broadly classified as shown in Figure 2.3.

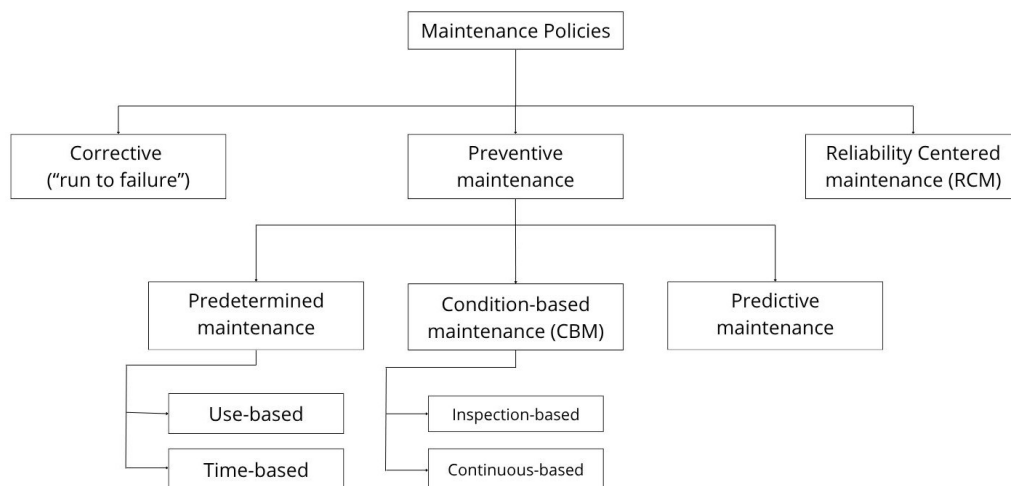


Figure 2.3: Classification of maintenance policies

Corrective maintenance, also referred to as run-to-failure, is performed after the occurrence of a failure, with the purpose of restoring the affected item to an operational condition. In most cases, it involves repairing or replacing the component responsible for the system failure (Sharma and Rai, 2023). Although this approach may be suitable for non-critical assets, its application

to critical equipment is frequently associated with unplanned downtime, production losses and higher repair costs (Mobley, 2002; Liu et al., 2024).

Preventive maintenance is based on planned interventions intended to preserve operating conditions and reduce the likelihood of unexpected failures. These interventions may be defined according to predetermined time intervals or according to the actual use of the asset, such as operating hours, production cycles or workload (Yazdi, 2024; Wang et al., 2019). Predictive maintenance relies on information regarding the actual condition or expected degradation of the asset, supporting maintenance decisions before functional failure occurs (Gulati and Smith, 2009).

A more detailed description of the main maintenance policy classifications is provided in Appendix A.

2.3 Fault Tree Analysis

Fault Tree Analysis (FTA) is a classical technique for assessing system failure and dependability. It uses a graphical and logical structure to decompose a predefined undesired event into the lower-level faults and combinations of events that may lead to its occurrence. Andrews and Lunt (nd) describe FTA as a model that expresses the causes of a given system failure mode in terms of component failure modes, while Kabir (2017) characterizes it as a well-established and widely used technique for dependability assessment in complex systems.

The primary analytical strength of FTA lies in its deductive logic. Unlike inductive approaches such as FMECA, which begin with a specific failure mode and examine its possible consequences, FTA starts from a predefined undesired system state and investigates the combinations of faults required for that state to occur (Vesely et al., 1981). This top-down reasoning makes FTA particularly suitable for analysing clearly defined system-level failures and for understanding how different contributing events may combine to produce them (Kabir, 2017).

2.3.1 Fault Tree Symbolology

A FTA is composed of three types of nodes: events, logic gates and, where necessary, transfer symbols. The events are further classified into specific categories, each serving a distinct function within the hierarchy, as shown in Figure 2.4.

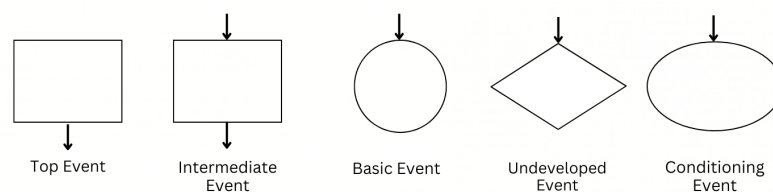


Figure 2.4: Fault tree event symbols. Adapted from: (Kabir, 2017)

A basic event in FTA is the simplest fault or component failure and is not developed further because the chosen level of detail has been reached. It is shown as a circle at the leaf level of the tree (Kabir, 2017).

The top event of the fault tree represents the specific undesired system state under investigation. As the starting point of the analysis, it defines the failure condition whose causes are progressively traced through the lower levels of the tree.

An intermediate event results from the logical combination of other events located at lower levels of the fault tree. Since it arises from antecedent causes rather than representing an initiating fault, it occupies an internal position within the tree structure and is linked to the relevant logic gate through which those causes are combined.

An undeveloped event denotes a fault event that is not analyzed beyond the current level of resolution, either because further decomposition is not required or the available information is insufficient to support additional development. It is conventionally represented by a diamond-shaped symbol.

A conditioning event represents a contextual condition or restriction attached to a logic gate, rather than a fault event in its own right. Its role is to specify the circumstances under which the associated gate relationship becomes applicable and it is conventionally represented by an elliptical symbol.

FTA utilizes logical gates, most notably the OR, AND, and XOR operators, to systematically map the causal relationships between lower-level faults and the resulting top event, as shown in Figure 2.5.



Figure 2.5: Fault tree logic gate symbols. Adapted from: (Kabir, 2017)

The OR gate is used when the output event occurs if at least one of the input events occurs. By contrast, the AND gate produces an output only when all input events occur. The typical XOR gate represents an exclusive relationship, meaning that the output event occurs when only one of the two input events occurs.

Finally, transfer symbols serve an exclusively organizational function, being utilized when the complexity of the tree requires the analysis to continue beyond the immediate diagram. Visually, these are represented by small triangular icons. The transfer-in triangle indicates that a specific branch is developed in a separate section, while a transfer-out triangle marks the corresponding entry point or continuation of that logic elsewhere in the model. By employing these markers, the analysis preserves traceability, preventing larger trees from becoming visually unmanageable.

2.3.2 Fault Tree Analysis Stages

According to Stamatelatos et al. (2002), the development of a FTA generally follows a structured sequence of eight stages:

1. Identify the objective for the FTA.
2. Define the top event of the FTA.
3. Define the scope of the FTA.
4. Define the resolution of the FTA.
5. Define ground rules for the FTA.
6. Construct the FTA.
7. Evaluate the FTA.
8. Interpret and present the results.

Figure 2.6 provides a visual representation of the eight-stage methodology outlined above.

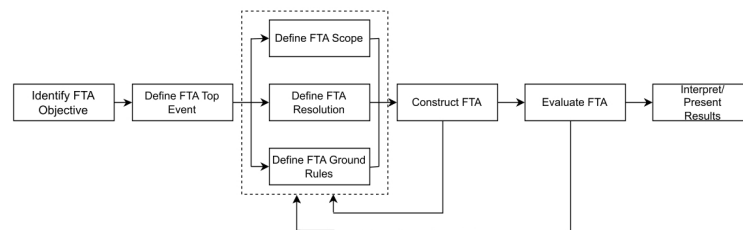


Figure 2.6: Fault Tree Analysis Steps. Adapted from: (Stamatelatos et al., 2002)

Although this process is often presented sequentially, certain stages, particularly those concerning scope, resolution and ground rules may evolve concurrently. Moreover, adjustments to the level of resolution and to the adopted assumptions may become necessary during tree construction and evaluation, reflecting the iterative nature of the method (Stamatelatos et al., 2002).

2.4 Failure Modes, Effects and Criticality Analysis

Failure Modes, Effects and Criticality Analysis (FMECA) is a structured analytical method used to identify potential failure modes, determine their causes and assess their effects on the performance of a system, process or product (International Electrotechnical Commission, 2018).

The origins of FMECA can be traced to the United States military context in the late 1940s, with MIL-P-1629 recognized as one of the earliest foundational documents for systematic failure analysis. The method emerged as a means of studying malfunctions in military systems and was subsequently refined through later standards and scientific publications (Rausand and Hoyland, 2004).

FMECA can be classified according to the object under analysis and the stage of the life cycle in which it is applied. These three major types are defined as follows:

- Design FMECA (DFMECA)
- Process FMECA (PFMECA)
- System FMECA (SFMECA)

DFMECA is applied during the product development phase with the purpose of identifying and eliminating weaknesses inherent to the design before they are transferred to production or operation. In this type of analysis, the focus is placed on potential malfunctions, reduced service life and safety or regulatory concerns that may arise from design-related factors such as material properties, geometry, interfaces with other components or systems, and the influence of operating environments. For this reason, DFMECA is especially valuable in the early stages of development, when design changes are still technically feasible and economically less costly (Teoh and Case, 2004).

PFMECA is directed at the manufacturing, assembly or operational process rather than at the product design alone. Its objective is to ensure that potential failure modes associated with the process have been identified before production takes place and that their causes and effects are properly understood. PFMECA targets faults with the potential to degrade product quality and process dependability, alongside those carrying adverse impacts for safety, environmental compliance, and consumer experience. Therefore, this methodology is particularly useful in industrial contexts where the product design may be acceptable, but the way it is produced, assembled or controlled can still generate defects or unreliability (Teoh and Case, 2004).

SFMECA extends the analysis to the level of integrated systems and larger assemblies. Rather than concentrating only on isolated components or individual process steps, SFMECA seeks to identify potential problems in complex systems, such as complete installations or production lines. Its relevance lies in the fact that failures at system level often emerge not only from the malfunction of a single item, but also from the interaction between subsystems, functions and interfaces. For that reason, SFMECA is closely connected with hierarchical system decomposition and functional analysis. This broader scope makes SFMECA particularly appropriate for systems in which performance depends on the coordinated operation of several subsystems (Stamatis, 2003).

Compared with Failure Mode and Effects Analysis (FMEA), FMECA provides a more comprehensive framework by incorporating criticality analysis into the assessment of failure modes. This additional analytical dimension supports the prioritisation of potential failures according to their relative significance and enables the identification of components that are particularly relevant from reliability, safety and operational perspectives (DAU Acquipedia, 2024). Nevertheless, although FMEA and FMECA refer to conceptually distinct approaches, the boundary between the two has become increasingly blurred, and the terms are often used interchangeably in both technical and academic contexts (Stamatis, 2003).

2.4.1 How to perform a FMECA

The FMECA is a rigorous and iterative analytical methodology that unfolds across a structured sequence of stages. According to Rausand and Hoyland (2004), the methodology comprises four sequential phases:

System Definition and Functional Analysis: A robust FMECA requires that the boundaries, operating environments and intended functions of the system are clearly established before any failure analysis is conducted. The system is decomposed into hierarchical indenture levels, from the overall system down to subsystems, which may themselves be further decomposed into lower-level assemblies and components (Borgovini et al., 1993). As noted by Brumbach and Clade (2013), distinguishing between active functions and passive features during this stage is critical to ensure that the scope of the analysis remains precise and focused.

Failure Mode, Effects and Potential Causes Identification: Once the system architecture has been defined, the analysis proceeds to identify the potential failure modes, their effects on the system, and the causes underlying each failure. This phase follows an internally consistent logical sequence comprising three interdependent sub-steps:

- **Identification of Failure Modes:** All probable independent failure modes are systematically defined. A failure mode represents the specific physical or functional mechanism by which a component fails to meet its operational requirements or intended performance baseline (Brumbach and Clade, 2013).
- **Evaluation of Failure Effects:** The systemic consequences of each failure mode are then thoroughly documented, covering the immediate local impact on the affected component, the resultant effect on the next-higher assembly and the worst-case consequence on the overall system mission (Brumbach and Clade, 2013).
- **Determination of Potential Causes:** The root causes underlying each failure mode are investigated. Understanding the origin of a failure mode is a prerequisite for eliminating it or reducing its probability of occurrence (Brumbach and Clade, 2013).

Criticality Assessment This stage is initiated only after the local and the higher-level effects of each failure mode have been fully delineated. Its primary objective is to rank each identified failure mode according to its relative significance, producing a prioritised hierarchy that reflects its potential impact on system safety, operational continuity, and mission success. The choice of analytical framework is primarily determined by the maturity and availability of reliability data (Borgovini et al., 1993):

- **Qualitative Approach:** Applied when empirical failure rates and detailed component data are unavailable. Risk ranking relies on structured expert-based categorisations.

- **Quantitative Approach:** Applied when robust statistical failure data are available, enabling the mathematical derivation of quantitative criticality indices and a data-driven ranking of failure modes.

Implementation of Corrective Measures and Systemic Standardization: The corrective action sections of the FMECA worksheet document the specific nature of the agreed interventions. Once implemented, a revised risk assessment verifies the resulting reduction in system risk. These corrective actions should subsequently be formalised into standard maintenance procedures and incorporated into the organisation's asset management practices, ensuring that the insights gained from the analysis are systematically applied across the asset fleet.

An alternative representation of the FMECA logical sequence, as established by International Electrotechnical Commission (2018), is illustrated in Appendix B.

2.5 Textual Data Analysis

The growing volume of textual data generated in maintenance operations creates opportunities to extract structured knowledge from records that were not originally conceived for analytical purposes. Although maintenance records may contain relevant information for reliability analysis, their content is typically recorded in semi-structured or unstructured natural language. In this context, Text Mining and Natural Language Processing (NLP) provide methods for transforming textual information into structured or computationally comparable representations.

2.5.1 Text Mining and NLP

Text Mining refers to the process of extracting patterns and knowledge from unstructured textual data. According to Hotho et al. (2005), this field combines techniques from information retrieval, natural language processing, data mining and statistics. This approach is particularly relevant when information is recorded in natural language, since textual records cannot be directly analysed in the same way as structured databases. In this sense, text mining provides the conceptual basis for transforming textual information into a form that can support computational analysis.

Natural Language Processing (NLP) supports this broader text mining process by providing methods for handling the linguistic structure of textual data. It enables operations such as text cleaning, normalisation, tokenisation and representation, making textual records suitable for comparison and computational modelling (Collobert and Weston, 2008; Rajman and Besançon, 1998).

2.5.2 TF-IDF

Term Frequency-Inverse Document Frequency (TF-IDF) is a classical term-weighting scheme widely used in text analysis and information retrieval. The method combines two complementary components: term frequency, which captures the occurrence of a term within a specific document and inverse document frequency, which reduces the influence of terms that appear frequently

across the overall corpus. The inverse document frequency component was originally introduced by Sparck Jones (1972) as a way to account for term specificity, assigning greater relevance to terms that are less common in the document collection. This combination is commonly referred to as TF-IDF (Kowsari et al., 2019).

The TF-IDF value of a term t in a document d is given by Equation 2.1.

$$\text{TF-IDF}(t, d) = \text{TF}(t, d) \times \text{IDF}(t) \quad (2.1)$$

The Term Frequency component, as shown in Equation 2.2, captures the local relevance of the term within the document:

$$\text{TF}(t, d) = \log(1 + \text{freq}(t, d)) \quad (2.2)$$

where:

$\text{freq}(t, d)$: frequency count of term t in document d .

The second component, Inverse Document Frequency (IDF), reflects the specificity of the term across the corpus, as defined in Equation 2.3.

$$\text{IDF}(t) = \log\left(\frac{N}{\text{df}(t)}\right) \quad (2.3)$$

where:

N : total number of documents in the corpus;

$\text{df}(t)$: number of documents containing term t .

TF-IDF can also be used as a vectorisation method. In this representation, each document is transformed into a numerical vector, where each dimension corresponds to a term in the vocabulary and each value corresponds to the TF-IDF weight of that term. This allows textual units with different lengths and structures to be represented within a common numerical space and compared computationally (Shahmirzadi et al., 2019).

Once the textual descriptions are represented as TF-IDF vectors, their similarity can be measured using cosine similarity. This metric compares the orientation of two vectors in the vector space making it suitable for assessing similarity between textual descriptions with different lengths (Wang and Dong, 2020). The cosine similarity between the TF-IDF vector of a maintenance record r_i and the TF-IDF vector of a failure mode f_j can be written as shown in Equation 2.4.

$$S_{TFIDF}(r_i, f_j) = \cos(\mathbf{v}_{r_i}, \mathbf{v}_{f_j}) = \frac{\mathbf{v}_{r_i} \cdot \mathbf{v}_{f_j}}{\|\mathbf{v}_{r_i}\| \|\mathbf{v}_{f_j}\|} \quad (2.4)$$

where:

$\mathbf{v}_{r_i}$: TF-IDF vector representation of maintenance record r_i ;

$\mathbf{v}_{f_j}$: TF-IDF vector representation of failure mode f_j .

2.5.3 BM25

BM25, also known as *Best Matching 25*, is a lexical ranking function widely used to estimate the relevance of a document with respect to a given query. The method is derived from the Probabilistic Relevance Framework and ranks documents according to the occurrence of query terms (Robertson and Zaragoza, 2009; Melo, 2023).

Compared with simpler frequency-based approaches, BM25 refines lexical ranking by considering how the contribution of query terms is weighted within each document. In particular, the method incorporates term frequency saturation, which prevents repeated occurrences of the same term from increasing the score indefinitely and document length normalisation, which compensates for differences in text length and reduces the tendency for longer documents to be favoured merely because they contain more terms (Robertson and Zaragoza, 2009).

The BM25 score of a document d with respect to a query q can be expressed as in Equation 2.5.

$$\text{BM25}(q, d) = \sum_{t \in q} \text{IDF}(t) \cdot \frac{f(t, d)(k_1 + 1)}{f(t, d) + k_1 \left(1 - b + b \frac{|d|}{\text{avgdl}}\right)} \quad (2.5)$$

where:

$f(t, d)$: frequency of term t in document d ;

$|d|$: length of document d ;

avgdl : average document length in the corpus;

k_1 : parameter controlling term frequency saturation;

b : parameter controlling document length normalisation.

The behaviour of these two mechanisms is controlled by the parameters k_1 and b . The parameter k_1 regulates the sensitivity of the score to repeated term occurrences, with lower values producing faster saturation and higher values allowing term frequency to have a stronger effect. The parameter b defines the degree of length normalisation, usually within the interval $0 \leq b \leq 1$: when $b = 0$, no length normalisation is applied and $b = 1$ corresponds to full normalisation (Robertson and Zaragoza, 2009).

The inverse document frequency component, given by Equation 2.6, gives higher relevance to terms that occur in fewer documents and therefore have greater discriminating value:

$$\text{IDF}(t) = \log \left(\frac{N - n_t + 0.5}{n_t + 0.5} + 1 \right) \quad (2.6)$$

where:

N : total number of documents in the corpus;

n_t : number of documents containing the term t ;

2.5.4 Jaccard Similarity

Jaccard similarity is a set-based measure used to quantify the degree of overlap between two sets. It has been widely adopted in text similarity tasks due to its simplicity and interpretability.

In textual applications, each text can be represented as a set of tokens and the similarity between two texts is computed as the ratio between the number of shared tokens and the total number of distinct tokens present in either set (Wang and Dong, 2020).

Given two token sets A and B , the Jaccard similarity is defined as in Equation 2.7.

$$\text{Jaccard}(A, B) = \frac{|A \cap B|}{|A \cup B|} \quad (2.7)$$

where:

$A \cap B$: set of tokens shared by both texts;

$A \cup B$: set of distinct tokens appearing in either text.

The resulting value ranges from 0 to 1. A value of 0 indicates that the two texts do not share any tokens, whereas a value of 1 indicates that both token sets are identical. Jaccard similarity provides a direct measure of lexical overlap, making it particularly useful when the objective is to assess whether two textual descriptions share explicit terms.

2.5.5 Sentence Embeddings

Text embeddings are numerical representations that convert textual information into vectors. Their purpose is to represent natural language in a form that can be processed computationally, while preserving relationships between textual units. In this type of representation, each word, sentence or text segment is mapped to a position in a multidimensional vector space, where textual units with related meanings tend to be represented by vectors that are close to one another.

Initial embedding approaches focused primarily on word-level representations, in which each term is mapped to a dense vector in a multidimensional space. Models such as Word2Vec and GloVe learn these representations from large text corpora, based on the distributional assumption that words occurring in similar contexts tend to have related meanings (Mikolov et al., 2013; Pennington et al., 2014). However, because word embeddings operate at the level of isolated terms, they do not directly provide a unified representation for the semantic content of larger and more complex textual units such as sentences, as illustrated in Figure 2.7.

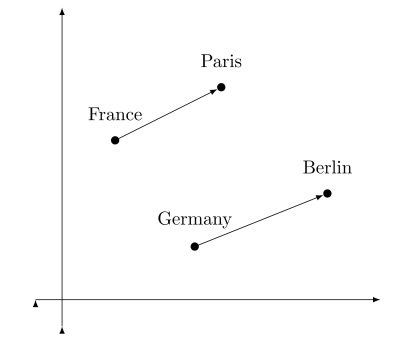


Figure 2.7: Example of Word Embeddings in a vector space.

Sentence embeddings are dense vector representations that encode the semantic content of complete textual units. Their main objective is to map text into a continuous vector space in which semantically related textual units are positioned close to one another. This representation is particularly relevant for tasks involving semantic textual similarity, clustering, information retrieval and semantic search, since it allows two textual descriptions to be compared according to their meaning (Reimers and Gurevych, 2019).

Among the different approaches for generating sentence embeddings, transformer-based methods are particularly relevant, as they rely on transformer encoders to produce contextual token representations that can subsequently be aggregated into a representation of the complete textual unit. Transformer-based models generate context-dependent representations, meaning that each token is encoded not only according to its isolated lexical form but also according to its position and the relations it establishes with the other elements of the input sequence (Reimers and Gurevych, 2019).

This contextualisation is achieved through the self-attention mechanism introduced in the Transformer architecture (Vaswani et al., 2017). After tokenisation, tokens are converted into vector representations and combined with positional information, allowing the model to consider both token meaning and word order. These representations are then processed by transformer encoder layers, where multi-head self-attention enables each token to incorporate information from the remaining tokens in the sequence, capturing both local and long-range dependencies. This contextual nature is particularly relevant because the meaning of a sentence or short textual description depends on the interaction between its constituent words (Vaswani et al., 2017; Wang and Dong, 2020).

The practical relevance of transformer-based embeddings also derives from the availability of pre-trained models, which can be used to encode text without training a language model from scratch. These models already incorporate general linguistic knowledge acquired from large text corpora and can be directly applied or adapted. Multilingual transformer-based embeddings extend the same principle to multilingual settings. Nevertheless, their effectiveness in highly specialised technical domains depends on the extent to which the model adequately represents the terminology and semantic distinctions specific to that domain (Reimers and Gurevych, 2020).

Chapter 3

Methodology - First Part

3.1 Hydropower Generation Context

Hydropower generation represents one of the most established and strategically significant sources of renewable electricity in Portugal, combining high operational flexibility with the capacity for large-scale dispatchable production. In 2025, renewable generation supplied 68% of national electricity consumption, with hydropower alone accounting for 27 percentage points of that total (REN, 2026). Within EDP, hydropower remained a relevant component of the generation portfolio, representing 25% of the group's total electricity generation (EDP - Energias de Portugal, 2026).

In Portugal, EDP operates 49 hydropower plants across three operational centres: Cávado-Lima, Douro and Tejo-Mondego, comprising a total of 110 generation units. The scale and geographical distribution of this portfolio highlight the complexity of managing hydropower assets. In this context, asset reliability and availability are directly linked to operational safety, generation continuity and the achievement of EDP's economic and environmental objectives. Failures in critical equipment may lead to the unavailability of the affected generation unit, with relevant economic consequences and a potential sustainability impact.

Asset management decisions exceeding a defined financial threshold are supported by structured assessment processes that consider the asset health index, including aspects such as asset age, inspection findings and condition monitoring indicators. This assessment is complemented by a reliability-based analysis, often supported by Weibull lifetime models, to enable portfolio comparison and investment prioritisation. However, the Weibull parameters currently used are typically derived from manufacturer data or technical literature rather than from historical maintenance records. This approach may create discrepancies between theoretical failure expectations and actual operational behaviour observed in the field. EDP Production's exploration and Reliability department has identified the need to strengthen reliability assessments by transforming historical maintenance records into structured failure mode information. This requires linking reported faults to specific failure modes, enabling the operational evidence recorded by technicians to support failure mode analysis and reliability-oriented decision-making.

3.2 Subsystem Selection

The initial scope of the study was established in collaboration with EDP and comprised four hydropower plant subsystems:

- Turbine
- Generator
- Power transformer
- Circuit Breakers

The selection is consistent with the functional relevance of these assets, as they represent key stages in the energy conversion and grid connection sequence of a hydropower plant, illustrated in simplified form in Figure 3.1.

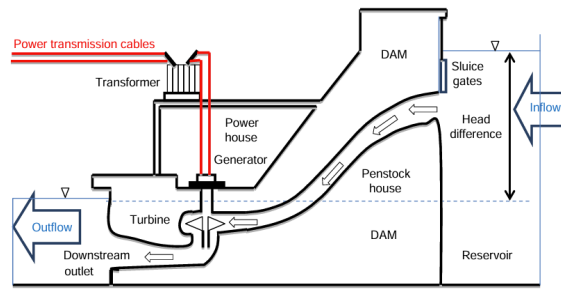


Figure 3.1: Simplified representation of a hydropower plant. Adapted from: (Şen, 2018)

The main electrical path between the generator and the grid connection point is represented in Figure 3.2. The scheme includes the generator circuit breaker, located on the generator side, the power transformer responsible for stepping up the generated voltage and the generation unit circuit breaker at the high-voltage side, which controls and protects the interface with the electrical grid.

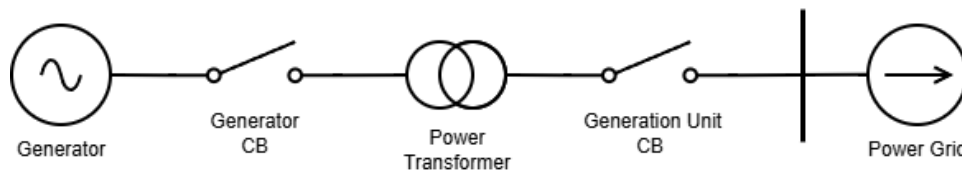


Figure 3.2: Simplified scheme of the generator connection to the electrical grid.

Table 3.1 summarises the main function of each selected subsystem within the hydropower generation and grid connection process. This scope allows the analysis to focus on assets with a direct role in generation continuity, while preserving an appropriate level of analytical depth within the constraints of the study.

Table 3.1: Selected subsystems and their main function in the hydropower plant.

Subsystem	Main function
Turbine	Converts hydraulic energy into mechanical rotational energy
Generator	Converts mechanical rotational energy into electrical energy
Power transformer	Adapts the voltage level of the generated electricity for grid connection
Circuit breakers	Provide switching, isolation and protection functions in the electrical path

3.3 Application of FMECA

3.3.1 Planning and Analysis Stage

The FMECA provided a common reference for reliability analysis and for the subsequent association with historical maintenance records. The development process followed three sequential stages: functional analysis and system decomposition, identification of failure modes and their criticality analysis, and iterative validation with EDP specialists.

Functional analysis and decomposition. A preliminary functional analysis was conducted for each subsystem to characterise its internal structure and identify the relevant components. The level of decomposition considered was consistent with the available technical documentation and the operational knowledge required for validation.

The functional analysis was supported by EDP specialists from each corresponding technical area, whose input was essential to ensure that the decomposition remained aligned with the operational configuration of EDP's hydropower assets.

Failure mode identification. The identification of failure modes, causes and effects was supported by a combination of technical literature, equipment-specific documentation and operational knowledge provided by EDP specialists. The literature review enabled the identification of failure mechanisms commonly associated with the subsystems under study, whilst an initial criticality assessment was established on a preliminary basis. The parameters and scales used in the criticality assessment are described in detail in Section 3.3.2.

Iterative validation. Once the FMECA worksheets had been completed, a validation round was carried out with specialists from each technical area. The objectives of this review were to assess whether the identified failure modes were technically adequate and consistent with the operational reality and to identify any relevant failure modes that had been omitted. The discussion of each failure mode during this stage also enabled the refinement of the initial criticality scores. This iterative process ensured that the FMECA neither remained a purely theoretical compilation of failure mechanisms nor became an overly narrow representation conditioned by a single source of knowledge.

3.3.2 Criticality Analysis

A criticality analysis was carried out to assign a numerical index to each failure mode, enabling the identified failures to be compared within the FMECA. This approach is aligned with the general principles of International Electrotechnical Commission (2018), in which criticality analysis complements the identification of failure modes and effects by supporting the relative assessment of their importance for decision-making. The purpose of this stage was not to obtain a measure of absolute risk but to establish a consistent and technically grounded basis for comparing the failure modes considered.

The criticality analysis was based on three parameters: Severity (S), Occurrence (O) and Detectability (D). Severity reflects the magnitude of the consequences associated with a failure mode, Occurrence represents its expected frequency and Detectability expresses the likelihood that the failure can be identified before producing its full functional effect. The assigned Severity, Occurrence and Detectability scores were combined into the Risk Priority Number (RPN).

3.3.2.1 Severity

The Severity scale was conceptually adapted from the Functional Failure Impact logic proposed by da Silva et al. (2023), in which the impact of a functional failure is assessed across multiple consequence dimensions. This rationale was incorporated into the FMECA framework by evaluating Severity through three impact axes:

1. Safety and Asset Integrity (SAI)
2. Environmental Impact (EI)
3. Operational Performance and Financial Impact (OPFI)

The criteria used to assign each severity level are presented in Table 3.2. The final Severity score, as defined in Equation 3.1, was assigned by selecting the maximum value obtained across the three impact axes:

$$S = \max(SAI, EI, OPFI) \quad (3.1)$$

This criterion ensures that the severity of a failure mode is determined by its most critical potential consequence. As a result, a failure mode with limited operational or safety impact but with severe implications for the environment is not underestimated by lower scores in the remaining axes. This approach is particularly appropriate in the hydropower context, where failures may have consequences across different dimensions of asset management and where high-impact events should remain clearly visible in the criticality analysis.

Table 3.2: Ranking the Severity

Severity	Safety and Asset Integrity (SAI)	Environmental Impact (EI)	Operational Performance and Financial Impact (OPFI)
1	Negligible impact on staff and no damage to facilities.	No significant environmental impact.	No relevant impact on availability or economic performance.
2	Minor injury or minor damage to facilities.	Minor environmental impact.	Degraded operating condition without unavailability or low economic impact.
3	Major injury or serious local damage to facilities.	Moderate environmental impact.	Noticeable loss of generation or significant economic impact.
4	Severe injury or critical damage to facilities.	Severe environmental impact.	Severe loss of generation or very high economic impact.
5	Fatality or catastrophic damage to facilities.	Catastrophic environmental impact.	Total loss of generation or huge economic impact.

3.3.2.2 Occurrence

The Occurrence scale was defined with reference to the Failure Mode Probability classification proposed by da Silva et al. (2023). The attribution of the Occurrence score was primarily supported by expert judgement from EDP specialists, whose operational knowledge was essential to assess the expected recurrence of each failure mode within the analysed subsystems. Since statistically robust historical failure records were not available for each failure mode, the resulting classification should be interpreted as an expert-informed estimate of expected frequency rather than as a direct calculation from maintenance history.

Table 3.3: Occurrence ranking criteria

Occurrence	Classification	Expected frequency of occurrence
1	Very Low	Failure mode is expected to occur very rarely, with an estimated MTBF greater than 60 months.
2	Low	Failure mode is expected to occur rarely, with an estimated MTBF between 36 and 60 months.
3	Medium	Failure mode is expected to occur occasionally, with an estimated MTBF between 12 and 36 months.
4	High	Failure mode is expected to occur frequently, with an estimated MTBF between 3 and 12 months.
5	Very High	Failure mode is expected to occur very frequently, with an estimated MTBF lower than 3 months.

3.3.2.3 Detectability

Detectability assesses the extent to which a failure mode, or its symptoms, can be identified before producing its full functional effect. Consistently with the RPN logic, higher Detectability scores correspond to lower detection capability, since undetected failure modes contribute to higher overall criticality.

A four-point scale was adopted for Detectability, in contrast to the five-point scale applied to Severity and Occurrence. This choice reflects the practical observation that detection capability can be meaningfully distinguished across four categories: failure modes detectable through continuous monitoring or protection systems; failure modes detectable through periodic inspection or condition-based checks; failure modes that require specific diagnostic procedures or detailed inspections for detection and failure modes for which no practicable detection means are available. The criteria used to assign each Detectability level are presented in Table 3.4.

Table 3.4: Ranking the Detectability

Detectability	Detection Probability	Description
4	Very Low	No practicable means are available to detect the failure mode.
3	Low	Failure mode is difficult to detect before failure and may only be identified through specific diagnostic procedures or detailed inspections.
2	Moderate	Failure mode may be detected before failure through periodic inspections, maintenance routines or condition-based checks.
1	High or Very High	Failure mode is likely to be detected before failure through continuous monitoring, protection systems, alarms or operational indicators.

3.3.2.4 Risk Priority Number (RPN)

The Risk Priority Number (RPN) was used as the numerical output of the criticality analysis, combining the scores assigned to Severity, Occurrence and Detectability. This approach is consistent with the FMECA logic described in International Electrotechnical Commission (2018), where the RPN is used to support the relative ordering of failure modes according to their criticality. The RPN, as defined in Equation 3.2, was calculated as:

$$RPN = S \times O \times D \quad (3.2)$$

Since Severity and Occurrence were rated on a scale from 1 to 5, while Detectability was rated on a scale from 1 to 4, the resulting RPN ranges from 1 to 100. Higher values indicate failure modes with greater relative criticality within the adopted FMECA framework.

3.3.3 FMECA Outputs

The FMECA developed in this work covers the failure modes identified for all four subsystems within the scope of the study. Given the extent of the analysis, the complete worksheets are provided in Appendix D, as presenting all four subsystems in the main body would disrupt the methodological flow without adding analytical clarity. Consequently, the chapter focuses on a representative application to illustrate the structure and the reasoning followed in the identification and criticality analysis, leaving the appendix for full reference.

The power transformer was selected as a representative application of the methodology. The power transformer transfers electrical energy between magnetically coupled windings by electromagnetic induction, changing the voltage and current levels of an alternating current system while maintaining the same frequency. In the context of a hydropower plant, this function enables the voltage produced by the generator to be adapted to the requirements of the grid.

To structure the FMECA, the power transformer was organised according to its main functional areas and components, as described in Appendix C. This decomposition was necessary because failure modes do not occur at the level of the transformer as a whole but are associated with specific elements that perform distinct electrical, mechanical, insulating, cooling, protection or control functions. The functional breakdown therefore provides the basis for associating each failure mode with the element where it originates and for interpreting it in terms of its causes and effects.

Figure 3.3 presents a selected set of failure modes from the power transformer FMECA. The examples were chosen to illustrate the technical reasoning underlying the analysis, with particular attention to failure modes associated with higher RPN values.

Component	Failure Mode	Effects	Cause	Severity	Occurrence	Detectability	RPN	
Core	Displacement of core steel	Core geometrical changes; Increase in core temperature; Progressive damage to adjacent insulation	Manufacturing defects; Mechanical deformation	5	Catastrophic	1 Very Low	4 Very Low	20
Protection system	Buchholz relay malfunction	Loss of the early-detection function (failure to operate); Spurious alarm or trip (unwanted operation)	Internal relay defect	5	Catastrophic	1 Very Low	4 Very Low	20
Protection system	Pressure relief valve malfunction	Overpressure is not adequately relieved (failure to operate) or pressure is released unnecessarily (unwanted operation); Risk of tank rupture; Unavailability due to unwanted operation	Device defect; Inadequate maintenance; Incorrect calibration	5	Catastrophic	1 Very Low	4 Very Low	20
Clamping	Failure of the clamping system	Reduction in the mechanical stiffness of the assembly; Relative displacement of the windings; Increased susceptibility to deformation under short-circuit; Increased risk of partial discharges	Mechanical ageing; Insufficient maintenance	4	High	1 Very Low	3 Low	12
Winding	Winding deformation	Geometrical changes; Degradation of conductor insulation; Weakening of clamping; Mechanical instability	Short-circuits; Ageing; Insufficient clamping; Mechanical damage	4	High	1 Very Low	3 Low	12
Winding	Insulation failure	Localised overheating; Progressive winding degradation; Short-circuits; Protection trips	Ageing; Abnormal deterioration; Mechanical damage; Contamination	4	High	3 Medium	1 High	12
Bushing	Bushing insulation degradation	Occurrence of partial discharges; Reduction in the dielectric strength of the insulation; Localised heating of the bushing	Contamination and ageing of the bushing; Moisture	4	High	3 Medium	1 High	12

Figure 3.3: Selected critical failure modes identified for the power transformer

Among the failure modes presented, the displacement of core steel was selected for further discussion due to its high criticality and its relevance to the integrity of the transformer active part. This failure mode refers to the displacement of one or more laminations from their intended position within the transformer core. Since the core provides the magnetic path that guides the flux between windings, its geometrical integrity is essential to maintain the transformer within its intended magnetic and thermal operating conditions. The laminated structure, typically composed of mutually insulated steel sheets, is designed to reduce core losses and limit circulating currents between laminations (Ponnaluri et al., 2001).

Displacement of core steel may result from manufacturing-related deficiencies, such as inadequate stacking or assembly of the laminations, but it may also result from mechanical deformation

during the transformer service life. Transportation, installation, vibration, shock loads or severe electrical fault events can impose mechanical stresses on the active part. In particular, short-circuit conditions can generate intense electromagnetic forces capable of deforming the core structure and disturbing the alignment of the lamination stack.

This failure mode alters the geometry of the magnetic circuit, disturbing the intended flux path and potentially increasing core losses and non-uniform flux distribution. If the displacement compromises adjacent insulation, local overheating may occur, promoting the formation of thermal hotspots. This degradation mechanism can progressively affect the cellulose insulation surrounding the core and adjacent windings, reducing dielectric strength and increasing the likelihood of internal electrical faults.

The severity of this failure mode was classified as catastrophic. If the degradation process evolves without effective detection or corrective intervention, insulation deterioration may culminate in dielectric breakdown or internal arcing, representing a destructive failure scenario with substantial economic losses, extended unavailability of the generating unit and, in severe cases, fire or explosion risk. Occurrence was classified as very low, reflecting the high manufacturing standards applied to power transformers and the relatively infrequent nature of events capable of producing significant core deformation. Detectability was classified as very low, since early-stage displacement does not usually produce clear external symptoms and may remain hidden until secondary effects, such as abnormal heating, dissolved gas formation or protection operation become evident.

The remaining failure modes included in the table also illustrate other relevant degradation mechanisms affecting different functional areas of the power transformer. Failure of the clamping system and winding deformation are associated with the mechanical stability of the active part. Insulation failure and bushing insulation degradation are directly related to the dielectric integrity and may lead to partial discharges, localised overheating or short-circuits. Overall, these examples highlight the need to interpret transformer failure modes from a system-level perspective, since their consequences may propagate from specific components to broader effects on insulation integrity, thermal performance, protection functions and generation availability.

3.4 Application of FTA

A Fault Tree Analysis was developed as a complementary representation of the failure modes identified through the FMECA. The two representations are complementary: the FMECA provides analytical depth at the failure mode level, whilst the FTA reorganises this information into a hierarchical graphical structure.

Consistent with this purpose, the FTA developed in this work does not introduce failure modes beyond those already identified in the FMECA. The complete fault tree is presented in Appendix E.

3.4.1 Structure of the Fault Tree

The top event of the fault tree was defined as the inability of the hydropower generation unit to produce electrical energy. This definition was adopted because it represents the most consequential functional failure at the system level.

From the top event, the tree was decomposed into four branches corresponding to the subsystems included in the study. These four branches are connected to the top event through an OR gate, reflecting the fact that the failure of any one of these subsystems is individually sufficient to prevent the generation unit from producing electrical energy.

Within each subsystem branch, the failure modes identified in the FMECA were reorganised according to the component or functional area to which they belong. Intermediate events were introduced only when they improved the interpretation of the tree, by grouping failure modes that shared a common functional or failure-related logic.

At the lowest level of the tree, circular nodes represent the individual failure modes previously defined in the FMECA. These events were not further decomposed, as they correspond to the lowest level of resolution adopted in the analysis. This structure ensures full traceability between the FTA and the FMECA, since each basic event in the tree can be directly linked to a specific failure mode in the FMECA worksheet.

3.4.2 Validation

The fault tree structure was reviewed with EDP specialists to ensure that the grouping of failure modes under intermediate events and their relationship with higher-level functional failures were consistent. Adjustments were made to the intermediate event definitions where the initial structure did not adequately reflect the dependencies observed in practice.

It should be noted that the FTA developed here is qualitative in nature. No quantitative evaluation of minimal cut sets or failure probability estimates was performed, as the objective was to produce a structural synthesis of the FMECA content rather than a probabilistic risk quantification.

Chapter 4

Methodology - Second Part

This chapter presents the second part of the methodology, concerned with the operational application of the framework developed in Chapter 3. Building on the FMECA previously developed, which defines the set of admissible failure modes for the assets under analysis, the present chapter develops a structured and replicable procedure to associate each maintenance record with the most plausible failure mode related to the reported event.

Figure 4.1 summarizes the overall structure of the procedure adopted, providing an overview of the main stages and the logical flow connecting them.

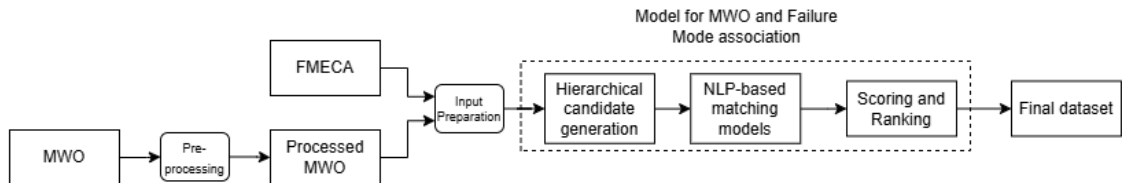


Figure 4.1: Framework for associating maintenance records with failure modes

As illustrated in Figure 4.1, the procedure operates from two primary inputs: the maintenance records provided and the FMECA previously developed. Prior to the association stage, both inputs are subject to a preparatory phase: the maintenance records are preprocessed to ensure consistency and usability and the FMECA is organized into a structured format suitable for comparison.

The association model follows a constrained logic because the comparison between maintenance records and failure modes is not performed exhaustively across all possible combinations. Instead, technical compatibility is first established through the functional hierarchy of the asset, which defines, for each maintenance record, a restricted set of candidate failure modes. These candidates are subsequently evaluated using NLP-based association models and ranked according to the resulting similarity scores. This two-stage approach is intended to improve the accuracy and interpretability of the associations produced.

The following sections describe each stage of the methodology in detail.

4.1 Characterization of Maintenance Records

Fault notifications and maintenance work orders represent two distinct types of records within the maintenance process, although they are closely interrelated. Understanding their individual purpose and the relationship between them is essential for the correct interpretation of maintenance data and, consequently, for the application of the proposed methodology.

A fault notification constitutes the initial record of an anomaly or failure condition identified in an asset or system. Its primary purpose is to communicate the existence of a problem, typically documenting what was observed, the location where it occurred and the symptoms detected at the time of identification.

A maintenance work order represents the logical subsequent step in the corrective maintenance process, following the creation of a fault notification. The work order formalises the maintenance intervention required to address the reported event. It is through the work order that the corrective action is planned, executed and controlled, documenting the tasks performed, the duration of the intervention and any additional technical observations recorded by the maintenance technicians.

4.1.1 Records and Corrective Maintenance Process

In the corrective maintenance process, fault notifications and maintenance work orders form two complementary records of the same failure event. While the fault notification captures the initial identification of the anomaly, the associated work order documents the maintenance intervention undertaken to restore the asset to its required operating condition. Together, these records provide a more complete representation of the failure occurrence.

Their relevance extends beyond operational control. From a maintenance management perspective, these records document the affected asset, the reported occurrence and the intervention carried out. From a reliability analysis perspective, they constitute historical evidence that can be used to identify recurrent failure patterns, characterise asset behaviour over time and, when the relevant temporal fields are properly recorded, support the calculation of reliability and maintainability indicators such as Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR).

For the proposed methodology, fault notifications and maintenance work orders are both considered relevant sources of information, as they may contain complementary data for identifying the most plausible failure mode associated with each reported occurrence.

4.1.2 Limitations of Raw Records

Although maintenance records constitute a valuable source of operational information, their direct use in the proposed methodology is constrained by several data quality limitations. The most

relevant limitation concerns the use of free-text description fields, which are neither fully standardised nor subject to consistent quality control. The content of these fields depends on the individual responsible for creating the record and on the level of detail provided. As a result, some records contain detailed information regarding the observed anomaly and intervention performed, whereas others include only brief or generic descriptions. This variability introduces inconsistencies, since the ability to associate a maintenance record with a failure mode depends on the specificity of the textual evidence available.

A second relevant limitation concerns the installation location associated with each record, which may be defined at an insufficiently granular level or not defined at all. Since the proposed methodology uses the functional hierarchy to restrict the set of candidate failure modes, incomplete or overly generic functional position information can reduce the technical specificity of the association process. Finally, inconsistencies in the dates and times recorded in the maintenance system may compromise the calculation of reliability and maintainability indicators. However, these temporal fields do not directly affect the association procedure developed.

4.1.3 Data Used

The execution of the proposed methodology required the use of data sources. The first source of data consisted of the files containing the fault notifications and the maintenance work orders. These records constituted the operational basis of the analysis as they contain the historical information associated with maintenance events. From both files, the following fields were used:

1. Title – short textual field containing a concise description of the reported fault or maintenance intervention;
2. Description – free-text field providing additional information on the occurrence, symptoms, intervention or technical observations recorded during the maintenance process;
3. Installation location – coded functional position used to identify the exploration zone, the hydroelectric power plant, the generation unit and the component or subsystem involved in the event.

For the maintenance work orders, the field containing the associated fault notification was also considered. This field enabled the relationship between the two types of records to be established. The procedure adopted consisted of using each fault notification as the reference record and searching, in the maintenance work order file, for the work order linked to it through the fault notification column. In this way, each historical failure could be analyzed together with the corresponding corrective intervention, ensuring that only work orders associated with corrective maintenance events were included in the study.

The title and description fields were used as the main source of textual information, since they contain the natural language evidence required to interpret each maintenance record and compare it with the failure modes defined in the FMECA. The installation location was used to identify the component or subsystem to which maintenance record refers.

In addition to the historical maintenance records, the FMECA developed in Chapter 3 was used as a central input of the methodology, providing the structured set of failure modes on which the matching and ranking procedure was based.

Two internal documents were also used to support the interpretation and standardisation of the data. The first consisted of a file containing the abbreviations commonly used in this maintenance context. This information was relevant because the textual fields of maintenance records frequently include abbreviated terms used by the technicians. The second document corresponded to an internal standard used to decode the component or subsystem embedded in the installation location.

The maintenance records considered in this study cover the period from October 2024 onwards and comprise more than 5.650 records.

Given the operational nature of these records and the variability associated with free-text descriptions, a preprocessing stage was required before applying the failure mode association model.

4.2 Data Preparation and Preprocessing

Before the association methodology could be applied, it was necessary to ensure that both input datasets were represented in a textual form that was consistent and structurally compatible with one another. Raw operational data is often affected by formatting inconsistencies, incomplete or heterogeneous descriptions and other sources of textual noise, all of which compromise the reliability of these types of analysis. Accordingly, a systematic preprocessing pipeline was implemented in Python, using dedicated data manipulation and text-processing libraries to support the cleaning, normalisation, tokenisation and export of the processed datasets. Prior to this computational phase, a preliminary integration step was carried out in *Microsoft Excel* to consolidate the relevant maintenance records into a single structured file. The following sections describe each stage of this process in full detail.

4.2.1 Maintenance Records

As previously discussed, the maintenance history was initially distributed across two distinct files: one containing the fault notifications and another containing the maintenance work orders. The work orders file included, when applicable, a dedicated column identifying the fault notification linked to each intervention, thereby establishing an explicit relational key between the two types of records.

From the unified dataset, the fields selected for use in the proposed methodology were retained and are presented in Figure 4.2.

Maintenance Records
- ID
- Installation Location
- Notification Title
- Notification Description
- Work Order Title
- Work Order Description

Figure 4.2: Maintenance Records

4.2.1.1 Installation Location

The functional installation location associated with each maintenance record served two purposes in the preprocessing stage. The first purpose was to restrict the dataset to the equipment groups considered within the scope of the study. For this reason, each record was assessed according to the functional position indicated in the installation location field. Records associated with relevant and properly defined functional positions were retained, whereas records referring to equipment groups outside the defined scope or records for which no identifiable functional position could be extracted, were discarded. This filtering step ensured that the subsequent association methodology was applied only to maintenance events related to the assets under analysis.

The second purpose was to provide a structured functional reference to be incorporated into the subsequent association methodology. For each retained record, the relevant functional position code was extracted from the installation location field by identifying the final five-digit sequence, as illustrated in Figure 4.3. This code was not treated merely as an administrative identifier, but as a structured descriptor of the equipment position within the functional hierarchy of the hydroelectric power plant.

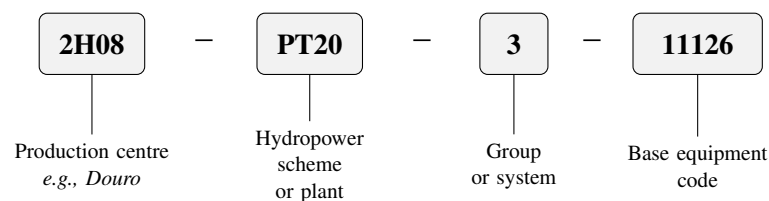


Figure 4.3: Illustrative decomposition of a functional position code.

The five-digit functional position code follows a hierarchical logic in which the first digit identifies the broadest equipment group considered in the study. As the code is read from left to right, each additional digit introduces a higher level of specificity, progressively narrowing the classification towards the most detailed functional position available in the maintenance event. Based on this logic, each code was decomposed into up to five hierarchical levels by progressively retaining more digits from left to right and replacing the remaining positions with zeros. For example, the code 23126 generates the sequence 20000, 23000, 23100, 23120 and 23126. When

the original code contains trailing zeros, these indicate that no finer functional detail was specified. Thus, a code such as 23000 only generates valid entries at levels 1 and 2.

The resulting hierarchical codes were translated into standardised functional descriptions using an EDP reference document defining the base equipment coding structure for hydroelectric power plants. This document acted as a decoding table, linking each code to the corresponding subsystem, equipment group or component designation. This ensured consistency in the description of functional positions and alignment with the hierarchical logic later applied to the FMECA dataset.

This multi-level representation was introduced to address a practical asymmetry between maintenance records and the FMECA: both sources do not necessarily describe equipment locations at the same level of functional granularity. By representing each functional position through successive hierarchical levels, the association methodology is not restricted to exact code correspondence at the most specific level. Instead, it can progressively identify functional proximity at broader levels of the asset hierarchy, thereby complementing textual similarity with structured information about the equipment context in which the failure was recorded.

4.2.1.2 Initial Textual Cleaning

This stage of the preprocessing pipeline consisted of a systematic cleaning of the free-text fields across all maintenance records. This operation was designed to eliminate textual noise that carries no semantic or lexical value for the purposes of failure mode identification.

Firstly, a line-level filtering function was applied to lines identified as containing only timestamp headers that were commonly used by technicians. Dates and times embedded within the narrative text were subsequently eliminated using targeted regular expressions. Additional formatting artefacts, such as irregular punctuation spacing, duplicate whitespace characters and excessive blank lines, were normalised to produce a clean and consistently formatted textual input.

Secondly, the entire content of each field was converted to lowercase and records containing null or placeholder values were reduced to empty strings.

4.2.1.3 Abbreviation Expansion

Maintenance record texts frequently contain domain-specific abbreviations reflecting the operational vocabulary of the maintenance team. If not resolved, these abbreviated forms would be treated as lexically distinct from their expanded equivalents, increasing textual fragmentation and potentially reducing the effectiveness of the method. To mitigate this issue, the abbreviation expansion procedure was based on an internal document containing the abbreviations most commonly used in this maintenance context. This document served as the reference for defining the abbreviation dictionary incorporated into the algorithm, where each abbreviated form was mapped to its corresponding expanded expression.

The abbreviation expansion procedure was applied independently to the four selected textual fields of the maintenance records. Whenever a token matched an entry in the abbreviation dictionary, the abbreviated form was replaced by its corresponding expanded expression. As a result, an expanded version of each textual field was created, preserving the structure and content of the original column, with the only difference being the substitution of the identified abbreviations by their respective full expressions.

4.2.1.4 Construction of the Representative Text Field and Tokenisation

A representative textual field was constructed for each maintenance event to support the comparison between maintenance records and the failure modes defined. This field constituted the main textual input of the association model and consolidated the information considered most relevant for characterising the event: the initial description of the anomaly, the additional content available in the notification and work order, and the standardised functional designation of the equipment or subsystem involved.

A central concern in the construction of this field was the reduction of informational redundancy. In the original records, different descriptive fields often contained partially overlapping or repeated information, which could artificially increase the weight of certain terms during the similarity calculation without adding meaningful technical content. For this reason, the representative text was generated through a selective aggregation procedure. The title and the description of the fault notification were always retained, while complementary information was only incorporated when it provided non-redundant content. The functional designation was added when a valid standardised match was available. As a result, each maintenance record was transformed into a compact textual representation, sufficiently informative for comparison with the available failure modes.

Tokenisation was applied to transform the complete textual representation into a sequence of individual textual units, such as words or numbers. This step is particularly relevant for lexical matching methods, since these approaches depend on the identification and comparison of explicit terms shared between maintenance records and failure mode descriptions. Figure 4.4 illustrates this logic through a simplified example, showing how an input sentence is decomposed into individual tokens.

Input: Fuga de óleo no sistema de refrigeração da chumaceira
Tokenisation: ['Fuga', 'de', 'óleo', 'no', 'sistema', 'de', 'refrigeração', 'da', 'chumaceira']

Figure 4.4: Example of tokenisation

A token-based version of the same field was generated by retaining only alphanumeric tokens with three or more characters. The resulting tokens were stored as pipe-delimited strings and

constituted the input representation for the lexical matching methods applied in the association methodology.

4.2.2 FMECA Dataset

The preprocessing of the FMECA dataset aimed to ensure compatibility with the maintenance records used in the association methodology. This preparation involved both the functional encoding of each failure mode and the construction of a standardised textual representation suitable for comparison.

Each failure mode was assigned to the most appropriate functional position within the asset hierarchy, based on the internal reference document corresponding to the base equipment coding standard for hydroelectric power plants. For each entry, the selected functional position code and its corresponding standardised designation were defined according to the most specific level justified by the available technical information.

In parallel, a structured textual field was created for each failure mode by consolidating the component designation, the failure mode description, the associated causes and the resulting effects. This field provided a consistent textual basis for the association methodology with the objective of reducing variability between failure modes.

Finally, the structured textual field was also tokenised to generate the input representation used by the lexical matching methods applied in the association methodology. The assigned functional position code was also decomposed into hierarchical levels, level 1 to level 5, following the same logic applied to the maintenance records. This ensured structural compatibility between both datasets and enabled the association methodology to combine textual similarity with functional proximity.

4.3 Failure Mode Association Models

Following the preprocessing stage, the association between historical maintenance records and the failure modes was addressed through three alternative models. Although the three models differ in the way textual similarity is computed, the overall framework was kept as consistent as possible across all approaches. This design choice ensured that the models followed the same association logic, allowing performance differences to be attributed mainly to the ranking strategy rather than to changes in the underlying procedure.

In all three models, the inputs consisted of the preprocessed FMECA and maintenance record datasets, considering two configurations: one based only on fault notifications and another also including the corresponding maintenance work orders, when available. For each configuration, every maintenance record was compared with the candidate failure modes, producing a ranked list of the four most plausible associations and their respective similarity scores. The process combined functional hierarchy information with the textual representations generated during preprocessing.

4.3.1 Hierarchical Candidate Generation

Before computing the similarity scores, the methodology first defines the subset of failure modes that can be considered for each maintenance record. This preliminary filtering stage is based on the functional hierarchy previously described and ensures that the ranking process is restricted whenever possible to failure modes that are related to the functional position recorded in the maintenance record. The purpose of this constraint is to reduce the number of comparisons to be performed, assuring technical coherence. A fault recorded for a given component should primarily be compared with failure modes defined for that same component, extending the search to broader functional levels only when no sufficiently specific candidates are available. Without this restriction, the model could rank failure modes from unrelated systems merely because their descriptions contain similar terms or contextual expressions.

For each maintenance record, the candidate generation procedure follows a progressive search logic designed to construct a fixed set of four candidate failure modes. This number was adopted as a methodological compromise between coverage and interpretability, since a single candidate could exclude plausible alternatives and a larger set would reduce the practical usefulness of the ranking. A top-four structure therefore provides a sufficiently broad set of alternatives for technical assessment. The number of candidates was maintained in every model to ensure that differences in performance could be attributed to the scoring strategy rather than to variations in output size.

The algorithm starts at the most specific available functional position level and selects the failure modes sharing the corresponding functional code. When more than four candidates are available at that level, they are scored according to the metric of the model being applied and only the four highest-scoring candidates are retained. When fewer than four candidates are found, all available candidates from that level are preserved and the search proceeds to the immediately subsequent level of the functional hierarchy. Candidates retrieved at broader levels are then added only as needed, until the predefined set of four failure modes is complete. In the least specific case, the search may extend to the broadest subsystem level associated with the maintenance record, such as the turbine or the power transformer, ensuring that the selected candidates remain functionally related to the recorded failure.

This mechanism can be illustrated by considering a record for a specific turbine component. Suppose that, at the most specific functional level available for that record, the algorithm identifies only two failure modes associated with the same component or subsystem. Since the predefined output requires four candidates, these two failure modes are retained but the search does not stop. The algorithm then moves to the next broader functional level, corresponding to the immediately higher functional level, the closest subsystem in which that component is integrated, and identifies five additional failure modes. These five candidates are scored and ranked according to the model-specific similarity metric but only the two highest-scoring ones are added to the candidate pool. The final output contains four failure modes, two identified using the functional code recorded in the maintenance record and two retrieved from the immediately subsequent level of the functional hierarchy. Once this set is complete, the algorithm does not consult any further levels.

This design establishes a clear separation between the two dimensions of the methodology. The functional position determines which failure modes are technically eligible for each maintenance record, while the similarity scores determine how those candidates are ranked and, when necessary, selected. Therefore, differences between the three models affect the candidate pool only in situations such as the one illustrated above, where a given hierarchy level contains more eligible failure modes than the number of remaining positions available in the pool.

4.3.2 Textual Similarity Models

Three alternative textual similarity models were implemented in this work:

- Lexical Similarity Model
- Semantic Similarity Model
- Hybrid Lexical-Semantic Similarity Model

The lexical model relies exclusively on explicit term overlap and term-weighting patterns. The semantic model uses sentence embeddings to capture the contextual meaning of the texts, reducing its dependence on exact lexical correspondence. The hybrid model combines both perspectives, integrating lexical evidence and semantic proximity into a single final score. This structure allows the study to compare three increasingly flexible forms of textual matching.

4.3.2.1 Lexical Similarity Model

This model adopts a purely lexical approach to candidate ranking. Each candidate failure mode is scored against the corresponding maintenance record using three complementary lexical metrics: BM25, TF-IDF vectorization with cosine similarity and Jaccard similarity.

The use of three lexical metrics was intended to capture complementary forms of textual evidence. BM25 and TF-IDF vectorisation with cosine similarity were included as established information retrieval approaches consistent with the work of Boban et al. (2020), who apply TF-IDF-based weighting and BM25 in sentence retrieval. Jaccard similarity adds a further dimension by providing a simpler and interpretable measure of explicit token overlap.

Table 4.1 summarises the input representation used by each lexical metric and its specific contribution to the proposed similarity model.

Table 4.1: Contribution of each method to the lexical similarity model

Method	Contribution to the lexical similarity model
BM25	Prioritisation of candidate failure modes according to the relevance, frequency and discriminative value of shared terms
TF-IDF vectorisation with cosine similarity	Compares maintenance records and failure mode descriptions based on the weighted importance of the terms they contain
Jaccard similarity	Provides a direct and interpretable measure of explicit token overlap between the two textual representations

BM25 was selected as the main retrieval-oriented component of the lexical model. In the proposed methodology, each maintenance record was treated as the query, while each candidate failure mode description was treated as a document to be ranked. Under this formulation, BM25 assigns higher scores to failure modes containing relevant and discriminating terms also present in the maintenance record. This is particularly suitable for the present application, since both maintenance records and failure mode descriptions are technical textual sources and may differ in length.

TF-IDF vectorisation with cosine similarity was introduced to provide an additional perspective on textual similarity between maintenance records and the candidate failure modes. To ensure compatibility between the two datasets, the TF-IDF vectoriser was fitted on a combined corpus composed of the preprocessed maintenance record texts and the normalised failure mode descriptions. This procedure generated a common vocabulary and represented both types of textual units within the same vector space.

TF-IDF vectorisation provides a numerical representation of each text, but it does not, by itself, produce a similarity score. For this reason, cosine similarity was used to compare the TF-IDF vector of each maintenance record r_i with the TF-IDF vector of each candidate failure mode f_j . The resulting value, $TFIDF_{cos}(r_i, f_j)$, corresponds to the TF-IDF component score used in the lexical similarity model.

Jaccard similarity was added as a direct and simpler measure of token overlap without relying on term weighting or vectors representation.

The BM25 parameters were set to $k_1 = 1.5$ and $b = 0.75$. These values were adopted as reference values and they are commonly used in similar contexts. The value $k_1 = 1.5$ provides an intermediate degree of term-frequency saturation, ensuring that repeated technical terms remain relevant without allowing repetition to dominate the score. The value $b = 0.75$ applies substantial document length normalisation, which is appropriate given the variability in length between maintenance records and failure mode descriptions. This configuration is consistent with studies that adopt the same BM25 parameter setting, including Shevchenko (2018), Boban et al. (2020) and Lù (2024).

For each maintenance record, the BM25 scores were normalised relative to the maximum BM25 value obtained among the failure modes considered in the comparison. This step was necessary because raw BM25 scores are not naturally bounded and therefore cannot be directly combined with the remaining two similarity measures without scale adjustment. The resulting normalised score, $BM25_{norm}$, was subsequently used as one of the components of the final lexical similarity score. The three components were then combined into a single lexical score through the weighted linear combination shown in Equation 4.1.

$$S_{lex}(r_i, f_j) = 0.50 \times BM25_{norm}(r_i, f_j) + 0.30 \times TFIDF_{cos}(r_i, f_j) + 0.20 \times Jaccard(r_i, f_j) \quad (4.1)$$

where:

$S_{lex}(r_i, f_j)$: lexical similarity score between maintenance record r_i and failure mode f_j ;

$BM25_{norm}(r_i, f_j)$: normalised BM25 score;

$TFIDF_{cos}(r_i, f_j)$: cosine similarity computed from the TF-IDF vector representations;

$Jaccard(r_i, f_j)$: Jaccard similarity between the corresponding token sets.

The weighting scheme gives priority to BM25 because it is the most complete metric among the three. TF-IDF vectorization with cosine similarity receives an intermediate weight because it provides complementary vector-space evidence based on weighted term distributions and Jaccard similarity receives the lowest weight because it is a simpler overlap measure. These weights should therefore be understood as a methodological design choice and not optimised parameters.

Given the nature of this lexical association model, its performance is particularly influenced by the quality of the preprocessing stage. Since the model relies on explicit textual correspondence, there are a lot of factors that may directly affect the similarity scores produced. Therefore, the effectiveness of this approach is strongly influenced by the quality and consistency of the textual representations used as input.

4.3.2.2 Semantic Similarity Model

This model represents each preprocessed textual description through a dense embedding, allowing descriptions with different wording but related meaning to be compared in a semantic vector space. In this work, the semantic component was implemented using the *paraphrase-multilingual-MiniLM-L12-v2* model, a multilingual sentence transformer model designed to map sentences and short textual descriptions into dense vector representations (Sentence Transformers, 2024).

This model was selected because it provides sentence-level representations in a compact 384-dimensional embedding space. Its use is consistent with the sentence transformers framework proposed by Reimers and Gurevych (2019), in which textual units are independently encoded and then compared through vector-based similarity measures. In the present methodology, the complete preprocessed textual descriptions associated with both maintenance records and failure modes were used as input to the model. Each maintenance record r_i and each candidate failure mode f_j was encoded into an embedding representation, denoted by $\mathbf{e}_{r_i}$ and $\mathbf{e}_{f_j}$, respectively.

The semantic similarity score, given by Equation 4.2, was computed as the cosine similarity between the embedding of maintenance record r_i and the embedding of failure mode f_j :

$$S_{sem}(r_i, f_j) = \cos(\mathbf{e}_{r_i}, \mathbf{e}_{f_j}) = \frac{\mathbf{e}_{r_i} \cdot \mathbf{e}_{f_j}}{\|\mathbf{e}_{r_i}\| \|\mathbf{e}_{f_j}\|} \quad (4.2)$$

where:

$S_{sem}(r_i, f_j)$: semantic similarity score between maintenance record r_i and failure mode f_j ;

4.3.2.3 Hybrid Lexical-Semantic Similarity Model

The hybrid lexical-semantic similarity model combine the two previous scoring approaches into a single ranking criteria. The objective was to integrate explicit lexical correspondence with semantic proximity.

The lexical component was computed according to the same formulation used in the lexical similarity model as well as the semantic component. In the hybrid model, both components were assigned equal weight, resulting in the final score shown in Equation 4.3.

$$S_{hyb}(r_i, f_j) = 0.50 \times S_{lex}(r_i, f_j) + 0.50 \times S_{sem}(r_i, f_j) \quad (4.3)$$

where:

$S_{hyb}(r_i, f_j)$: hybrid score between maintenance record r_i and failure mode f_j ;

$S_{lex}(r_i, f_j)$: lexical similarity score;

$S_{sem}(r_i, f_j)$: semantic similarity score.

Chapter 5

Results

This chapter presents the results obtained across both methodological stages of the dissertation. The first part reports the outputs of the FMECA developed in Chapter 3. The second part evaluates the failure mode association methodology developed in Chapter 4, reporting the performance of the three proposed models under two input configurations and providing a qualitative analysis of representative association examples.

5.1 FMECA Results

5.1.1 Overview of Identified Failure Modes

A total of 94 failure modes were considered distributed across the four subsystems within the scope of the study. Table 5.1 presents the number of failure modes identified for each subsystem.

Table 5.1: Distribution of identified failure modes by subsystem.

Subsystem	Failure modes identified	Percentage of total
Turbine	27	28.7%
Generator	29	30.9%
Power transformer	27	28.7%
Circuit breaker	11	11.7%
Total	94	100%

The generator, turbine and power transformer present relatively similar numbers of identified failure modes, suggesting a comparable complexity level across these three subsystems. Each of them comprises multiple components and functional areas, creating several potential points of failure across mechanical, electrical, hydraulic, thermal or insulating domains. By contrast, the circuit breaker presents a smaller number of failure modes due to its narrower functional scope and lower structural complexity.

5.1.2 Classification by Failure Type

To characterise the technical nature of the identified failure modes, each entry was classified according to its primary degradation mechanism into one of five categories:

- **Mechanical and structural:** failures associated with the physical integrity or mechanical condition of components and structures.
- **Electrical and dielectric:** failures associated with electrical condition or insulation performance.
- **Lubrication and fluid systems:** failures associated with the condition of lubricating or hydraulic fluids.
- **Cooling systems:** failures primarily associated with heat removal, temperature control or thermal stress affecting equipment operation.
- **Control systems:** failures associated with monitoring, protection, regulation or control functions.

Table 5.2 presents the resulting distribution.

Table 5.2: Classification of identified failure modes by type and subsystem.

Category	Turbine	Generator	Transformer	CB	Total
Mechanical & structural	18	10	9	4	41
Electrical & dielectric	0	10	9	5	24
Lubrication & fluid	5	2	4	0	11
Cooling & thermal	1	4	2	0	7
Electronic & control	3	3	3	2	11
Total	27	29	27	11	94

Mechanical and structural failures represent the largest category overall, accounting for 41 of the 94 identified failure modes (43.6%). This predominance is particularly pronounced in the turbine, where 18 of the 27 failure modes are mechanical in nature, reflecting the direct exposure of turbine components to hydraulic forces, abrasive flow conditions and high mechanical stresses.

Electrical and dielectric failures constitute the second largest category, with 24 failure modes (25.5%). These are concentrated in the generator and power transformer, where insulation integrity is critical for safe and reliable operation.

Lubrication and fluid system failures account for 11 failure modes (11.7%), distributed across the turbine, generator and power transformer. Their relatively consistent distribution across subsystems reflects the widespread use of oil-based systems for both lubrication and hydraulic actuation across the hydropower plant.

Cooling system failures account for 7 failure modes (7.4%), with the generator exhibiting the highest count in this category, while control system failures also total 11 failure modes (11.7%).

5.2 Validation Procedure

Since the proposed methodology follows an unsupervised approach, no previously labelled dataset was available for direct model evaluation. For this reason, the results were assessed through manual validation of a randomly selected sample of maintenance records. The validation was carried out by the author, based on personal knowledge of the FMECA developed and on a careful reading of the textual information available in each record.

The validation sample consists of 80 maintenance records for which an unambiguous association with a specific failure mode identified previously could be established. These records were assembled from a broader random selection process in which approximately 240 records were reviewed. A substantial proportion of the initial draws contained insufficient or excessively generic textual information to support a reliable association and were consequently excluded. The 80 retained records represent cases in which the textual content is specific enough to support a confident manual association.

Two evaluation indicators were used, as summarised in Table 5.3.

Table 5.3: Evaluation indicators used in the validation procedure

Indicator	Interpretation
Top-1 accuracy	Proportion of records for which the correct failure mode was ranked as the first candidate. Reflects primarily the scoring capability of the specific similarity model.
Top-4 hit rate	Proportion of records for which the correct failure mode appeared among the four candidates proposed. Considered the most appropriate indicator for assessing the effectiveness of the hierarchical candidate generation procedure.

These two indicators capture distinct aspects of the methodology. The Top-4 hit rate assesses whether the hierarchical candidate generation step correctly includes the relevant failure mode within the restricted candidate pool. Top-1 accuracy, in turn, evaluates whether the similarity model is capable of positioning the correct failure mode at the top of the resulting ranking.

5.3 Input Data Availability

As noted in Chapter 4, the maintenance records initially extracted covered the period from October 2024 onwards and comprised more than 5.650 records. Following the preprocessing stage described in Section 4.2.1, the dataset was restricted to records associated with functional positions within the scope of this study, resulting in a final dataset of 1.885 maintenance records available for the association methodology.

Table 5.4 summarises the availability of the main textual fields used to construct the maintenance record representations. Although fault notification titles were available for all records,

other fields presented lower availability. In particular, the work order description was only available for a limited subset of records, which is relevant when interpreting the impact of including maintenance work order information.

Table 5.4: Availability of textual fields in the maintenance record dataset

Textual field	Number of available records
Fault notification title	1885
Fault notification description	1187
Work order title	1050
Work order description	330

When the combined input configuration was used, the textual content from the fault notification and the maintenance work order was concatenated only when work order information was available and was not a verbatim duplicate of the notification text. This approach was intended to incorporate additional operational detail while avoiding unnecessary repetition in the textual input.

5.4 Performance of the Association Models

Tables 5.5 and 5.6 present the performance obtained by the three association models under the two input configurations considered.

Table 5.5: Performance of the association models using fault notifications and work orders

Model	Top-1 accuracy	Top-4 hit rate
Lexical	52.50% (42/80)	88.75% (71/80)
Hybrid lexical-semantic	61.25% (49/80)	86.25% (69/80)
Semantic	41.25% (33/80)	73.75% (59/80)

Table 5.6: Performance of the association models using fault notifications only

Model	Top-1 accuracy	Top-4 hit rate
Lexical	52.50% (42/80)	88.75% (71/80)
Hybrid lexical-semantic	58.75% (47/80)	86.25% (69/80)
Semantic	42.50% (34/80)	73.75% (59/80)

The results show that the lexical and hybrid models achieved the strongest overall performance. The lexical model obtained the highest Top-4 hit rate, reaching 88.75% in both input configurations.

Overall, the Top-4 results can be considered satisfactory, since the correct failure mode was included in the candidate pool in more than 70% of the validated records for all models. This provides a positive indication regarding the ability of the methodology to reduce the failure mode search space while still preserving the correct association among a limited set of technically plausible alternatives.

The differences in the Top-4 observed between the three models are mainly explained by the scoring stage used when more candidate failure modes are available at a certain level than the four positions allowed in the output. In those situations, the specific ranking criterion of each model determines which failure modes are retained in the final candidate pool, thereby affecting the Top-4 hit rate.

The hybrid lexical-semantic model achieved the highest Top-1 accuracy in both configurations. When using only fault notifications, the hybrid model correctly ranked the exact failure mode in first position for 58.75% of the validated records. When work order information was included, this value increased to 61.25%. This suggests that the combination of lexical and semantic evidence improved the ability of the model to place the correct failure mode at the top of the ranking.

The semantic model presented the lowest performance, both in terms of Top-1 accuracy and Top-4 hit rate. This indicates that semantic similarity alone was less effective than lexical or hybrid scoring in this specific association task. The result is particularly relevant because it shows that, despite the conceptual advantages of embedding-based representations, explicit technical terminology remains highly important when matching maintenance records with candidate failure modes.

5.5 Effect of Including Work Order Information

The comparison between the two input configurations shows that the inclusion of work order information, whenever was available, had a limited effect on model performance. Table 5.7 presents the variation observed after incorporating work order information into the textual input.

Table 5.7: Variation in performance after including work order information

Model	Top-1 variation	Top-4 variation
Lexical	0.00 p.p.	0.00 p.p.
Hybrid lexical-semantic	+2.50 p.p.	0.00 p.p.
Semantic	-1.25 p.p.	0.00 p.p.

The lexical model produced exactly the same results in both configurations, suggesting that the additional information provided by work orders did not materially alter the lexical evidence available for matching. The semantic model also maintained the same Top-4 hit rate, although its Top-1 accuracy decreased slightly. The improvement was observed in the hybrid model, whose Top-1 accuracy increased by 2.50 percentage points when work order information was included.

The null variation in the Top-4 results is consistent with the role of the functional hierarchy in the methodology. Since the hierarchy strongly constrains the candidate search space by selecting failure modes associated with compatible functional positions, the similarity model mainly becomes decisive when several candidate failure modes are available within the same hierarchy-based pool or when their final ordering must be determined.

Overall, the inclusion of work order information had only a limited impact on the results. Although small variations were observed in some indicators, the overall performance of the models remained largely unchanged. This suggests that adding work order text did not substantially improve the ability of the models to retrieve the correct failure mode among the four proposed candidates. Even in the hybrid model, where a slight improvement in Top-1 accuracy was observed, the magnitude of this variation was limited, suggesting that the additional information had only a marginal effect on candidate ordering.

Chapter 6

Discussion and Conclusion

This dissertation addressed the challenge of transforming historical maintenance records into information that can support failure mode analysis.

The FMECA played a central role in the framework, since it established the set of failure modes against which the historical records were evaluated. For this reason, the relevance of the association results depends not only on the performance of the similarity models, but also on the adequacy of the FMECA to the operational context under study.

The results presented in the previous chapter demonstrate that the proposed framework provides a robust basis for structuring the association process. More importantly, they show that failure mode identification benefits from the combined use of functional, lexical and semantic information. The combination of the functional hierarchy and the similarity models are particularly relevant given the nature of the available data: maintenance records and FMECA descriptions often contain specific references to components, subsystems, symptoms and failure descriptors. When these terms are explicitly shared, lexical similarity provides strong evidence for identifying technically plausible failure modes.

The hybrid lexical-semantic model, in turn, achieved the best Top-1 performance. This suggests that semantic information can add value when combined with lexical evidence, particularly in cases where several candidate failure modes present similar terminology. In these situations, the semantic component can contribute to a more precise ordering of the candidates, as it captures the contextual meaning of the maintenance record in combination with the lexical evidence.

The weaker performance of the semantic model when used alone should be interpreted as an indication of the limitations of applying a general-purpose embedding model to a highly technical domain. In such conditions, broad semantic proximity may not be sufficient to distinguish between technically close failure modes without the support of explicit lexical and functional information.

The limited impact of incorporating maintenance work order information also deserves attention. Although work orders could provide additional operational detail, their contribution depends strongly on the quality and specificity of the descriptions entered by maintenance technicians. For this reason, the inclusion of additional text did not necessarily translate into a substantial improvement in the association performance. Nevertheless, the improvement observed in the hybrid model

indicates that work order information can still be useful when it provides complementary context and is combined with both lexical and semantic evidence.

The functional hierarchy represents one of the main added values of the proposed methodology. Its relevance lies in the fact that a more accurate identification of the functional position directly restricts the set of possible failure modes, providing a robust starting point for the association process. In this sense, the failure mode identification does not depend only on textual similarity but also on the quality and granularity of the functional position associated with each maintenance record. Improving the precision with which functional positions are assigned in future maintenance records should therefore be considered an important development direction, as it would allow the candidate pool to be defined more accurately.

The FMECA developed in this work should not be interpreted as a closed or definitive representation of all possible failure modes. Its level of detail necessarily involves a trade-off. A highly detailed FMECA may provide greater technical specificity, but it can also become difficult to manage and apply consistently. The FMECA should be adapted to the current knowledge available about the EDP operational context, rather than as a final model. As historical maintenance records continue to be analysed, failures may occur that are not yet represented in the existing structure. The progressive validation of maintenance records against the FMECA can support its continuous improvement, allowing new failure modes to be incorporated, making the analysis increasingly complete and tailored to the operational reality of EDP.

From a practical perspective, the proposed methodology should be interpreted primarily as a decision-support tool rather than as a fully autonomous association mechanism. The assignment of a failure mode would still require caution. However, reducing the search space to a small set of plausible candidates has operational value. It can reduce the time required to analyse large volumes of maintenance records and promote a more systematic connection between historical maintenance data and structured failure mode knowledge.

Despite these contributions, several limitations must be acknowledged. An initial limitation concerns the construction of the FMECA itself. The identification of failure modes was strongly supported by scientific literature and technical documentation, since the systems and components under analysis required specific technical knowledge. However, the available bibliography was limited. This limitation is relevant because the purpose of the FMECA was not merely to compile theoretical failure modes, but to identify the most representative ones. To mitigate this limitation, the FMECA was subsequently reviewed and corrected with the support of EDP specialists, ensuring greater technical consistency and practical relevance. Nevertheless, the final structure remains conditioned by the availability of literature and by the degree of specificity with which failure mechanisms are documented for each system or component.

A second limitation concerns the quality of the textual information available in the maintenance records, which affected both model performance and the validation process. Short descriptions or generic statements reduced the amount of evidence available for the association task, particularly when the text did not explicitly identify the affected component, the observed symptom or the underlying failure mechanism.

This limitation was also reflected in the manual validation stage. Since no previously labelled ground truth was available, the reference associations had to be established manually by the author. As mentioned in the previous chapter, only about one third of the reviewed records contained enough useful information to support an exact association with a failure mode, highlighting the limited informative value of a significant part of the available maintenance history.

Another limitation concerns the functional position information. Some maintenance records presented missing, incorrectly assigned or overly generic functional position codes. In certain cases, the textual description of the failure did not fully correspond to the functional position indicated in the record. Since the functional hierarchy is used to define the candidate pool before the similarity scores are applied, errors or excessive generality in the functional position can directly affect the set of failure modes available for ranking.

The limitations discussed above do not reduce the relevance of the proposed methodology, but they clarify the conditions required for its future development. In particular, they show that the value of the proposed framework depends on two complementary foundations: the quality of the FMECA used as technical reference and the quality of the maintenance information recorded in the operational systems. Table 6.1 summarises the main future work directions identified from this dissertation.

Table 6.1: Main future work directions

Area	Future work direction	Expected contribution
FMECA improvement	Progressively update and refine the FMECA as additional maintenance records are analysed and validated, incorporating new failure mechanisms when relevant.	Improve the completeness and practical alignment of the FMECA with the operational reality of EDP.
Maintenance record quality	Promote more complete and technically precise descriptions in fault notifications and work orders, including symptoms, affected components and corrective actions.	Increase the value of historical maintenance data for failure mode analysis.
Functional position coding	Improve the accuracy and consistency of the functional positions assigned to maintenance records.	Strengthen the hierarchy-based candidate generation process and reduce ambiguity in failure mode identification.
Association methodology	Test alternative weighting schemes for the hybrid model and improve the semantic component through domain-adapted embeddings, fine-tuning or technical glossaries.	Improve the balance between candidate retrieval and candidate prioritisation, especially for technically similar failure modes.

Table 6.1 – *continued from previous page*

Area	Future work direction	Expected contribution
Reliability modelling	Apply Weibull analysis to model the lifetime behaviour of the identified failure modes using maintenance data available.	Enable quantitative estimation of failure rates per failure mode, supporting more rigorous reliability analysis.
Predictive maintenance policies	Use reliability-based models to establish maintenance policies grounded in observed field behaviour rather than manufacturer specifications.	Support a transition in the maintenance planning within EDP.
Asset health indices	Develop asset health indices driven by maintenance data, using the structured failure mode information produced by the proposed framework as the operational evidence base.	Replace manufacturer-based health assumptions with data-driven indicators that reflect the real condition and failure history of the assets.

Overall, this dissertation demonstrates that combining a FMECA adapted to the EDP operational context with a functional hierarchy-based association methodology provides a feasible approach for structuring maintenance knowledge. Although expert validation remains necessary, the proposed framework offers a scalable basis for reducing manual effort and improving the use of maintenance records in failure mode analysis. Its future potential will depend not only on the refinement of the models and on the continuous improvement of the FMECA and of the maintenance information recorded at source. It will also depend on the extent to which the structured failure mode information produced can be leveraged to support quantitative reliability modelling, predictive maintenance policies and the development of asset health indices grounded in actual field data.

6.1 Sustainable Development Goals (SDGs)

This dissertation contributes, directly and indirectly, to several United Nations Sustainable Development Goals (United Nations, 2015). By improving the reliability and availability of critical hydropower assets and by developing a structured, data-driven methodology to support maintenance decision-making, the work addresses challenges related to clean energy supply, industrial innovation and the responsible use of operational resources. Table 6.2 summarises the SDGs identified as relevant to this project, the contribution of the work to each target and the performance indicators considered to assess this contribution.

Table 6.2: Alignment of the dissertation with the Sustainable Development Goals

SDG	Target	Contribution	Performance indicators and metrics
7	7.2 - Increase substantially the share of renewable energy in the global energy mix	Supporting the reliability of hydropower generation units helps maintain their contribution to the renewable energy mix and reduces unplanned unavailability.	Proportion of EDP's hydropower capacity (6.7 GW, 49 plants, 110 generation units) for which a structured reliability reference now exists (94 failure modes, across 4 critical subsystems).
	7.b - Expand infrastructure and upgrade technology for supplying modern and sustainable energy services	The FMECA and FTA framework upgrade the technical basis used to manage maintenance records, enabling a more data-driven approach.	Percentage of maintenance records made usable for reliability analysis.
9	9.5 - Enhance scientific research, upgrade the technological capabilities of industrial sectors	Application of NLP techniques (lexical, semantic and hybrid models) to associate maintenance records to a failure mode represents a technological upgrade relative to manual interpretation of free-text records.	Top-1 accuracy of the best-performing model (61.25%, hybrid model); Top-4 hit rate of the best-performing model (88.75%, lexical model)
12	12.2 - Achieve the sustainable management and efficient use of natural resources	By supporting a more precise identification of the failure mode underlying each maintenance event, the methodology can help target interventions more accurately, reducing unnecessary resource use.	Reduction of the candidate search space from 94 to 4 failure modes per maintenance record (95.7% reduction), supporting more targeted and efficient diagnostic decisions.

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Appendix A

Complementary Background on Maintenance Policies

As illustrated in Figure 2.3, maintenance policies can be broadly classified according to the moment at which the intervention is performed and the type of information used to support the maintenance decision.

A.1 Corrective Maintenance

Corrective maintenance, also referred to as run-to-failure (RTF), consists of actions performed on a repairable system after the occurrence of a failure in order to restore it to an operational condition. In most cases, it involves repairing or replacing the component responsible for the system failure (Sharma and Rai, 2023).

The implementation of this approach is relatively uncomplicated, as it demands minimal planning and managerial effort, thereby helping to limit indirect maintenance-related costs (Mobley, 2002). Although this approach allows components to be used until the end of their useful life and may be suitable for non-critical assets, it is often associated with unplanned downtime, production losses, higher repair costs, and increased safety risks (Liu et al., 2024).

A.2 Preventive Maintenance

Preventive maintenance is founded on the principle of anticipating potential failures even before they occur. Rather than waiting the break down of the assets, this approach relies on planned interventions intended to preserve operational performance and reduce the likelihood of unexpected malfunctions. Its main objective is to maintain the regular functioning of equipment and to identify signs of deterioration at an early stage, thereby preventing minor issues from developing into more serious and costly failures (Yazdi, 2024).

Preventive maintenance may be implemented in different ways, with time-based and use-based maintenance being two of the most common approaches.

A.2.1 Time-Based Predetermined Maintenance

Time-based preventive maintenance is based on interventions scheduled at predetermined calendar intervals, independently of the actual level of asset utilization (Yazdi, 2024). In this context, the bathtub curve provides a useful framework for understanding this logic, since it describes the typical variation in failure rate over the life cycle of equipment.

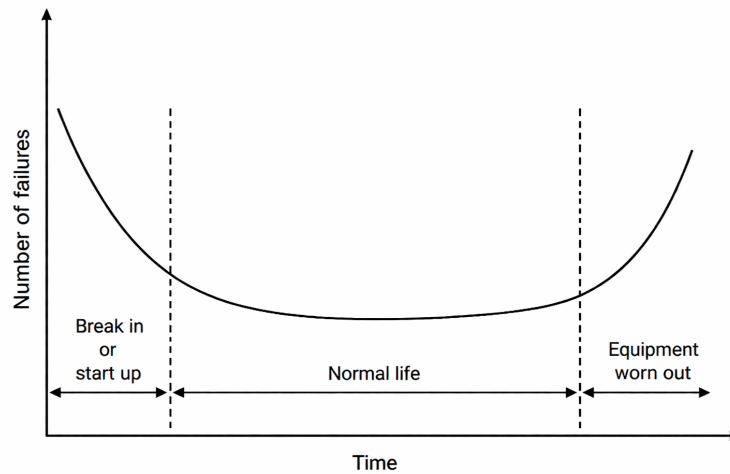


Figure A.1: Bathtub curve. Adapted from: (Mobley, 2004)

As shown in Figure A.1, the failure rate of an equipment is initially high during the break-in phase, remain relatively stable throughout the normal life period and rise again at the end of the life cycle. One of the main difficulties associated with this approach concerns the definition of suitable maintenance intervals, which are commonly determined according to manufacturer recommendations and the practical experience accumulated by maintenance personnel. Despite its limitations, this approach remains widely used due to the predictability and simplicity it provides (Yazdi, 2024).

A.2.2 Use-Based Predetermined Maintenance

Use-based preventive maintenance is characterized by the scheduling of maintenance actions according to the actual utilization of the asset, with interventions typically determined on the basis of operational indicators such as operating hours, production cycles, traveled distance, or workload (Wang et al., 2019). By aligning maintenance activities with real operating conditions, this approach allows interventions to more accurately reflect the wear experienced by the equipment, which may improve maintenance efficiency while reducing unnecessary interventions (Yazdi, 2024).

A.2.3 Predictive Maintenance

Predictive maintenance is based on the evaluation of the actual condition of assets in order to estimate their health state and degradation over time, thereby supporting timely and well-informed maintenance decisions. Its purpose is to anticipate the occurrence of failure and to identify the most appropriate moment for intervention, before functional failure takes place. For this reason, its implementation depends on effective monitoring and on the integration of different types of information that make it possible to understand the behavior of the equipment and the evolution of its condition (Gulati and Smith, 2009). According to Schmidt et al. (2017), predictive maintenance should make use of:

- Equipment-related data, including machine type, location, and physical constitution.

- Work order information, such as maintenance actions previously carried out, descriptions of faults or failures, replacement parts used, their causes and the methods applied to resolve them.
- Operating and supervisory data, including monitored parameters such as temperature, pressure and vibration, as well as information obtained from supervisory and data acquisition systems, such as the number of operating cycles and production variants.

The application of predictive maintenance may be complex, depending on the characteristics of the asset and on the availability of reliable information. Nevertheless, when properly implemented, it can support a more efficient allocation of maintenance resources, reduce unnecessary interventions, and contribute to lower downtime and improved asset performance.

A.2.4 Condition Based Maintenance

Condition-Based Maintenance (CBM) has emerged as one of the leading maintenance strategies in modern engineering systems, particularly because it relies on information collected during asset operation rather than on predetermined maintenance intervals (Quatrini et al., 2020). CBM is especially relevant in situations where degradation or failure may generate significant economic consequences, since it enables maintenance decisions to be more closely aligned with the evolving condition of the equipment (Quatrini et al., 2020). Gulati and Smith (2009) defined CBM as maintenance based on the actual condition of assets, obtained through in-place tests and measurements.

The value of CBM lies not merely in its capacity to monitor equipment, but in the way it shifts the logic of intervention from routine replacement to informed decision-making. CBM is characterized as a proactive maintenance strategy in which interventions are triggered only when signs of wear or performance metrics indicate a potential failure (Yazdi, 2024).

The effectiveness of CBM depends on the quality of condition monitoring and on the ability to interpret the information collected, and it should therefore not be reduced to a simple set of diagnostic tools, since its implementation involves broader strategic and organizational choices. In this sense, CBM may be regarded as a structured maintenance approach that combines data acquisition, feature extraction, fault detection, fault diagnosis, and fault prediction in order to improve reliability, availability, and maintenance efficiency as shown in Figure A.2.

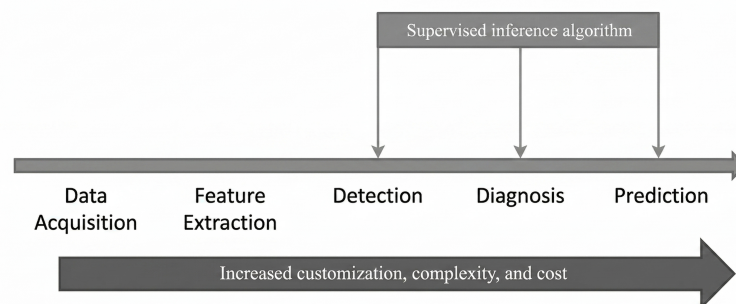


Figure A.2: Condition Based Maintenance. Adapted from: (Liu et al., 2024)

According to Gulati and Smith (2009), CBM can be implemented through two main monitoring logics:

- Inspection based approach
- Continuous based approach

Inspection based CBM relies on periodic condition assessments, typically obtained through spot readings collected along inspection routes with hand-held instruments. For Gulati and Smith (2009), this type of monitoring is considered sufficient for maintenance decision-making, since the degradation of many assets is not so rapid as to require online reporting. By contrast, continuous based CBM depends on permanently installed data acquisition systems, such as thermographic inspections and vibration analysis, that provide real condition data while the asset is operating. This solution is generally reserved for critical and expensive assets, particularly when failure may cause significant operational or economic losses (Gulati and Smith, 2009).

A.3 Reliability Centered Maintenance

According to Kobbacy and Murthy (2008), reliability centered maintenance (RCM) can be understood as:

“a systematic approach for identifying effective and efficient preventive maintenance tasks for items in accordance with a specific set of procedures and for establishing intervals between maintenance tasks”.

RCM was first implemented in the aircraft industry and was later adopted in other industrial sectors, mainly because it demonstrated the ability to reduce preventive maintenance costs while maintaining, and in some cases improving, system availability (Rausand, 1998).

As the concept evolved, RCM became less associated with fixed and routine maintenance schedules and more closely linked to a logical framework for determining what must be preserved within a system and how that preservation should be achieved (Rausand, 1998). In this context, RCM is commonly structured around seven fundamental questions addressing system functions, functional failures, failure causes, failure effects, failure consequences, proactive maintenance tasks, and the actions to be taken when no suitable preventive task can be identified. This question-based logic is particularly relevant because it shifts the focus from the physical asset itself to the functions that the asset is required to perform within its operating context (Rausand, 1998). The general structure of the RCM process is schematically illustrated in Figure A.3.

Within this framework, different supporting methodologies may be used to strengthen the analysis. Among these, Failure Modes, Effects and Criticality Analysis (FMECA) is one of the most widely used, as it enables failure modes, their causes, their effects, and their criticality to be assessed in a systematic and structured manner (Yssaad et al., 2014). In addition, decision logic trees are employed in some RCM formulations to classify failure consequences and support the identification of applicable and effective maintenance tasks (Yssaad et al., 2014). Other methodological supports, such as functional block diagrams, may also be used to represent system functions and to provide a basis for the subsequent analysis of functional failures and failure modes (Kobbacy and Murthy, 2008).

Therefore, although the core of RCM lies in its functional and consequence-based reasoning, its implementation is often reinforced by complementary methodologies that improve the quality and consistency of the analysis.

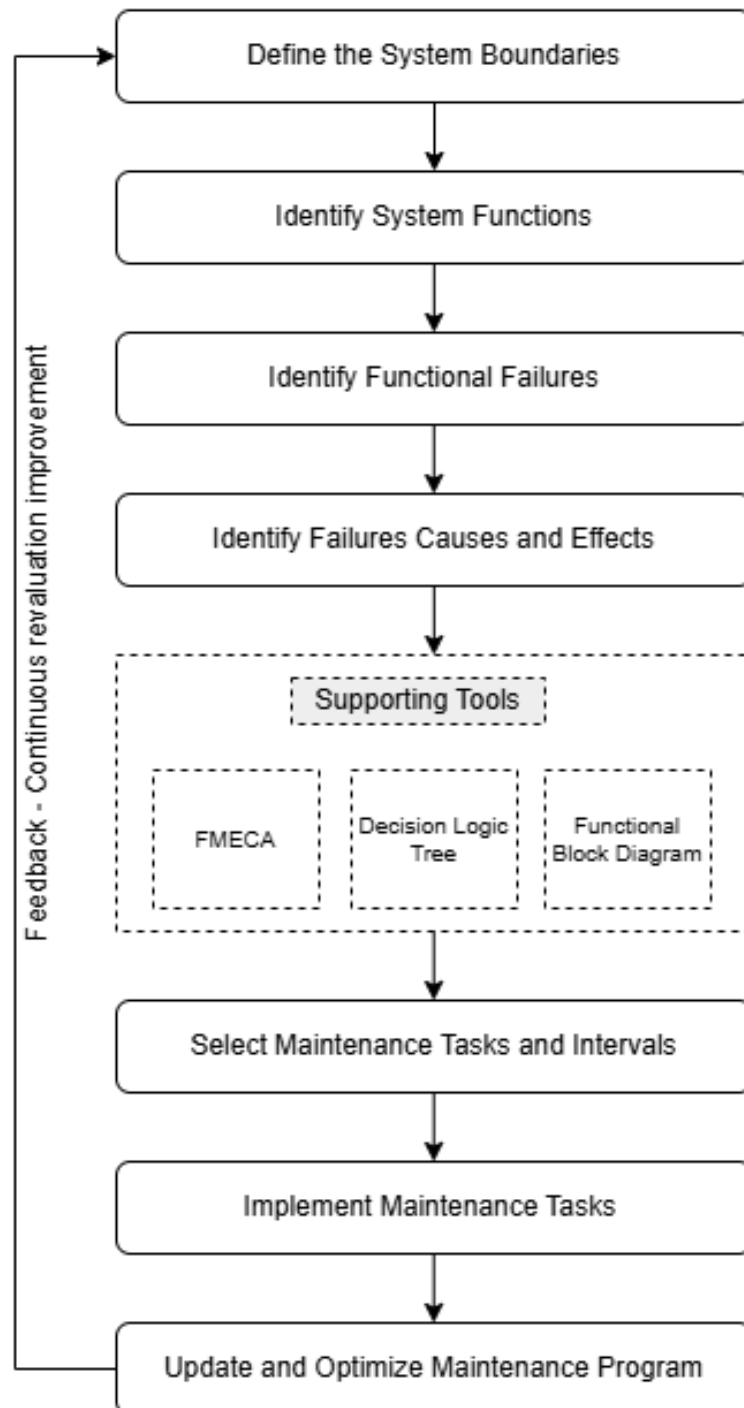
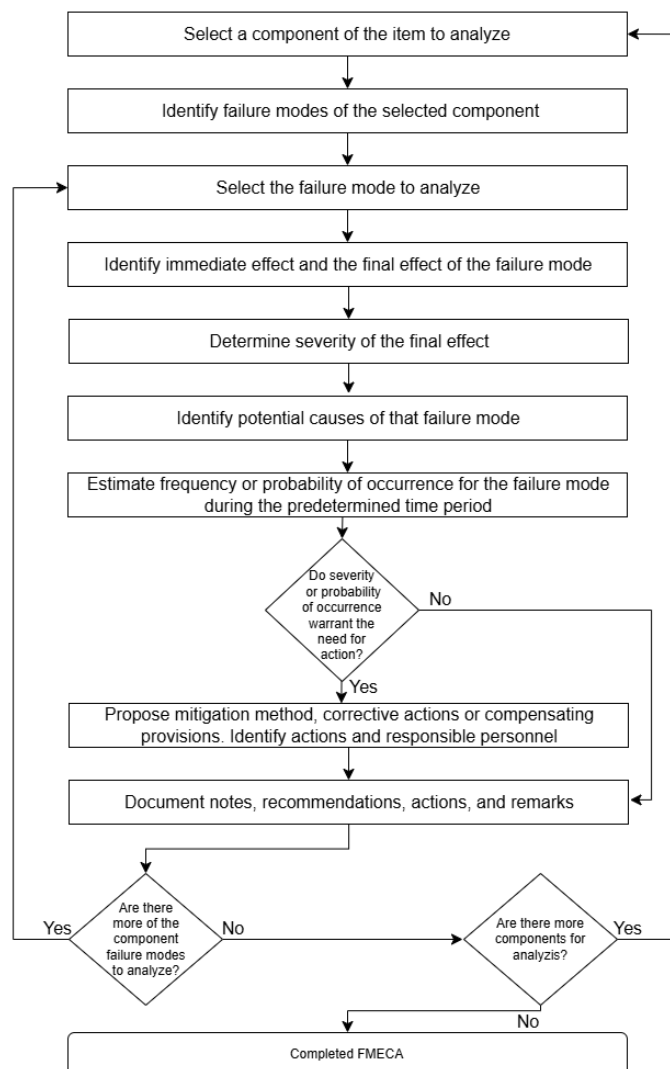


Figure A.3: Reliability Centered Maintenance.

Appendix B

FMECA Logical Sequence



Appendix C

Power Transformer Functional Breakdown

Table C.1: Functional breakdown of the power transformer components considered in the FMECA

Component	Functional area	Main function within the transformer
Core	Core and winding assembly (Active Part)	Provides a low-reluctance path for the magnetic flux, enabling electromagnetic coupling between windings.
Windings	Core and winding assembly (Active Part)	Constitute the electrical circuits of the transformer and enable the transfer of electrical energy through electromagnetic induction, according to the required voltage ratio.
Clamping structure	Core and winding assembly (Active Part)	Provides mechanical support to the core and windings, maintaining their position and helping them withstand mechanical stresses.
Paper and oil insulation	Insulation system	Ensures dielectric insulation between conductive parts and contributes to heat transfer. The solid insulation provides electrical separation and mechanical support, while the insulating oil contributes to dielectric strength and cooling.
Tank	Mechanical enclosure and oil containment	Contains the insulating oil, provides mechanical protection to the active part and supports auxiliary transformer equipment.
Bushings	External connections and insulation	Provide insulated passages for conductors through the transformer tank, allowing electrical connection between the internal windings and the external network.
Oil-air or oil-water cooling system	Cooling system	Removes the heat generated by transformer losses and maintains the oil and winding temperatures within admissible operating limits. Depending on the transformer design, heat may be dissipated through oil-air or oil-water cooling arrangements.
Buchholz relay	Protection and monitoring devices	Detects gas accumulation or sudden oil movement caused by internal faults, supporting alarm or trip functions.

Component	Functional area	Main function
Pressure relief device	Protection and monitoring devices	Relieves excessive internal pressure in the tank, reducing the risk of tank deformation, rupture or escalation of internal faults.
Electrical protection	Protection and monitoring devices	Detects abnormal electrical operating conditions and initiates the appropriate protection action.
On-Load Tap changer (OLTC)	Voltage regulation system	Changes the tapping connections of a winding to adjust the transformer voltage ratio while the transformer is energised or carrying load.
De-energised Tap changer (DETC)	Voltage regulation system	Changes the tapping connections of a winding to adjust the transformer voltage ratio only when the transformer is de-energised.

Appendix D

FMECA

Table D.1: FMECA of the circuit breaker

Componente	Função	Modo de Falha	Efeitos	Causas	Severidade		Ocorrência		Detectabilidade		RPN	Ref. Bibliográfica
Molas	Armazenar/libertar energia para mover os contactos e executar a abertura/fecho do disjuntor	Molas frouxas	Redução da força de operação; abertura ou fecho lento ou incompleto dos contactos; falha de operação de abertura/fecho do disjuntor	Fadiga/envelhecimento das molas que provoca a perda de rigidez das mesmas	2	Baixo	1	Muito Baixa	1	Elevada	2	(Forootani et al., 2017)
Sistema de encravamento	Assegura a retenção correta do mecanismo e a sequência pretendida de abertura/fecho. Previne o mecanismo de voltar à posição anterior	Falha de encravamento	Depois da manobra, os contactos ficam numa posição diferente da correta; aquecimento localizado; degradação do material dos contactos	Fricção excessiva devido a lubrificação insuficiente e/ou manutenção atrasada	3	Médio	1	Muito Baixa	1	Elevada	3	(Forootani et al., 2017)
Ligações mecânicas internas/transmissão	Garantir integridade estrutural, alinhamento e suporte do conjunto do disjuntor	Falhas nas ligações mecânicas internas	Operação irregular; aumento de vibração; desacoplamento parcial entre mecanismo e polos	Envelhecimento dos materiais; desaperto de componentes; vibrações cíclicas de operação; esforços mecânicos repetidos; corrosão	2	Baixo	2	Baixa	3	Baixa	12	–
Bobinas de abertura e fecho	Atuadores eletromagnéticos do disjuntor que, quando ordenado, libertam ou acionam o mecanismo responsável pela abertura ou fecho do disjuntor	Falhas das bobinas de abertura e fecho	Anomalias na abertura ou no fecho do disjuntor; indisponibilidade do disjuntor	Falha interna da bobina; bobina queimada	1	Muito Baixo	3	Média	3	Baixa	9	–
Polo (contactos)	Peças condutoras concebidas para estabelecer a continuidade do circuito quando entram em contacto e que abrem ou fecham um circuito	Desgaste dos contactos	Perda de massa e alterações da geometria dos contactos; degradação da capacidade de condução e interrupção da corrente; aquecimento; degradação da capacidade interruptiva	Fadiga/envelhecimento dos materiais de contactos; ação repetida do arco elétrico	3	Médio	1	Muito Baixa	1	Elevada	3	(Owoeye, 2018)
Polo (câmara de corte)	Dispositivo concebido para confinar o arco e auxiliar na sua extinção	Falha de interrupção do arco	Persistência do arco elétrico após abertura dos contactos	Falha dielétrica; aumento da resistência de contacto; desgaste/erosão dos contactos	5	Catastrófico	1	Muito Baixa	1	Elevada	5	(Razi-Kazemi, 2024)
Polo (isolamento a vácuo)	Garantir isolamento dielétrico e auxiliar a interrupção do arco em disjuntores a vácuo	Falha no meio de isolamento (vácuo)	Diminuição da eficácia do controlo do arco e da interrupção do arco; incapacidade de interromper corretamente a corrente e restabelecer o isolamento após a abertura	Redução da rigidez dielétrica no interior da câmara de vácuo; presença de pequenas partículas no espaço entre contactos	2	Baixo	1	Muito Baixa	3	Baixa	6	(Han et al., 2023)
Polo (isolamento a SF ₆)	Garantir isolamento dielétrico e auxiliar a interrupção do arco em disjuntores a SF ₆	Falha no meio de isolamento (SF ₆)	Diminuição da eficácia do controlo do arco e da interrupção do arco; incapacidade de interromper corretamente a corrente e restabelecer o isolamento após a abertura	Perda de estanqueidade; fugas de SF ₆ ; envelhecimento de vedações	2	Baixo	1	Muito Baixa	1	Elevada	2	(Owoeye, 2018)
Polo (isolamento a óleo)	Garantir isolamento dielétrico e auxiliar a interrupção do arco em disjuntores a óleo	Falha no meio de isolamento (óleo)	Diminuição da eficácia do controlo do arco e da interrupção do arco; incapacidade de interromper corretamente a corrente e restabelecer o isolamento após a abertura	Baixo nível de óleo isolante; intrusão de humidade; falha de buchas isolantes; deterioração gradual do óleo	2	Baixo	2	Baixa	1	Elevada	4	(Iberraken et al., 2013)
Relés de proteção	Processar sinais e emitir ordens no sentido de proteger o disjuntor	Falha de relés de proteção	Pode impedir a transmissão correta da ordem da atuação; atuação indevida ou não-atuação	Defeito interno do relé; falha de contacto na saída do relé	1	Muito Baixo	3	Média	3	Baixa	9	(Xue et al., 2012)
Contactores	Comutação de circuitos auxiliares	Falha de contactores	Comutação instável ou inexistente; atraso na atuação; bloqueio do movimento; operação irregular do circuito auxiliar; falha de comando do disjuntor	Poeira; humidade; temperatura elevada; desgaste eletromecânico; adesão dos contactos	1	Muito Baixo	3	Média	3	Baixa	9	(Zou et al., 2026)

Table D.2: FMECA of the power transformer

Componente	Modo de Falha	Efeitos	Causas	Severidade		Ocorrência		Detectabilidade		RPN	Ref. Bibliográfica
Núcleo	Saturação / sobreexcitação	Aumento das perdas no núcleo; aquecimento localizado do núcleo; aumento da corrente de magnetização; envelhecimento acelerado do isolamento; possível atuação de proteção	Falha na refrigeração e circulação do óleo; operação fora das condições de projeto	4	Elevado	1	Muito Baixo	2	Moderado	8	(Silva, 2024)
Núcleo	Deslocamento do aço do núcleo	Alteração geométrica do circuito magnético; aumento da temperatura do núcleo; dano progressivo do isolamento adjacente	Defeitos construtivos; deformação mecânica	5	Catastrófico	1	Muito Baixo	4	Muito Baixo	20	(Ugli et al., 2025; Singh et al., 2019)
Núcleo	Curto-circuito entre lâminas	Aumento de perdas devido a correntes circulantes parasitas entre lâminas; sobreaquecimento local do núcleo	Falha do isolamento interlaminar do núcleo; sobre-excitação; envelhecimento térmico	5	Catastrófico	2	Baixo	1	Elevado	10	(Ugli et al., 2025; Singh et al., 2019)
Estrutura mecânica ativa (clamping)	Falha no sistema de aperto	Redução da rigidez mecânica do conjunto; deslocamento relativo dos enrolamentos; aumento da suscetibilidade à deformação sob curto-circuito; risco acrescido de descargas parciais	Envelhecimento mecânico; manutenção insuficiente	4	Elevado	1	Muito Baixo	3	Baixo	12	(Singh et al., 2019)
Enrolamento	Curto-circuito entre espiras	Aquecimento localizado; degradação progressiva do isolamento envolvente; deterioração rápida do enrolamento	Degradação do isolamento; envelhecimento; contaminação; dano mecânico	4	Elevado	1	Muito Baixo	1	Elevado	4	(Silva, 2024; Azevedo, 2023)
Enrolamento	Deformação dos enrolamentos	Alteração geométrica do enrolamento; quebra de isolamento do condutor; enfraquecimento do aperto; instabilidade mecânica	Curto-circuitos; envelhecimento; aperto insuficiente; esforço mecânico excessivo	4	Elevado	1	Muito Baixo	3	Baixo	12	(Silva, 2024)
Enrolamento	Mau contacto nos terminais dos enrolamentos	Resistência elevada; sobreaquecimento localizado; geração de gases; envelhecimento acelerado do isolamento	Afrouxamento de ligações; envelhecimento/desgaste dos terminais; deterioração de conexões	3	Moderado	3	Moderado	1	Elevado	9	(Zile, 2020; Akbari et al., 2013)
Enrolamento	Falha no isolamento	Sobreaquecimento localizado; degradação progressiva do enrolamento; curto-circuito interno no transformador; atuação das proteções elétricas	Envelhecimento; deterioração anormal; dano mecânico; contaminação	4	Elevado	3	Moderado	1	Elevado	12	(Cheim et al., 2024)
Travessia	Degradação do isolamento da travessia	Ocorrência de descargas parciais; aumento das perdas dielétricas; redução da rigidez dielétrica do isolamento; aquecimento localizado da travessia	Contaminação e envelhecimento da travessia; humidade	4	Elevado	3	Moderado	1	Elevado	12	(Couto, 2022)
Cuba	Fuga de óleo na ligação tampa-cuba	Perda de óleo; perda de estanqueidade; entrada de humidade na ligação tampa-cuba; comprometimento do isolamento e arrefecimento	Junta e O-ring degradada; aperto inadequado; envelhecimento da vedação	2	Baixo	3	Moderado	1	Elevado	6	–
Cuba	Oxidação externa da cuba	Corrosão e oxidação do aço da cuba	Desgaste ambiental, incluindo humidade, vibrações e radiação solar; gases de alta pressão	1	Muito Baixo	4	Elevado	1	Elevado	4	(Couto, 2022)
Isolamento sólido (papel)	Deterioração do papel isolante	Perda de resistência dielétrica do papel isolante e das suas propriedades mecânicas; aumento do risco de descarga parcial; redução da vida útil do isolamento; curto-circuito entre enrolamentos	Entrada de humidade; envelhecimento do material; sobrecarga	4	Elevado	1	Muito Baixo	1	Elevado	4	(Couto, 2022)
Isolamento (óleo)	Contaminação do óleo isolante	Perda das propriedades dielétricas; aceleração do envelhecimento; sobreaquecimento	Entrada de humidade; contaminação por partículas condutivas	4	Elevado	1	Muito Baixo	1	Elevado	4	(Cheim et al., 2024)
Sist. de Refrigeração (ar-óleo)	Fuga de óleo do radiador	Perda de óleo; perda de estanqueidade; entrada de humidade; comprometimento do isolamento e arrefecimento	Degradação das vedações; fadiga; aperto inadequado	2	Baixo	3	Moderado	1	Elevado	6	(Silva, 2024)
Sist. de Refrigeração (ar-óleo)	Falha do motoventilador	Perda de ventilação forçada; perda de circulação de ar; redução da troca térmica; arrefecimento insuficiente	Desgaste mecânico; danos na parte elétrica; sobrecarga; obstrução	2	Baixo	4	Elevado	1	Elevado	8	(Silva, 2024)
Sist. de Refrigeração (água-óleo)	Falha no permutador	Perda de estanqueidade e de óleo isolante; redução da transferência térmica; aumento da temperatura de operação	Corrosão; fugas; deterioração de juntas; defeito construtivo	2	Baixo	4	Elevado	1	Elevado	8	(Cheim et al., 2024)
Sist. de Refrigeração (água-óleo)	Válvula de admissão em posição incorreta	Restrição ou interrupção do circuito de arrefecimento; caudal reduzido	Manutenção incorreta; ausência de verificação pós-intervenção	2	Baixo	1	Muito Baixo	1	Elevado	2	(Cheim et al., 2024)
Sist. de Refrigeração (água-óleo) e (ar-óleo)	Falha da bomba de circulação de óleo	Caudal de óleo insuficiente; transferência térmica insuficiente; temperaturas mais elevadas no óleo e enrolamentos; alarme/trip térmico	Envelhecimento de rolamentos e motor; desgaste do impulsor	2	Baixo	1	Muito Baixo	1	Elevado	2	(Cheim et al., 2024)

Componente	Modo de Falha	Efeitos	Causas	Severidade		Ocorrência		Detectabilidade		RPN	Ref. Bibliográfica
Sist. de Refrigeração (controle)	Falha do termostato	Ventiladores e bombas não entram ou entram tardiamente; temperatura opera acima do esperado	Sensor/comando defeituoso; manutenção deficiente	2	Baixo	3	Moderado	1	Elevado	6	(Ugli et al., 2025)
Relé Buchholz	Mau funcionamento do relé de Buchholz	Perda da função de detecção precoce, por não atuação; alarme ou disparo indevido, por atuação indevida	Defeito interno do relé	5	Catastrófico	1	Muito Baixo	4	Muito Baixo	20	(Araújo, 2018)
Válvula de segurança	Mau funcionamento da válvula de segurança	Sobrepresão não é libertada adequadamente, por não atuação, ou pressão é libertada sem necessidade, por atuação indevida; risco de deformação/rotura da cuba; indisponibilidade por atuação indevida	Defeito do dispositivo; manutenção inadequada; calibração incorreta	5	Catastrófico	1	Muito Baixo	4	Muito Baixo	20	(Araújo, 2018)
Proteção elétrica (relés da subestação ou grupo)	Defeito de proteção elétrica	Disparo indevido; não-atuação; interrupção de serviço	Defeito interno do relé; ajuste incorreto; perturbações elétricas	5	Catastrófico	1	Muito Baixo	1	Elevado	5	–
Regulação de tensão com comutação em carga	Falha do comutador	Impossibilidade de mudar tomada; perda gradual de condição do comutador	Desgaste progressivo por operação; desgaste nos contactos; variações de carga	1	Muito Baixo	1	Muito Baixo	1	Elevado	1	(Cheim et al., 2024)
Regulação de tensão com comutação em carga	Falha nos contactos	Aumento de resistência de contacto; aquecimento localizado; erosão e degradação do comutador	Desgaste nos contactos; comutações frequentes	4	Elevado	1	Muito Baixo	1	Elevado	4	(Cheim et al., 2024)
Regulação de tensão com comutação em carga	Degradação do óleo	Aumento de humidade/partículas carbonosas; pior desempenho de isolamento; falha de comutação	Envelhecimento e contaminação do óleo	4	Elevado	2	Baixo	1	Elevado	8	Sem referência indicada
Regulação de tensão com comutação sem carga	Falha do comutador	Impossibilidade de mudar tomada; perda gradual de condição do comutador	Desgaste progressivo por operação; desgaste nos contactos; variações de carga	1	Muito Baixo	1	Muito Baixo	1	Elevado	1	(Cheim et al., 2024)
Regulação de tensão com comutação sem carga	Falha nos contactos	Aumento de resistência de contacto; aquecimento localizado; erosão e degradação do comutador	Desgaste nos contactos; comutações frequentes	4	Elevado	1	Muito Baixo	1	Elevado	4	(Cheim et al., 2024)

Table D.3: FMECA of the generator

Componente	Função	Modo de Falha	Efeitos	Causas	Severidade		Ocorrência		Detectabilidade		RPN	Ref. Bibliográfica
Bobina do enrolamento estatórico	Unidade do enrolamento estatórico constituída por condutores ligados em série que conduz a corrente alternada induzida	Falha na ligação à terra	Comprometimento da proteção total do enrolamento do estator	Evolução de curto-circuito entre espiras; descarga parcial prolongada; deterioração do isolamento do enrolamento do estator	4	Elevado	3	Média	1	Elevada	12	(Tai et al., 2002)
Estrutura do estator	Suportar e fixar o núcleo estatórico e os enrolamentos do estator, garantindo rigidez estrutural ao conjunto	Falha da estrutura do estator devido a vibrações excessivas	Elevação de deformação, tensão e extensão mecânica na estrutura; perda de rigidez estrutural; aumento do risco de dano no núcleo e no enrolamento estatórico; dano do isolamento	Desalinhamento rotor-estator; desgaste de mancais/apoios	5	Catastrófico	1	Muito Baixa	1	Elevada	5	(Thakur et al., 2023; Zhang et al., 2022)
Barra do enrolamento estatórico	Conduzir corrente nas ranhuras do estator	Falha de fixação da bobina na ranhura	Vibração da bobina na ranhura; erosão do isolamento por impacto ou desgaste abrasivo; descargas parciais entre superfície de bobina e núcleo; deterioração acelerada do isolamento; descarga parcial na ranhura	Perda de eficácia do sistema de calagem; desapertos	3	Médio	3	Média	2	Moderada	18	(Stone and Wu, 2009)
Enrolamento estatórico	Produzir a tensão terminal trifásica do gerador	Sobreaquecimento do enrolamento estatórico	Degradação do material do enrolamento estatórico	Curto-circuitos; contaminação; bloqueio do sistema de refrigeração	2	Baixo	1	Muito Baixa	1	Elevada	2	(IEEE, 2005)
Enrolamento estatórico	Produzir a tensão terminal trifásica do gerador	Degradação do isolamento do enrolamento estatórico	Descargas parciais; ataque químico ao isolamento	Envelhecimento natural; descargas parciais; temperaturas e esforços elevados	2	Baixo	4	Alta	2	Moderada	16	(Stone and Wu, 2009)

Component	Function	Failure Mode	Effects	Causes	Severity		Occurrence		Detectability		RPN	Ref. Biblio.
Núcleo estatórico	Conduzir o fluxo magnético principal da máquina e suportar o enrolamento estatórico	Falha mecânica do núcleo do estator	Formação de pontos quentes; dano localizado das chapas do núcleo; possível propagação da falha; degradação do isolamento dos condutores adjacentes	Degradação mecânica do núcleo; má projeção, ou erro de projeto	5	Catastrófico	1	Muito Baixa	2	Moderada	10	(Bertenshaw et al., 2012)
Núcleo estatórico	Conduzir o fluxo magnético principal da máquina e suportar o enrolamento estatórico	Falha devido à falta de isolamento no núcleo do estator	Curto-circuito entre lâminas; criação de pontos quentes no núcleo estatórico	Erosão do isolamento entre lâminas ao longo da vida útil; degradação mecânica, nomeadamente vibrações entre lâminas	4	Elevado	2	Baixa	3	Baixa	24	(Znidarich, 2008)
Enrolamento rotórico	Gerar o campo magnético de excitação do rotor	Curto-circuito entre espiras do enrolamento rotórico	Assimetria do campo magnético induzido; enfraquecimento dos polos adjacentes; vibração forte	Envelhecimento térmico; contaminação	3	Médio	3	Média	2	Moderada	18	(Wu et al., 2017)
Entreferro rotor-estator	Manter folga radial adequada entre rotor e estator durante todo o regime de operação	Contacto/rubbing rotor-estator	Dano mecânico e sobreaquecimento nas faces dos polos; desequilíbrio magnético; vibração forte; desprendimento do polo	Colapso mecânico do grupo; má projeção, ou erro de projeto	5	Catastrófico	1	Muito Baixa	3	Baixa	15	(Alber and Markert, 2014)
Jante do rotor	Assegurar a integridade estrutural mecânica de suporte dos polos do rotor	Falha na jante do rotor	Distorção da jante; vibrações	Aumento das forças centrífugas; rigidez radial não simétrica do corpo do rotor ou das juntas do polo	5	Catastrófico	1	Muito Baixa	3	Baixa	15	(Yeboah et al., 2016)
Ligação polo-jante	Fixar mecanicamente o polo ao corpo do rotor e transmitir os esforços mecânicos, incluindo os centrífugos	Falha da fixação polo-jante	Necessidade de remoção dos polos para inspeção detalhada; libertação de polo como cenário limite	Fadiga devido a carregamento cíclico estrutural associado a ciclos start-stop; falha do projeto	5	Catastrófico	1	Muito Baixa	3	Baixa	15	(Sire et al., 2021)
Enrolamento amortecedor	Amortecer fluxos/correntes transitórias no rotor e proteger o enrolamento do rotor	Falha devido a quebra do amortecedor de enrolamento	Maior solicitação mecânica e térmica às barras adjacentes; mudanças de carga, start-stop	Ligação deficiente; número elevado de arranques e paragens; tensões termo-mecânicas	1	Muito Baixo	4	Alta	1	Elevada	4	(Ehya and Nysveen, 2022)
Enrolamento rotórico	Gerar o campo magnético de excitação do rotor	Falha do isolamento do enrolamento	Redução da integridade dielétrica; evolução para curto-circuito entre espiras; vibração severa; aumento de temperatura do rotor	Aquecimento elevado; vibração excessiva; contaminação do isolamento	3	Médio	2	Baixa	1	Elevada	6	(Wu et al., 2017)
Frenagem do alternador	Controlar a velocidade rotacional do alternador durante arranque e paragem, garantindo desaceleração controlada do rotor	Falha na frenagem	Desaceleração inadequada do rotor; resposta de travagem inconsistente; aumento de vibração e ruído; variações inesperadas de velocidade; perda de integridade mecânica do freio	Desgaste da pista de frenagem e dos calços; manutenção inadequada	2	Baixo	1	Muito Baixa	1	Elevada	2	–
Anéis coletores (excitação estática)	Transferir a corrente de excitação do sistema de excitação para o rotor	Perda de contacto nos anéis coletores	Mudança de geometria; deformação localizada do anel; degradação da condição dos anéis	Mau posicionamento; mau aperto	2	Baixo	3	Média	1	Elevada	6	(Yeboah et al., 2016)
Escovas (excitação estática)	Fazem contacto elétrico com os slip-rings para a transferência da corrente de excitação para o rotor	Desgaste excessivo das escovas	Perda de qualidade do contacto elétrico; acumulação de pó condutivo no compartimento dos anéis; criação de arco elétrico	Desgaste gradual por utilização; contaminação da película superficial das escovas por óleo e sujidades	2	Baixo	3	Média	1	Elevada	6	(de Oliveira Salles et al., 2025)
Transformador de excitação	Fornecer a alimentação adequada ao sistema de excitação estática	Falha do transformador de excitação	Ruído/vibração anormal do transformador; excitação insuficiente do alternador; instabilidade do campo magnético; risco de perda de sincronismo	Sobretensão ou sobre-esforço elétrico; desgaste térmico ao longo da vida útil; falha no sistema de refrigeração	3	Médio	2	Baixa	1	Elevada	6	–
Regulador de tensão	Regular a tensão terminal do alternador, ajustando a excitação	Falha do regulador de tensão	Regulação incorreta ou perda de regulação da excitação; tensão terminal instável; sobreaquecimento/queima de componentes da placa	Defeito ou degradação dos componentes eletrónicos internos; falha nos circuitos de controlo	4	Elevado	2	Baixa	1	Elevada	8	(Littler, 1991)
Disjuntor de campo	Interromper a excitação e permitir a desexcitação segura do campo do rotor	Falha na desexcitação	Dissipação lenta da energia armazenada no campo; supressão de tensão mais lenta do que o necessário	Dano nas bobinas de abertura/fecho; falha do mecanismo de operação; abertura tardia ou não abertura	3	Médio	1	Muito Baixa	2	Moderada	6	(Mutukutti et al., 2010)
Unidade retificada a tiristores (excitação estática)	Subconjunto do sistema de excitação cuja função é converter corrente alternada de excitação em corrente contínua	Falha da ponte conversora / unidade retificadora a tiristores do AVR	Perda ou degradação da capacidade de conversão/controlo da excitação; condição de sobre-excitação ou sub-excitação; em sobrecorrente prolongada, disparo da excitação pelo disjuntor de campo	Falha de componentes próprios	3	Médio	2	Baixa	2	Moderada	12	(Littler, 1991)

Component	Function	Failure Mode	Effects	Causes	Severity		Occurrence		Detectability		RPN	Ref. Biblio.
Ponte retificadora girante – díodos girantes (excitação brushless)	Retificar a saída AC da excitatriz principal e alimentar em DC o rotor	Falha de díodo girante	Retificação anômala na ponte de díodos girante; alteração dos sinais elétricos da excitatriz; degradação local da função de alimentação ao rotor	Abertura do díodo, open-circuit, ou curto-circuito do díodo, short-circuit; alta velocidade de rotação provoca vibração e pode danificar o díodo	3	Médio	2	Baixa	2	Moderada	12	(Littler, 1991)
Sistema de refrigeração (refrigerador)	Remover calor do meio de arrefecimento do alternador	Falha no refrigerador	Perda de estanqueidade do refrigerador; fuga de fluido de arrefecimento; tubos do refrigerador soltos	Degradação mecânica; vibração dos tubos do refrigerador	3	Médio	2	Baixa	2	Moderada	12	(IEEE, 2005)
Sistema de refrigeração (condutores do estator)	Permitir circulação de água nos condutores do estator para remoção de calor	Obstrução dos canais de arrefecimento dos condutores do estator	Redução do caudal de água e arrefecimento deficiente do enrolamento estatórico; sobreaquecimento do enrolamento estatórico	Deposição de óxidos de cobre	2	Baixo	2	Baixa	2	Moderada	8	(Svoboda, 2018)
Chumaceiras	Suportar o veio, assegurando apoio radial/axial, garantindo o alinhamento e a rotação suave do conjunto turbina-alternador	Desgaste e fadiga do Babbitt	Contacto metal-metal; aquecimento localizado; desgaste da superfície da chumaceira; excentricidade do rotor, não alinhado com o centro do estator; contacto rotor-estator	Perda do filme de óleo; falha do sistema de lubrificação; stress; vibrações	4	Elevado	3	Média	1	Elevada	12	(Iliev, 1999)
Chumaceiras	Suportar o veio, assegurando apoio radial/axial, garantindo o alinhamento e a rotação suave do conjunto turbina-alternador	Degradação do óleo da chumaceira	Perda de qualidade do filme lubrificante; aquecimento e desgaste	Entrada de contaminantes; filtro sujo; humidade	4	Elevado	4	Alta	1	Elevada	16	–
Chumaceiras	Suportar o veio, assegurando apoio radial/axial, garantindo o alinhamento e a rotação suave do conjunto turbina-alternador	Desalinhamento da chumaceira	Aumento de carga localizada nas chumaceiras; alteração do entreferro; vibração anormal	Desgaste; deformação do veio; falhas de apoio	4	Elevado	3	Média	1	Elevada	12	(Shanbhag et al., 2025)
Chumaceiras	Localizar e suportar o veio, assegurando apoio radial/axial, garantindo alinhamento	Perda de estanqueidade nas juntas	Perda de estanqueidade nas juntas de chumaceira; maior desgaste na camisa à volta do veio; contaminação do lubrificante	Envelhecimento e degradação das vedações por calor e desgaste; paragem prolongada com condensação acumulada; existência de lixo	3	Médio	1	Muito Baixa	2	Moderada	6	(U.S. Bureau of Reclamation, 2024)
Chumaceiras	Assegurar a remoção de calor do óleo da chumaceira, mantendo condições térmicas adequadas para a lubrificação e operação da chumaceira	Falha no sistema de refrigeração	Perda de capacidade de arrefecimento do óleo e/ou contaminação do óleo por água; sobreaquecimento da chumaceira; aumento do risco de dano nos patins	Colmatação e fugas nos filtros; rotura de tubagens; desapertos mecânicos; corrosão	3	Médio	2	Baixa	1	Elevada	6	–
Chumaceiras	Suportar o veio, assegurando apoio radial/axial, garantindo o alinhamento e a rotação suave do conjunto turbina-alternador	Erosão elétrica	Pitting, ou microcrateras; marcas riscadas no metal Babbitt; aumento de fricção e ruído; degradação do lubrificante	Tensão induzida no veio; degradação do isolamento da chumaceira	3	Médio	1	Muito Baixa	2	Moderada	6	(Mailula and Saha, 2025)

Table D.4: FMECA of the turbine

Componente	Função	Modo de Falha	Efeitos	Causas	Severidade		Ocorrência		Detectabilidade		RPN	Ref. Bibliográfica
Regulador de Velocidade – Sistema eletrônico	Processar sinais de controlo e comandar a abertura do distribuidor ou injetor para ajustar a potência da turbina	Falha do módulo eletrónico / cartas do regulador	Regulação incorreta; perda ou degradação do sinal de comando; sobreaquecimento/queima de componentes da placa; perda de controlo da turbina	Defeito interno da carta; envelhecimento; contaminação; ligações soltas ou danificadas	3	Médio	2	Baixa	2	Moderada	12	(Bravo et al., 2023)
Regulador de Velocidade – Sistema eletrônico	Processar sinais de controlo e comandar a abertura do distribuidor ou injetor para ajustar a potência da turbina	Falha de sensores / perda de feedback do regulador	Perda do sinal de controlo do regulador de velocidade	Defeito interno do sensor	2	Baixo	2	Baixa	2	Moderada	8	–
Regulador de Velocidade – Sistema hidráulico	Fornecer pressão hidráulica aos servomotores e posicioná-los corretamente	Falha dos servomotores	Erro de abertura/fecho; perda de força; em lógica de segurança, fecho do distribuidor, no caso Francis e Kaplan, e do injetor, no caso Pelton; perda de controlo do distribuidor	Falha de resposta ao comando elétrico; perda de pressão hidráulica; fugas de óleo / perdas internas no servomotor	4	Elevado	1	Muito Baixa	2	Moderada	8	(U.S. Bureau of Reclamation, 2024)
Regulador de Velocidade – Sistema hidráulico	Fornecer pressão hidráulica aos servomotores e posicioná-los corretamente	Falha em válvulas de comando do sistema hidráulico	Incapacidade de posicionar corretamente o servomotor	Falha de resposta ao comando elétrico; perda de pressão hidráulica; fugas de óleo	3	Médio	2	Baixa	1	Elevada	6	(U.S. Bureau of Reclamation, 2024)
Regulador de Velocidade – Sistema hidráulico	Fornecer pressão hidráulica aos servomotores e posicioná-los corretamente	Fuga de óleo (perda de pressão)	Redução de volume de óleo disponível no circuito; interrupção da atividade; acidente ambiental	Desgaste de juntas ou vedações; rompimento de flanges, soldaduras e tubagem	4	Elevado	2	Baixa	2	Moderada	16	–
Regulador de Velocidade – Distribuidor	Controla a posição angular das pás diretrizes para regular o volume de água que alimenta a roda da turbina	Falha nas ligações mecânicas às pás-diretrizes	Perda do comando direto sobre as diretrizes	Desgaste mecânico progressivo de ligações e componentes; falta de lubrificação; desalinhamento	3	Médio	4	Alta	1	Elevada	12	(U.S. Bureau of Reclamation, 2024)
Pás diretrizes	Controlar e orientar o escoamento de água para a roda da turbina	Degradação das pás diretrizes	Vibrações por desequilíbrio hidráulico; erosão e obstrução das pás diretrizes	Presença de sedimentos e partículas abrasivas, como areia e sílica, na água e objetos maiores, como troncos; cavitação	2	Baixo	1	Muito Baixa	1	Elevada	2	(Shanbhag et al., 2025)
Injetor / Nozzle (Pelton)	Gera um jato de alta velocidade de água que incide nos baldes da roda Pelton	Funcionamento irregular do injetor	Aplicação assimétrica de carga no balde; aparecimento de forças axiais indesejadas; aumento de tensões num dos lados do balde; vibrações anormais; fadiga acelerada dos baldes	Desgaste por erosão de sedimentos abrasivos; fadiga; corrosão	3	Médio	1	Muito Baixa	3	Baixa	9	(Egusquiza et al., 2017)
Chumaceiras	Localizar e suportar o veio, assegurando apoio radial/axial, garantindo alinhamento	Desgaste e fadiga do Babbitt	Contacto metal-metal; aquecimento localizado; desgaste da superfície da chumaceira; vibrações	Perda do filme de óleo; falha do sistema de lubrificação; alinhamento deficiente; abrasão por sedimentos	4	Elevado	3	Média	1	Elevada	12	(Iliev, 1999)
Chumaceiras	Localizar e suportar o veio, assegurando apoio radial/axial, garantindo alinhamento	Degradação do óleo da chumaceira	Perda de viscosidade ou do filme lubrificante; corrosão; aumento de atrito; vibrações	Entrada de água; oxidação; contaminação com partículas estranhas; envelhecimento térmico	3	Médio	2	Baixa	1	Elevada	6	–
Chumaceiras	Localizar e suportar o veio, assegurando apoio radial/axial, garantindo alinhamento	Desalinhamento da chumaceira	Vibração anómala; cargas axiais/radiais elevadas; distribuição irregular de carga no apoio; desgaste acelerado	Sistema de balanceamento defeituoso; desequilíbrio radial/axial; erro de montagem	3	Médio	1	Muito Baixa	3	Baixa	9	(Shanbhag et al., 2025)
Chumaceiras	Localizar e suportar o veio, assegurando apoio radial/axial, garantindo alinhamento	Perda de estanquidade nas juntas	Perda de estanquidade nas juntas de chumaceira; maior desgaste na camisa à volta do veio; contaminação do lubrificante	Envelhecimento e degradação das vedações por calor e desgaste; paragem prolongada com condensação acumulada; existência de lixo	3	Médio	1	Muito Baixa	2	Moderada	6	(U.S. Bureau of Reclamation, 2024)
Chumaceiras	Assegurar a remoção de calor do óleo da chumaceira, mantendo condições térmicas adequadas para a lubrificação e operação da chumaceira	Falha no sistema de refrigeração	Perda de capacidade de arrefecimento do óleo e/ou contaminação do óleo por água; sobreaquecimento da chumaceira; aumento do risco de dano nos patins	Colmatação e fugas nos filtros; rotura de tubagens; desapertos mecânicos; corrosão	3	Médio	2	Baixa	1	Elevada	6	–

Componente	Função	Modo de Falha	Efeitos	Causas	Severidade		Ocorrência		Detectabilidade		RPN	Ref. Bibliográfica
Circuito hidráulico	Fornecer óleo sob pressão para acionar e controlar os servomotores e mecanismos do regulador, permitindo a manobra dos órgãos reguladores da turbina	Falha no circuito hidráulico do grupo	Fugas nas comportas; desgaste acelerado das buchas das pás diretrizes/lâminas; aumento do atrito nos pivôs, ou pontos de articulação	Rotura na conduta; problemas nas vedações; falha da eletroválvula; obstrução dos filtros de aspiração	3	Médio	1	Muito Baixa	2	Moderada	6	–
Veio	Transmitir o binário mecânico da roda da turbina ao alternador	Fadiga do veio	Vibração anômala; desequilíbrio de massa; aquecimento excessivo das chumaceiras	Fadiga por cargas cíclicas; defeitos de material; corrosão	5	Catastrófico	1	Muito Baixa	1	Elevada	5	(U.S. Bureau of Reclamation, 2024)
Acoplamento do veio	Ligar troços da linha de veios e transmitir o binário mantendo alinhamento entre os eixos	Problemas no acoplamento do veio	Fadiga nos pernos de aperto entre veio e roda; aumento de vibrações	Alinhamento deficiente	5	Catastrófico	1	Muito Baixa	1	Elevada	5	(Pennacchi and Vania, 2008)
Drenagem	Remover água de infiltração e controlar o nível em zonas sensíveis	Incapacidade de drenagem adequada do grupo	Acumulação de água; risco de inundação da central	Falha da eletrobomba; falha em juntas de estanqueidade ou nas chumaceiras das pás diretrizes	2	Baixo	4	Alta	1	Elevada	8	–
Roda – Balde (Pelton)	Converter a energia cinética do jato de água em energia mecânica de rotação por impacto	Desgaste do perfil da roda Pelton	Perda de material; desequilíbrio da roda; formação de fissuras; vibrações	Erosão por sedimentos na água; fadiga	3	Médio	2	Baixa	1	Elevada	6	(Shanbhag et al., 2025)
Roda – Labirinto (Francis/Kaplan)	Reduzir fugas internas e ajudar a controlar o equilíbrio hidráulico do conjunto	Aumento da folga do labirinto (perda de estanquidade interna)	Aumento das perdas por fuga no labirinto; redução da eficiência hidráulica	Grupo desalinhado	3	Médio	1	Muito Baixa	3	Baixa	9	(Kamal et al., 2024)
Roda – Kaplan	Converter energia hidráulica em binário com ângulo de pá ajustável	Contacto pá-manto	Geração de forças de contacto; aumento de vibração e desgaste localizado	Folga pequena entre pá e manto; desalinhamento da roda	3	Médio	2	Baixa	2	Moderada	12	(Thiery et al., 2015)
Roda – Pás Kaplan	Superfícies fixadas ao cubo da roda que contactam com a água e geram binário mecânico no eixo	Desgaste do perfil da roda Kaplan	Aumento de vibrações; desequilíbrio da roda; fugas de água; perda de material da pá	Contacto pá-manto; erosão; cavitação	3	Médio	2	Baixa	1	Elevada	6	(Zhang et al., 2019)
Roda – Pás Francis	Superfícies fixadas ao cubo da roda que contactam com a água e geram binário mecânico no eixo	Desgaste do perfil da roda Francis	Aumento de vibrações; desequilíbrio da roda; fugas de água; perda de material da pá	Erosão por sedimentos na água; fadiga	3	Médio	2	Baixa	1	Elevada	6	(Luna-Ramírez et al., 2016)
Roda – Sistema de Regulação Kaplan	Garantir o sincronismo entre a abertura das pás diretrizes e o ângulo das pás da roda Kaplan, otimizando continuamente o ponto de operação da turbina	Descoordenação entre abertura do distribuidor e pás	Escoamento desorganizado; aumento significativo de vibrações	Falha das cartas; falha do sistema de controlo	4	Elevado	1	Muito Baixa	1	Elevada	4	(Yan et al., 2024)
Cone (Francis/Kaplan)	Promover a diminuição da pressão da água e restituição do escoamento à saída da roda	Falha funcional do cone	Aumento da turbulência; comportamento instável; maior solicitação mecânica do conjunto	Flutuações anómalas de pressão; fadiga; cavitação	3	Médio	2	Baixa	2	Moderada	12	(Mohammadi et al., 2023)
Tubo de aspiração	Garantir a evacuação eficiente do escoamento a jusante da roda, promovendo a desaceleração do fluido	Gama de funcionamento inadequada	Aumento da vibração do tubo de aspiração; elevada variação de tensão nos parafusos; fadiga e fratura frequente dos parafusos	Operação frequente da turbina fora do ponto de melhor rendimento; criação de pressões e depressões	4	Elevado	2	Baixa	1	Elevada	8	(Casanova, 2009)
Tubo de aspiração	Garantir a evacuação eficiente do escoamento a jusante da roda, promovendo a desaceleração do fluido	Corrosão do tubo de aspiração	Descontinuidades do material; degradação localizada da chapa; fissuras	Vibrações; existência de partículas estranhas	4	Elevado	2	Baixa	1	Elevada	8	(Horynová et al., 2017)
Válvula de alívio de pressão (Francis)	Desviar parte do caudal da turbina durante o fecho rápido das palhetas diretrizes, limitando o aumento de pressão na conduta	Válvula de alívio não abre quando solicitada durante o fecho das pás diretrizes	Aumento excessivo de pressão; danos na conduta	Fuga de óleo no dashpot; encravamento da válvula piloto; falha na ligação mecânica; falha do sistema de controlo	3	Médio	1	Muito Baixa	2	Moderada	6	(Leyland, 2002)

Appendix E

Fault Tree Analysis

