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Reliability and Risk Centered Maintenance: A Novel Method for Supporting Maintenance Management

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Abstract: Proper maintenance planning is critical for maintenance management to contribute to increasing availability, ensuring quality requirements, and controlling the safety and environmental risks associated with physical assets. As supporting tools for developing maintenance strategies, Reliability-Centered Maintenance (RCM) and Risk-Based Maintenance (RBM) methods are currently used in several organizations. Nevertheless, these strategies are often approached separately although they are complementary. In this context, this paper proposes a novel method that effectively integrates RCM and RBM by adapting the traditional RCM method to incorporate risk management into maintenance planning decision-making to support maintenance management. The proposed Reliability and Risk Centered Maintenance (RRCM) method allows organizations to determine maintenance plans that ensure the reliability of the physical assets while considering and prioritizing the risks associated with their potential functional failures. The proposed method was demonstrated through a case study considering the operational context of a hydroelectric power plant. The results show the ability of RRCM to assist in the development and implementation of maintenance plans oriented to reliability, risk, and cost.

Keywords: reliability-centered maintenance; RCM; risk-based maintenance; RBM; maintenance planning; RRCM

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1. Introduction

Proper maintenance management is crucial to ensure competitiveness and profitability in all industry sectors [1]. With the increase in the complexity and size of the physical asset portfolio covered by maintenance management, there is pressure for better maintenance performance as it was recognized as strategic for physical asset management [2]. In other words, the continuous pursuit of productivity and less waste as a competitive factor brought greater importance to maintenance management in organizations [3].

Maintenance progress over time is typically represented across generations [4–6]. Each generation is influenced by the economic and technological contexts of its period which influenced the development of different strategies and methods to support maintenance management. With the rise of physical asset management, formalized mainly with the introduction of the international ISO 55000 series for asset management in 2014, a new milestone was established for maintenance whose management is a strategic process in organizations in a sustainable perspective [7,8].

Maintenance management is confronted with increasing availability, ensuring quality requirements, and controlling the safety and environmental risks associated with physical assets. Thus, the development of appropriate failure management policies is essential but also a challenge for maintenance planning [9]. As failure management is a coordinated activity of an organization that deals with the recognition, prevention, and reaction to failures [10], maintenance management shall be supported with strategies and methods to properly define its policies.

The Reliability-Centered Maintenance (RCM) method was developed within civil aviation as a logical discipline for the development of scheduled maintenance programs to ensure the reliability capabilities of the physical asset at a minimum cost [11]. Hence, it defines the maintenance plans economically to restore and preserve the operational ability of equipment [12]. For that, the item under review is individually analyzed to identify all its functions, functional failures, potential failure modes, failure effects, and failure consequences, and select the maintenance tasks [6]. Since its first publication in the late 1970s, RCM has been applied in almost every industry sector and industrialized country [13].

With the increasing awareness of environmental impacts and ensuring the health and safety of personnel in industrial processes driven by the occurrence of major accidents in the mid-80s, a Risk-Based Maintenance (RBM) strategy has emerged. According to Khan and Haddara [14], this strategy aims at reducing the overall risk of failure of operational facilities by assigning focused maintenance efforts in high and medium-risk areas while the efforts are minimized in low-risk areas, reducing the overall scope and cost of the maintenance plan. Therefore, the RBM method is designed to study all failure modes, determine the associated risks, and develop a maintenance plan that minimizes the occurrence of high-risk failure modes [4].

Although RCM and RBM can be complementary, these methods are not generally addressed together in the literature. A search conducted in the Web of Science Core Collection in August 2023 showed only 23 documents associating the terms "RCM" or "Reliability-Centered Maintenance" with "RBM" or "Risk-Based Maintenance" in their titles, abstracts, or keywords. However, none of these documents integrate or combine the methods, instead, they approach or discuss them separately [15–18].

Faced with a current scenario in which equipment and processes are increasingly complex and the concern for the safety of workers and the environment is higher, reliability and risk should guide maintenance planning together. As derived from different maintenance strategies, RCM and RBM methods provide different focus and features to conduct maintenance planning. Accordingly, discussing the integration of RCM and RBM into a single method is extremely relevant to this field of research.

Accordingly, this paper proposes a novel method that integrates RCM and RBM strategies to support maintenance management. The proposed Reliability and Risk Centered Maintenance (RRCM) method adapts the traditional RCM method to incorporate risk management into maintenance planning decision-making. Thus, it allows the organization to determine cost-effective maintenance plans that ensure the reliability of its physical assets while considering and prioritizing the risks associated with their potential functional failures. The proposed method application is demonstrated through a case study considering the operational context of a hydroelectric power plant.

The remaining of this paper is organized as follows: Section 2 provides an overview of the RCM and RBM methods within maintenance management. Section 3 presents the proposed RRCM method. Section 4 presents a case study with the application of the proposed method considering the context of a hydroelectric power plant. Finally, Section 5 presents the authors' conclusions and recommendations for future work.

2. RCM and RBM Methods as Support for Maintenance

Maintenance management is responsible for defining its maintenance strategies following its main objectives such as ensuring the reliability of a physical asset to perform its function as required at optimum costs, considering the safety aspects and the impacts on the environment, and upholding the quality of the product or service provided by the organization [19]. However, this is far from simple and has been challenging managers as well as driving the evolution of maintenance over the years. In response, RCM and RBM were methods developed to support the thriving in maintenance management.

As a process used to determine the maintenance requirements of any physical asset in its operating context [6], RCM is a traditional method that has supported maintenance planning for over 40 years. Currently, it is covered by different technical standards and guidelines [13,20–22] that lead organizations toward success in their application as well as corroborate the importance of the methodology. Nevertheless, the RCM does not appear to have evolved significantly since its conception despite increasing maintenance challenges.

To better understand the subject, a literature review was carried out in August 2023 on the Web of Science Core Collection and IEEE Xplore, two of the most relevant scientific production databases. Documents with both the terms "RCM" or "Reliability-Centered Maintenance" and "maintenance" in their title, abstract, or keywords were searched in the database. Furthermore, the document type and search period fields were not restricted to identifying all types of publications throughout the database coverage time. This search protocol returned a total of 1124 distinct documents, aggregated from both databases, as shown in the publication trend in Figure 1.

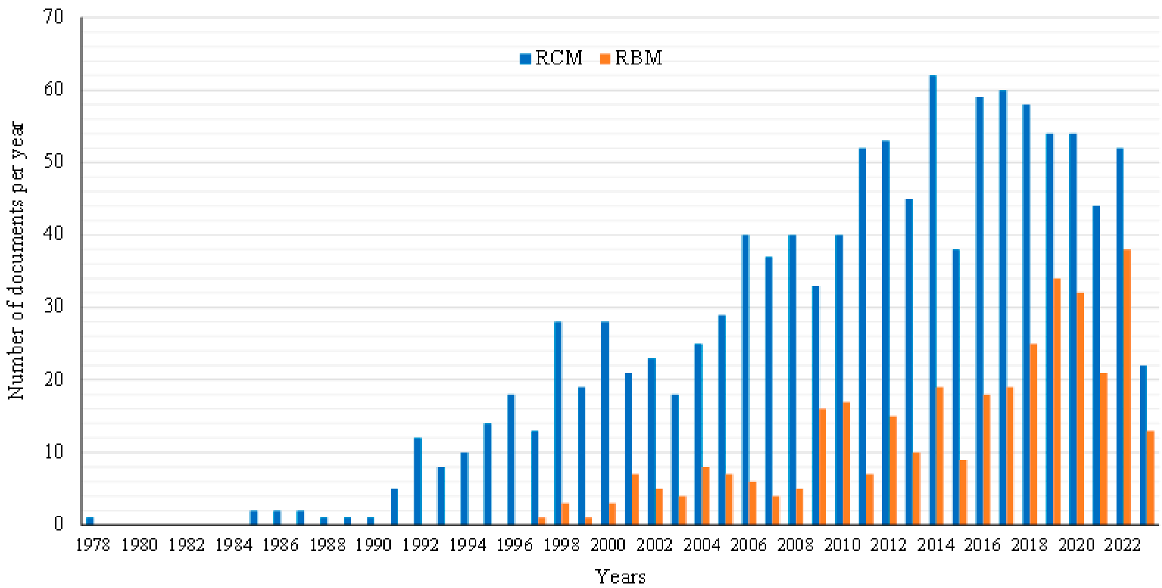

Figure 1. The number of documents published over the years on RCM and RBM.

The first document identified dates from 1978 and it relates to the origin of the RCM with the report developed by Nowlan and Heap commissioned by the U.S. Department of Defense [11]. Beyond the aviation sector, in the late 1980s, the first documents advocated the use of RCM for the effective determination of maintenance plans as they impact preventing unscheduled downtime is a major concern in complex facilities such as nuclear power plants [23,24]. Although publications on the RCM began to be more present in the late 90s, followed by an increasing trend, the number of published documents is still considerably low. In addition, the literature has not shown any tendency to modify the methodology since the standards emerged in the early 2000s, focusing mostly on the application of the RCM to different industry sectors through case studies [25–28].

In parallel with the diffusion of RCM, the risk-based strategy through the RBM method had its first publication in the late 1990s [29,30]. Since then, it has progressively expanded into the field of maintenance. Recently, RBM has gained greater interest and, in the last five years, has accounted for around two-thirds of the published RCM documents. This can be evidenced by the result of the literature review, which also searched for the terms "RBM" or "Risk-Based Maintenance" and "maintenance" in their title, abstract, or keywords on the Web of Science Core Collection and IEEE Xplore in a second search protocol in August 2023. This search protocol returned a total of 347 distinct documents, condensed from both databases, as shown in Figure 1.

Different risk-based approaches from the 1990s already indicated a trend to use risk as a criterion to plan maintenance tasks [31]. By reducing the likelihood and/or consequence of equipment failure, maintenance acts as a risk control measure [29]. The RBM as a method for risk-based inspection and maintenance was proposed by Khan and Haddara in 2003 [14] composed of three main steps: risk estimation, risk evaluation, and maintenance planning. Therefore, it aims to reduce the overall risk in the operating facility by using the risk level as a criterion to plan maintenance tasks [32].

While the two strategies have supported maintenance management over the last years, they are often approached separately. To the best of the authors' knowledge, no method has been proposed to integrate RCM with RBM to consider reliability and risk in a novel single methodology for decision-making on cost-effective maintenance plans. For instance, RCM was extended to consider a broader risk perspective with the use of an uncertainty analysis incorporated into the traditional RCM method [33]. Moreover, RCM, Risk-Based Inspection (RBI), and Safety Instrumented Function Process (SIFpro) were merged into a new methodology that still treats RCM and RBI individually, sharing a common step of preparation [34]. Nonetheless, these two works offer more of an expansion upon RCM by incorporating elements related to risk analysis, rather than outright merging RCM and RBM into a single method.

For better comprehension, the main features of the RCM and RBM methods [13,14] as well as those considered for the proposed Reliability and Risk Centered Maintenance (RRCM) were analyzed and summarized in Table 1.

Table 1. Comparison of main features of RCM, RBM, and RRCM methods.

		RCM	**RBM**	**RRCM**
Item study	Select the item	X	X	X
	Determine the functions and performance standards	X		X
	Determine functional failures/failure scenarios	X	X	X
	Determine the associated failure modes	X		X
	Determine the failure effects for each failure	X		X
	Determine the failure consequence category (FCC) for the functional failures	X		
Risk estimation and evaluation	Perform hazard quantification/impact assessment		X	X
	Perform a probabilistic assessment		X	X
	Estimate/classify the risk		X	X
	Set up acceptance risk criteria		X	
	Compare the assessed risk with acceptance criteria		X	
Maintenance planning	Select the failure management policy based on FCC	X		
	Select the failure management policy based on the failure mode risk classification			X
	Apply a decision tree diagram as support for cost-effective decisions	X		X
	Determine maintenance tasks and interval	X		X
	Determine maintenance plans to reduce risk to items that exceed the acceptance criteria		X	
Periodic review	Re-estimate/reclassify the risk		X	X
	Review the input information and decisions made	X		X

As can be seen in Table 1, the RCM establishes a more detailed study of the item under analysis when compared to the RBM. As it is oriented to reliability, it needs a deep understanding of the item's functions and functional failures, to later determine what shall be carried out to ensure that the item continues to do what its users want it to do in its operational context. On the other hand, RBM provides a more detailed estimation and assessment of risks associated with functional failures when compared to RCM. The risk allows identifying which items do not meet the acceptable risk and shall be prioritized by maintenance management.

Although the RBM indicates that it is necessary to determine the maintenance plans to reduce the risk to items that exceed the acceptance criteria, it does not provide further guidance. As for the RCM, the selection of the fault management policy guides the definition of cost-effective maintenance tasks for the item under analysis, which is usually supported by decision tree diagrams. Finally, it should be noted that the proposed RRCM was conceived to integrate both RCM and RBM strategies into a novel and single method that allows the definition of maintenance plans oriented to reliability, risk, and cost. Therefore, it combines their main features to take advantage of both RCM and RBM strengths, as will be presented in detail in the next section.

3. The Proposed RRCM Method

The proposed RRCM method is composed of a set of activities that support to define and periodically update the maintenance plans of an engineering system. Figure 2 presents a method that depicts such activities.

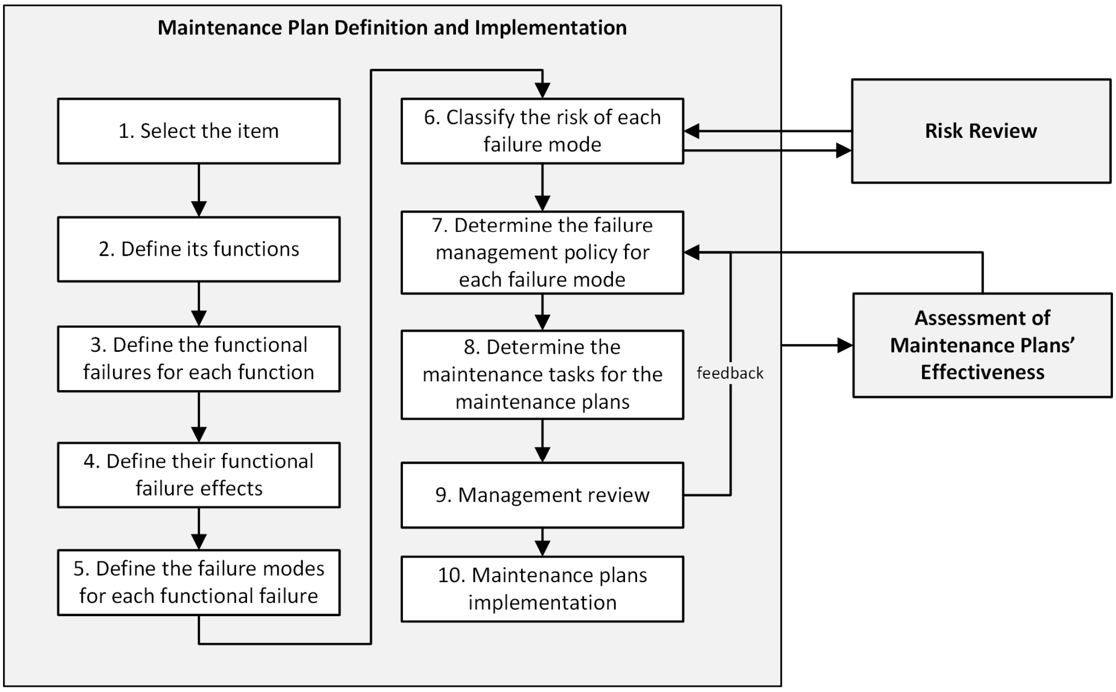

Figure 2. The activities comprised in the proposed RRCM method.

As can be seen in Figure 2, the RRCM method comprises three main processes: the Maintenance Plan Definition and Implementation, the Risk Review, and the Assessment of Maintenance Plans' Effectiveness. The first one, which will be described in more detail in Section 3.1, is the main process and is responsible for determining the best set of maintenance tasks for each failure mode based on the failure mode risk classification and recommended failure management policy.

The second process, Risk Review, is responsible for periodically reassessing the risk level of each failure mode to verify if there has been any significant change that would imply a change in failure management policies. Periodic reviews allow the organizations to update the input data used for risk categorization as well as review the method and decisions made to be better aligned with the organization's context.

Finally, the third process, the Assessment of Maintenance Plans' Effectiveness, aims to assess whether the maintenance plans defined and implemented in the process present the expected results. This assessment can be supported by predetermining several maintenance performance indicators, such as benchmarks for unscheduled downtime, mean time between failures, maintenance costs, and others. Thus, it is possible to verify whether the implementation of the maintenance plans derived from the determined maintenance policies has achieved the maintenance objectives and, eventually, update them.

It is worth mentioning that both proposed periodic reviews through the second and third process of the RRCM intends to ensure that the method is a living application. In other words, the RRCM does not end with the implementation of maintenance plans as the organization needs to periodically review the risks of failure modes and the effectiveness of the defined maintenance plans.

3.1. Maintenance Plan Definition and Implementation

The first RRCM process, the Maintenance Plan Definition and Implementation, comprises ten steps, as shown in Figure 2. Steps 1 to 5, briefly described below, comprise a series of activities that are also covered in a traditional RCM [13].

The first step consists of the simple selection of all items, e.g., physical assets, that will be studied and that will have their maintenance plans determined by the method individually. Due to the increasing complexity and number of items in modern engineering systems, some techniques can support this definition to be carried out in an organized and structured way, such as the Functional Tree or a Block Definition Diagram. In general, organizing assets into systems and subsystems and presenting them in a tree-like structure can help to define the items that will be analyzed. It is worth noting, therefore, that the RRCM does not require or define a specific technique for selecting items and is capable of being executed even with the one that is eventually used by any organization.

The second step is the definition of the functions performed by each of the previously selected items. The functions of a given physical asset represent what its owner wants it to do, including issues of protection, control, appearance, structural integrity, and other secondary aspects. After determining the functions of an item, it is possible to define the functional failures for each function in the third step. Then, in step four, the effects that each identified functional failure can have on the system, people, and the environment need to be defined. Finally, in step five, the failure modes that can cause each listed functional failure also need to be identified.

From the sixth step, the RRCM starts to distance itself from the traditional RCM. Here, the risk associated with the eventual occurrence of each failure mode shall be evaluated, which will be used in the next step to determine a recommended maintenance policy. There are several techniques used for risk assessment, which in general quantify both the severity of the impact and the probability of occurrence of the uncertain event (in this case, the failure mode) and classify it in a risk category. Such quantification and classification shall be designed following the organizational objectives and context.

Although the RRCM does not require the use of a specific technique for risk classification of the failure modes, it requires that it be classified into five possible risk levels: very high, high, medium, low, and very low. By postulating that risk assessment should be limited to these five categories, the proposed method can properly prioritize failure management policies according to each Failure Mode Risk Level (FMRL) to ensure reliability while considering the costs.

Once the risk level of each failure mode has been determined, the seventh step of the RRCM method determines a tailored failure management policy for each of them. Each failure management policy comprises guidelines for each type of maintenance task that can be used for failure mode control and mitigation. There are proposed seven possible failure management policies:

- On-condition: it recommends the continuous monitoring of the physical asset condition, for instance through online measurements or periodic inspection routes. In this policy, maintenance tasks are scheduled and performed only when there are signs of degradation that indicate the future occurrence of the failure mode;
- Scheduled restoration or replacement: it recommends preventive maintenance as it comprises a set of pre-scheduled periodic maintenance tasks of replacement or restoration of the item, regardless of its condition, to avoid the occurrence of the failure mode;
- Combination of tasks: it recommends a combination of on-condition and scheduled restoration or replacement tasks;
- Failure finding: it recommends a set of periodic maintenance tasks that seek to verify the occurrence of a hidden failure mode, i.e., a failure mode not perceptible to the system operators;
- No scheduled task; run to failure: it recommends that maintenance tasks only intervene in the physical asset when the failure mode occurs, i.e., when the item does not perform at least one of its functions;
- No scheduled task; redesign may be desirable: it includes a consideration to be made by the maintenance team about a possible update or modification in the physical asset. It is a one-time task to allow other types of policies to be used or to reduce the risk associated with the occurrence of the failure mode;
- Redesign is mandatory: it indicates that none of the previous failure management policies can effectively reduce the risk associated with the failure mode, requiring, therefore, that an asset redesign is carried out to make the risk acceptable according to organizational objectives.

To determine the appropriate failure management policy for each of the failure modes, five decision diagrams are used to support the decision-making based on their corresponding FMRL as input, as presented in Figures 3–7. For instance, if a given failure mode was classified as a very high FMRL in step 6, the questions presented in Figure 3 shall be properly answered to determine which of the possible seven failure management policies is the most appropriate.

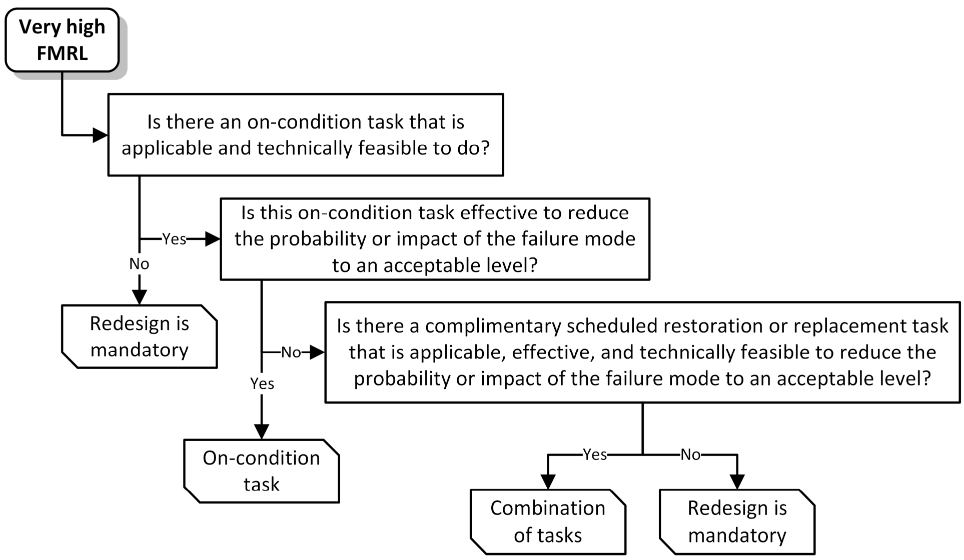

Figure 3. Diagram for determining failure management policy for a very high FMRL.

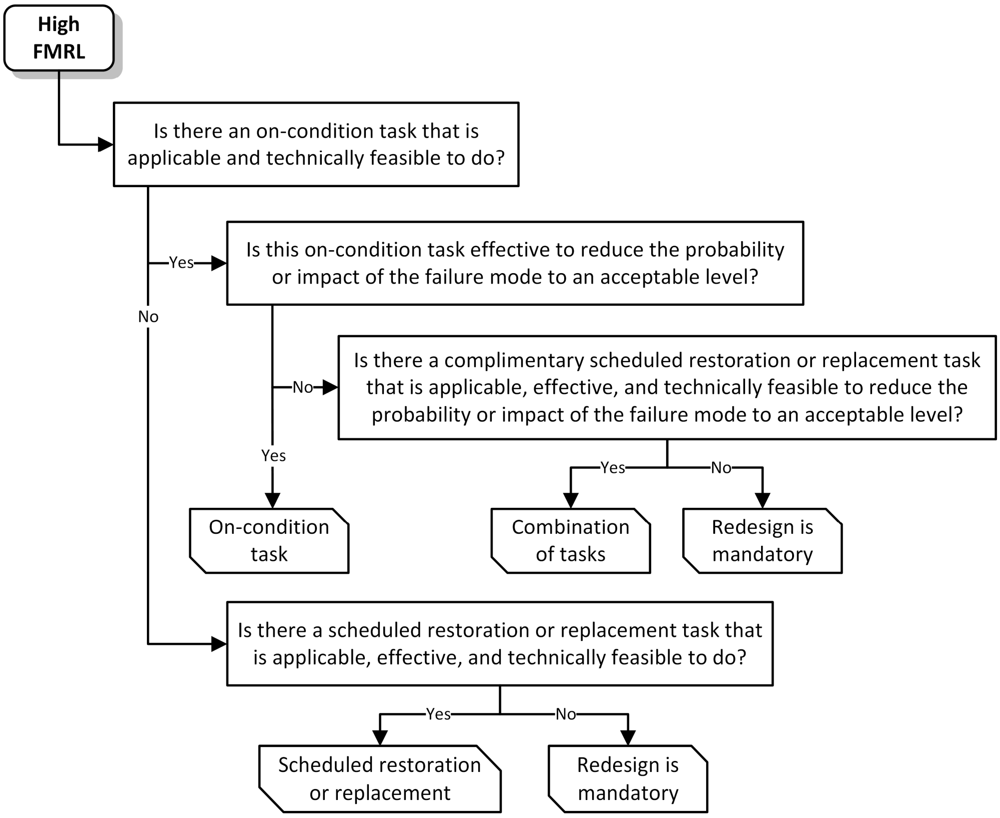

Figure 4. Diagram for determining failure management policy for a high FMRL.

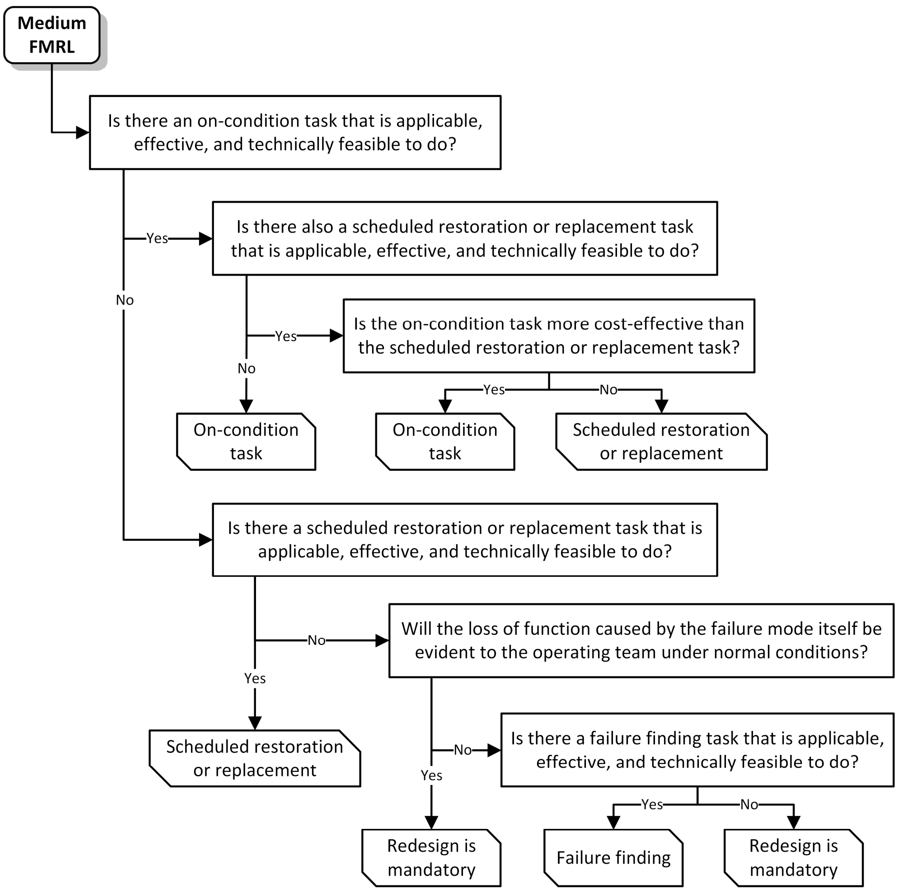

Figure 5. Diagram for determining failure management policy for a medium FMRL.

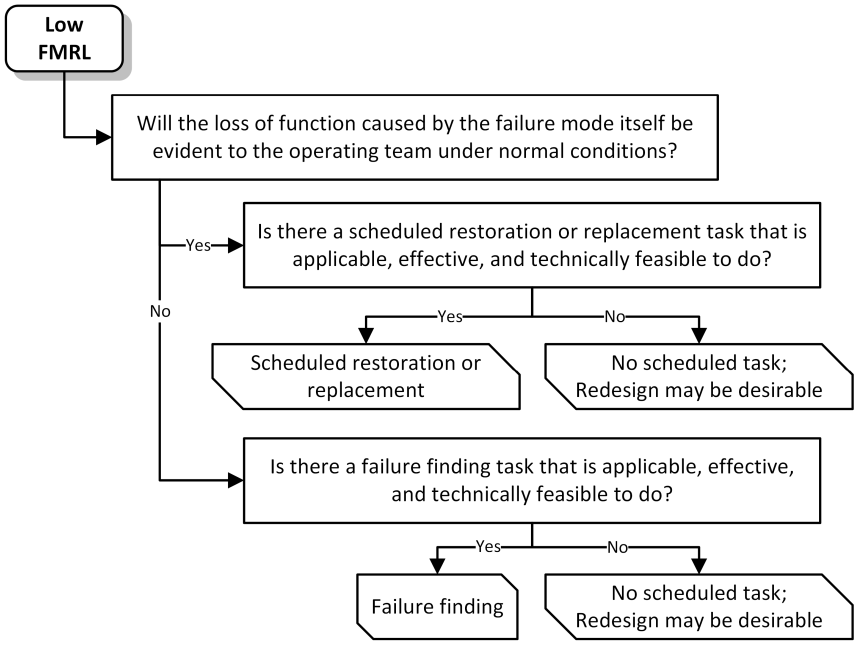

Figure 6. Diagram for determining failure management policy for a low FMRL.

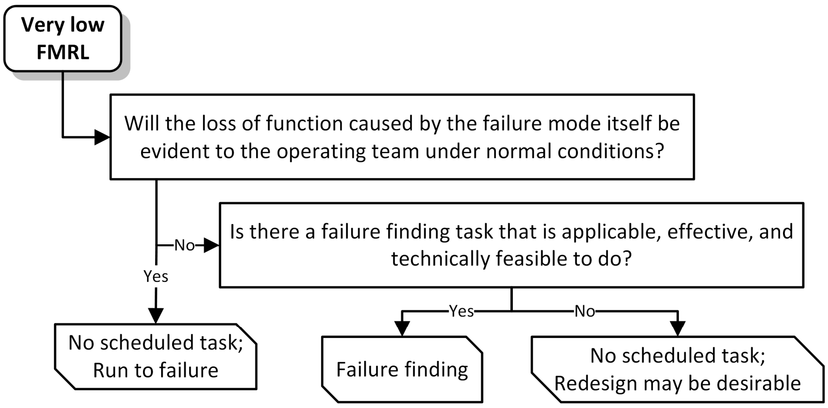

Figure 7. Diagram for determining failure management policy for a very low FMRL.

It is worth noting that in the previous decision diagrams, the on-condition tasks, scheduled restoration or replacement, and failure-finding policies are always confronted as to their applicability, technical feasibility, and effectiveness. For that, Figure 8 provides support to properly interpret these three criteria according to each policy. This represents an advancement of the proposed method when compared to traditional RCM standards that lack further discussion and guidance on these criteria, which can lead to dubious interpretations and implementation barriers.

Once the fault management policies have been determined, step 8 requires the determination of the maintenance tasks corresponding to them. These tasks will integrate the maintenance plans that may also include the necessary manpower, spare parts, and tools, the associated costs, and their periodicity. The derived maintenance plans shall then be validated through a management review, in step 9, which will verify if they meet the cost and labor requirements, and if it has the potential to address the risks associated with the failure modes analyzed. Once approved, the maintenance plans can be implemented as in step 10. However, if they are not approved, step 7 shall be revisited to make adjustments to the previously determined plans based on the feedback provided by management.

On-condition task

Is an on-condition task applicable?
The task will be considered applicable if:
- It allows the observation of the Failure Mode symptoms;
- It allows the identification of the 'failure development period'.

Is an on-condition task technically feasible?
The task will be considered technically feasible if:
- It is physically possible to be performed in a shorter interval than the 'failure development period';
- The 'failure development period' is long enough so that the maintenance repair can be planned and executed.

Is an on-condition task effective?
The task will be considered effective if:
- It reduces the risk of failure to an acceptable level;
- The costs associated with its implementation shall not exceed the ones associated with the failure occurrence.

Scheduled restoration or replacement task

Is a restoration or replacement task applicable?
The task will be considered applicable if:
- The failure mode shall present a clearly increasing failure rate from a given time;
- The failure mode shall not present a significant number of occurrences before this given time.

Is a restoration or replacement task technically feasible?
The task will be considered technically feasible if:
- It ensures, after its completion, the failure rate shall return to an acceptable level;
- It does not introduce possible sources of premature failures.

Is a restoration or replacement task effective?
The task will be considered effective if:
- It reduces the risk of failure to an acceptable level;
- The costs associated with its implementation shall not exceed the ones associated with the failure occurrence.

Failure finding task

Is a failure finding task applicable?
The task will be considered applicable if:
- The effects and symptoms of the failure mode are hidden;
- It is capable of verifying the functional state of all items covered by the failure mode.

Is a failure finding task technically feasible?
The task will be considered technically feasible if:
- It is physically possible to be performed in an interval that reduces the probability of multiple failures to an acceptable level;

Is a failure finding task effective?
The task will be considered effective if:
- It reduces the risk of failure to an acceptable level;
- The costs associated with its implementation shall not exceed the ones associated with the failure occurrence.

Figure 8. Guidelines for verifying the applicability, technical feasibility, and effectiveness of a maintenance task.

4. Case Study

To demonstrate an application of the proposed RRCM method, a Brazilian hydroelectric power plant with four generating units and an installed capacity of approximately 200 MW was considered. Three items from one of the generating units were selected: 2.1. water intake gates, 2.2. water intake grids, and 6.7. turbine guide bearing. As they are systems of different complexities, their selection contributed to demonstrating the application and results of the RRCM for different FMRLs. A total of 17 potential failure modes were analyzed. Figure 9 presents the developed hierarchical functional tree of the generating unit with the items that were analyzed highlighted in gray.

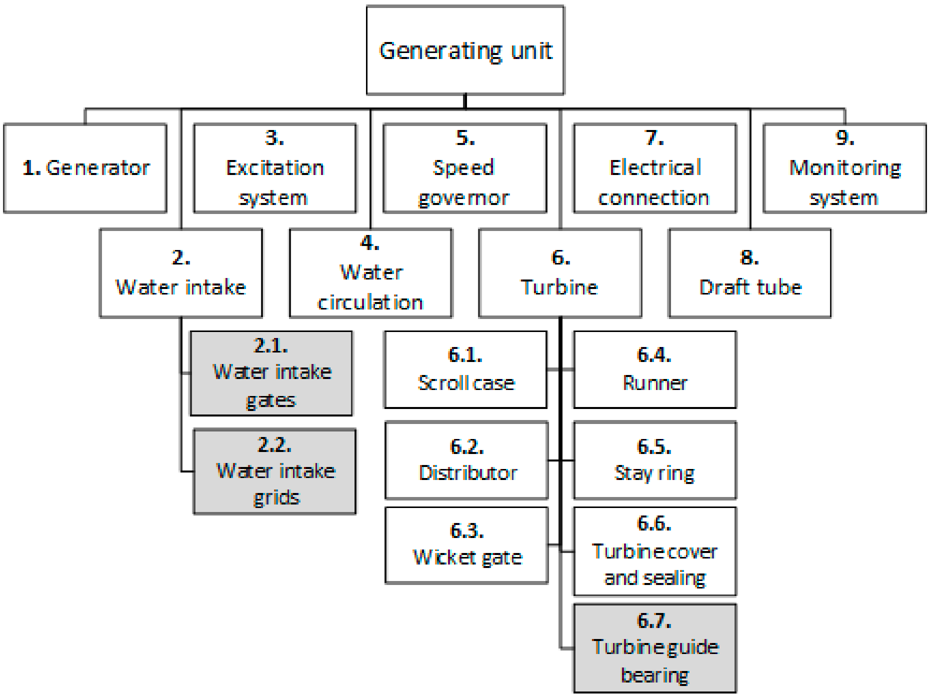

Figure 9. Case study functional tree with analyzed items highlighted.

As presented in the Maintenance Plan Definition and Implementation process, the first five steps are related to the item study and are similar to those applied in a traditional RCM analysis: 1. select the item; 2. define its functions; 3. define the functional failures for each function; 4. define their functional failure effects; and 5. define the failure modes for each functional failure. The results of these five steps for the selected items are presented in Table 2.

Table 2. Study of the selected items.

Item	Functions	Functional Failures	Functional Failure Effects	Failure Modes
2.1. Water intake gates	Allow water intake when the generating unit is in operation	Do not allow the water intake to flow	Water does not flow through the turbine	Gate locked in a closed position
				Inoperative drive system
		Allow a low-intake water flow	Turbine water flow is lower than rated	Gate locked in an intermediary position
				Low pressure in the hydraulic drive system
	Ensure the water intake watertightness	Do not ensure water intake watertightness	Residual water flow in the intake system with the unit inoperative	Lack of watertightness in the water intake system when closed
	Automatically close in case of generating unit overspeed	Do not automatically close when necessary	Water continues to flow through the turbine	Auto-close command not executed
				Gate locked in an open position

Table 2. *Cont.*

Item	Functions	Functional Failures	Functional Failure Effects	Failure Modes
2.2. Water intake grids	Protect the water intake components and turbine	Do not protect systems from debris carried by the river	Loss of protection of the intake components and turbine	Deformed or ruptured water intake grids
	Allow water intake when the generating unit is in operation	Do not allow the water intake to flow	Water does not flow through the turbine	Water intake grids are completely clogged
		Allow a lower intake water flow	Turbine water flow is lower than rated	Water intake grids are partially clogged
6.7. Turbine guide bearing	Constrain the radial displacement of the turbine shaft	Do not restrict the radial displacement of the turbine shaft	Excessive shaft vibration	Excessive clearance in the bearing housing
				Insufficient lubrication
				Inadequate viscosity of oil
				Overheated lubricating oil
				Damaged bearing components
	Ensure the hydrogenator shaft alignment	Do not ensure the proper hydrogenator shaft alignment	Excessive shaft vibration	Improper bearing elements positioning
	Prevent oil leakage	Do not prevent oil leakage	Oil leakage to the plant's facilities and the river	Cracks in the bearing housing

These fundamental five steps are followed by the classification of the risk of each failure mode according to the five possible Failure Mode Risk Level (FMRL) categories: very high, high, medium, low, and very low. As the RRCM does not indicate or restrict how the analysis to categorize each FMRL should be performed, it allows for the utilization of supporting tools that are better suited to the characteristics and context of each system being analyzed. In this case study, a risk matrix was chosen to be used and each FMRL is obtained from the relationship between the Functional Failure Impact (FFI) and the Failure Mode Probability (FMP) given by the risk matrix presented in Figure 10.

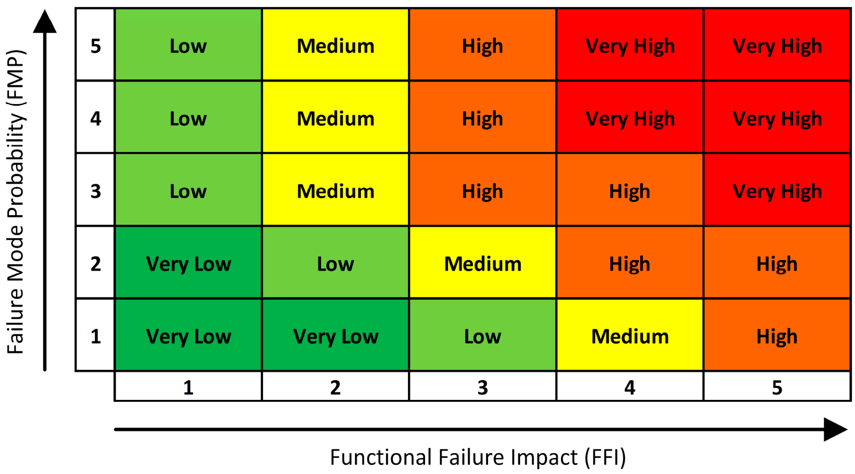

Figure 10. Risk matrix for FMRL classification.

The FFI value is obtained from Equation (1), in which the Environmental Impact (EnI), the Personnel and Facilities Impact (PFI), and the Power Generation and Availability Impact (PGAI) of the functional failure are considered.

$$FFI = \max\,(EnI, PFI, PGAI) \quad (1)$$

For better comprehension, Tables 3–5 show the classification of each impact type (namely, EnI, PFI, and PGAI) resulting from functional failures. Additionally, Table 6 presents the criteria for classifying the FMP in the context of this specific case study.

Table 3. Environmental Impact (EnI) rating.

Level	Description	Functional Failure Impacts on the Environment
1	Very Low	Not enough to cause significant environmental impacts
2	Low	May cause minor environmental impacts
3	Medium	May cause medium environmental impacts
4	High	May cause severe or major environmental impacts
5	Very High	May cause catastrophic environmental impacts

Table 4. Personnel and Facilities Impact (PFI) rating.

Level	Description	Functional Failure Impacts on Personnel and Facilities' Safety
1	Very Low	Not enough to cause injury to staff or damage to facilities
2	Low	May cause minor injuries to personnel or minor damage to facilities
3	Medium	May cause major injury to personnel or serious damage to facilities
4	High	May cause severe injury to personnel or critical damage to facilities
5	Very High	May cause fatalities or catastrophic damage to facilities

Table 5. Power Generation and Availability Impact (PGAI) rating.

Level	Description	Functional Failure Impacts on Generating Unit Power Generation and Availability
1	Very Low	The failure does not impact the availability or generation capacity of the generating unit
2	Low	Failure does not cause unavailability but affects the operating condition of the generating unit
3	Medium	Failure does not cause unavailability but affects the power generation of the generating unit
4	High	Failure does not cause unavailability but severely affects the power generation of the generating unit
5	Very High	Failure causes the unavailability of the generating unit

Table 6. Failure Mode Probability (FMP) rating.

Level	Description	Failure Mode Probability
1	Very Low	Failure rate is very low (up to 1 failure every 60 months)
2	Low	Failure rate is low (1 failure between 36 and 48 months)
3	Medium	Failure rate is moderate (1 failure between 12 and 24 months)
4	High	Failure rate is high (1 failure between 3 and 6 months)
5	Very High	Failure rate is very high (1 or more failures every month)

The classification and rating presented in Tables 3–5 were obtained from a consensus with those responsible for the hydroelectric power plant. In turn, the classification depicted in Table 6 was derived from the analysis of the failure history of the selected items of the plant under examination in this case study.

In this case example, Table 7 presents the FMRL classification for the respective failure modes. It serves as an extension of Table 2, which included ratings for EnI, PFI, and PGAI to evaluate the FFI for the functional failure effects and ratings for FMP to evaluate each failure mode. By combining the FFI and FMP assessments using the risk matrix presented in Figure 10, the FMRL is determined. In addition, it should be noted that each failure mode is assigned a unique ID to facilitate its tracking in subsequent steps of the RRCM method.

Table 7. Failure Mode Risk Level (FMRL) classification.

Item	Functions	Functional Failures	Functional Failure Effects	EnI	PFI	PGAI	FFI	Failure Mode ID	Failure Mode	FMP	FMRL
2.1. Water intake gates	Allow water intake when the generating unit is in operation	Do not allow the water intake to flow	Water does not flow through the turbine	1	1	5	5	FM.2.1.A	Gate locked in a closed position	1	High
								FM.2.1.B	Inoperative drive system	1	High
		Allow a low-intake water flow	Turbine water flow is lower than rated	1	1	4	4	FM.2.1.C	Gate locked in an intermediary position	1	Medium
								FM.2.1.D	Low pressure in the hydraulic drive system	2	High
	Ensure the water intake watertightness	Do not ensure water intake watertightness	Residual water flow in the intake system with the unit inoperative	1	2	1	2	FM.2.1.E	Lack of watertightness in the water intake system when closed	2	Low
	Automatically close in case of generating unit overspeed	Do not automatically close when necessary	Water continues to flow through the turbine	1	5	1	5	FM.2.1.F	Auto-close command not executed	1	High
								FM.2.1.G	Gate locked in an open position	1	High
2.2. Water intake grids	Protect the water intake components and turbine	Do not protect systems from debris carried by the river	Loss of protection of the intake components and turbine	1	4	4	4	FM.2.2.A	Deformed or ruptured water intake grids	2	High
	Allow water intake when the generating unit is in operation	Do not allow the water intake to flow	Water does not flow through the turbine	1	5	5	5	FM.2.2.B	Water intake grids are completely clogged	2	High
		Allow a lower intake water flow	Turbine water flow is lower than rated	1	2	3	3	FM.2.2.C	Water intake grids are partially clogged	4	High
6.7. Turbine guide bearing	Constrain the radial displacement of the turbine shaft	Do not restrict the radial displacement of the turbine shaft	Excessive shaft vibration	1	2	4	4	FM.6.7.A	Excessive clearance in the bearing housing	1	Medium
								FM.6.7.B	Insufficient lubrication	2	High
								FM.6.7.C	Inadequate viscosity of oil	3	High
								FM.6.7.D	Overheated lubricating oil	2	High
								FM.6.7.E	Damaged bearing components	1	Medium
	Ensure the hydrogenator shaft alignment	Do not ensure the proper hydrogenator shaft alignment	Excessive shaft vibration	1	1	3	3	FM.6.7.F	Improper bearing elements positioning	1	Low
	Prevent oil leakage	Do not prevent oil leakage	Oil leakage to the plant's facilities and the river	4	2	2	4	FM.6.7.G	Cracks in the bearing housing	1	Medium

As can be noticed in Table 7, each functional failure may have one or more failure modes associated with it. However, the assessment of the impact of a functional failure is not dependent on them. In other words, each Functional Failure Impact (FFI) is associated with the consequences estimated when the functional failure occurs. On the other hand, as different failure modes have different probabilities of occurrence, they are directly associated with the FMP.

After establishing FMRLs for all defined failure modes, the subsequent steps 7 and 8 of the RRCM were executed. From the risk classification obtained, it is possible to determine the appropriate failure mode management policy and then the maintenance tasks to compose the maintenance plans. The definition of failure mode management policies follows the decision diagrams for each risk level presented in Figures 3–7 as well as the guidelines for verifying the applicability, technical feasibility, and effectiveness of a maintenance task presented in Figure 8. The results obtained for the failure modes listed in Table 7 are presented in Table 8.

To enhance the understanding of the proposed method and its practical implementation, the reasoning utilized to determine the maintenance management policy for failure mode FM.6.7.G, cracks in the bearing housing, are provided. Firstly, the FFI score assigned to the functional failure associated with this particular failure mode (FFI = 4) is mainly related to its impact on the environment. If the turbine guide bearing housing loses its function of restricting the lubricating oil to the inside of the bearing, in this case, due to the development of cracks in the bearing housing, oil leaks may occur. In milder cases, the main consequence is the accumulation of oil puddles in the plant's facilities. However, due to the position of the turbine guide bearing in the generating unit and its proximity to the water flow, in some cases, the oil may not accumulate in the installations and leak directly into the river, which becomes a serious environmental problem.

On the other hand, the probability of the development of cracks in the bearing housing of the generating units of the plant considered is very low, with no case being reported in its almost five decades of operation. In this way, the score associated with FMP is the lowest possible value (FMP = 1). Consequently, from the FFI and FMP scores, the risk level associated with the failure mode is medium.

From the medium FMRL diagram (Figure 5), the initial question to address is if there is an on-condition task that is applicable, effective, and technically feasible to be performed. In this instance, it would not be possible to continuously monitor the development of cracks in the bearing housing, resulting in a negative response to the first question. Consequently, the second question delineated by the decision diagram is whether there is a scheduled, applicable, effective, and technically feasible restoration or replacement task. However, the answer is negative as periodic replacement of the bearing housing proves economically unfeasible.

Thus, the third question outlined in the diagram would be whether the loss of function caused by the failure mode itself would be evident to the operational team under regular operating conditions. Given that cracks in a bearing housing are not easily identifiable through inspection routes typically conducted in hydroelectric power plants, the answer to this final question is also negative. Identifying cracks in such cases usually requires the implementation of specialized non-destructive techniques executed by trained professionals. Moreover, the primary evidence of the existence of cracks in a bearing housing, in this case, the observation of oil leakage, is not always noticeable, especially when the oil flows into the river water flow.

Accordingly, the subsequent question specified in the decision diagram examines whether there is a failure-finding task that is applicable, technically feasible, and effective to be performed. As stated earlier, techniques such as ultrasound or penetrant liquid testing, performed periodically by outsourced teams specializing in non-destructive testing, fulfill these criteria. Consequently, the answer to this fourth question is affirmative, thereby suggesting the most suitable failure mode management policy to be employed for this particular failure mode is failure finding.

Table 8. Failure mode management policies and maintenance tasks.

Failure Mode ID	Failure Mode	FMRL	Failure Mode Management Policy	Maintenance Task	Task Frequency
FM.2.1.A	Gate locked in a closed position	High	Scheduled restoration or replacement	Align the gate guides and free them from obstacles. Lubricate moving components	Follow the unit maintenance downtime plan
FM.2.1.B	Inoperative drive system	High	Scheduled restoration or replacement	Inspect the hydraulic system, retighten gaskets and connections, and replace components such as bearings and seals	Follow the unit maintenance downtime plan
FM.2.1.C	Gate locked in an intermediary position	Medium	Scheduled restoration or replacement	Align the gate guides and free them from obstacles. Lubricate moving components	Follow the unit maintenance downtime plan
FM.2.1.D	Low pressure in the hydraulic drive system	High	Scheduled restoration or replacement	Inspect the condition of the hydraulic system and correct leaks. Check the drive oil level and top up if necessary	Follow the inspection route plan
FM.2.1.E	Lack of watertightness in the water intake system when closed	Low	No scheduled task. Redesign may be desirable	-	-
FM.2.1.F	Auto-close command not executed	High	Scheduled restoration or replacement	Periodically replace the drive components of the automatic gate-closing system	Follow the unit maintenance downtime plan
FM.2.1.G	Gate locked in an open position	High	Scheduled restoration or replacement	Align the gate guides and free them from obstacles. Lubricate moving components	Follow the unit maintenance downtime plan
FM.2.2.A	Deformed or ruptured water intake grids	High	Scheduled restoration or replacement	Check the structural condition of the water intake grids from visual inspections. Carry out repairs when necessary	Follow the unit maintenance downtime plan
FM.2.2.B	Water intake grids are completely clogged	High	On-condition task	Continuously monitor the water pressure upstream and downstream of the grids and clean them with a hydraulic grate cleaner whenever the pressure difference is significant	Continuous
FM.2.2.C	Water intake grids are partially clogged	High	On-condition task	Continuously monitor the water pressure upstream and downstream of the grids and clean them with a hydraulic grate cleaner whenever the pressure difference is significant	Continuous
FM.6.7.A	Excessive clearance in the bearing housing	Medium	Scheduled restoration or replacement	Check the bearing housing fastening elements and retighten or replace them when necessary	Follow the unit maintenance downtime plan

Table 8. *Cont.*

Failure Mode ID	Failure Mode	FMRL	Failure Mode Management Policy	Maintenance Task	Task Frequency
FM.6.7.B	Insufficient lubrication	High	On-condition task	Continuously monitoring oil flows and levels throughout the bearing lubrication system	Continuous
FM.6.7.C	Inadequate viscosity of oil	High	On-condition task	Analyze the quality of the oil and replace it in case of contamination	Follow the oil analysis plan
FM.6.7.D	Overheated lubricating oil	High	On-condition task	Continuously monitoring the inlet and outlet temperatures of the oil in the bearings and heat exchangers	Continuous
FM.6.7.E	Damaged bearing components	Medium	On-condition task	Continuously monitor turbine shaft vibration. If excessive vibration not associated with other failure modes is observed, check the bearing conditions	Continuous
FM.6.7.F	Improper bearing elements positioning	Low	Scheduled restoration or replacement	Check the condition of the bearings periodically and reposition their elements when necessary	Follow the unit maintenance downtime plan
FM.6.7.G	Cracks in the bearing housing	Medium	Failure finding	Check the conditions of the bearing housing and carry out non-destructive tests to verify the presence of cracks	-

The same reasoning was developed for each failure mode under consideration. For each case, starting from the FMRL established for the specific failure mode, the corresponding decision diagram was navigated based on the responses provided to each question. Through this process, the failure management policies were determined, subsequently leading to the determination of the maintenance tasks as shown in Table 8.

Once these results are approved through a management review and implemented, the Maintenance Plan Definition and Implementation process reaches its conclusion. However, as RRCM is a dynamic methodology, the other two processes outlined in the method should be conducted periodically. The Risk Review entails periodic reviews of the FMRL for the defined failure modes based on updated failure history, FFI ratings, impact scales, and decisions. Similarly, the Assessment of Maintenance Plans' Effectiveness can be derived from specific maintenance performance indicators aligning with the overall maintenance management performance evaluation process. The frequency of these processes should be tailored to the needs and expectations of the RRCM within the context of maintenance management and the organization.

RRCM Application Discussion

The demonstration of the RRCM method in this case study contributed to highlighting its distinct features and evidence of how it expands upon the capabilities of individual RCM and RBM methods. In essence, the proposed RRCM method integrates the key aspects from both methods into a singular and innovative methodology that supports maintenance management to economically determine maintenance plans while considering reliability and risk. Consequently, the outcomes derived from this RRCM application, as presented in Tables 2, 7 and 8, could not have been achieved through the implementation of either RCM or RBM separately.

For better comprehension, Table 9 presents a comparison of the applications of traditional RCM [13] and RBM [14] methods, as demonstrated by case studies from the literature review, with the proposed RRCM. All the applications were analyzed considering aspects such as item study, risk estimation and evaluation, maintenance planning, and periodic review, as presented in Table 1.

While the traditional RCM method shares similarities with the proposed RRCM in terms of conducting item studies, it lacks the inclusion of activities for risk estimation and evaluation, which are incorporated for the selection of appropriate failure management policy for each failure mode in RRCM. It is worth mentioning that some recent applications of RCM may include a risk estimation and evaluation activity that derives a metric for failure mode prioritization [35,36]. However, it is not usually considered for the selection of the failure management policies, concentrating on the use of the failure consequences for that purpose. Accordingly, the proposed FMRL classification of RRCM, which addresses risk estimation and evaluation and drives the determination of the appropriate failure management policies and, consequently, the maintenance tasks, offers a more comprehensive perspective compared to the FCC classification of RCM [13].

The quantification of hazards and the probabilistic assessment to classify the risk associated with the failure mode is typically exclusive to the RBM method [39–43]. Thus, compared to traditional RCM, RRCM provides a risk assessment that is considered for the selection of appropriate failure management policies. Additionally, the proposed RRCM method advances the field by providing enhanced support during the maintenance planning decision-making, offering more detailed decision diagrams and guidelines to verify the applicability, technical feasibility, and effectiveness of a potential maintenance task.

Table 9. Comparison of RCM, RBM, and RRCM applications.

Authors	Method	Item Study	Risk Estimation and Evaluation	Maintenance Planning	Periodic Review
Yang et al. (2020) [35]	RCM	The paper presents a study of the items, including their functions, failure modes, failure causes, and Risk Priority Number (RPN).	Although the paper presents the RPN for prioritization of the failure modes, it is not associated with the failure management policy selection.	The paper presents a decision tree to support the selection of an appropriate failure management policy for each failure mode.	The paper does not specifically mention periodic review procedures review procedures such as reviewing input information and decisions made.
Fang et al. (2019) [36]	RCM	The paper presents a study of the items, including their functions, failure modes, failure causes, and fault levels.	Although the paper presents the fault level for prioritization of the failure mode, it is not associated with the failure management policy selection.	The paper presents a decision tree to support the selection of an appropriate failure management policy for each failure mode.	The paper does not specifically mention periodic review procedures review procedures such as reviewing input information and decisions made.
Umpawanwong and Chutima (2015) [25]	RCM	The paper presents a study of the items, including their functions, functional failures, failure modes, and FCC.	The paper does not present any type of risk estimation or evaluation for the identified failure modes.	The paper presents a decision tree to support the selection of an appropriate failure management policy for each failure mode.	The paper does not specifically mention periodic review procedures review procedures such as reviewing input information and decisions made.
Tavares et al. (2012) [37]	RCM	The proposed RRCM includes a broad study of the items, including their functions, functional failures, failure modes, failure effects, and FCC.	The paper does not present any type of risk estimation or evaluation for the identified failure modes.	The paper presents a decision tree to support the selection of an appropriate failure management policy for each failure mode.	The paper does not specifically mention periodic review procedures review procedures such as reviewing input information and decisions made.
Deshpande and Modak (2002) [38]	RCM	The paper presents a study of the items, including their functions, functional failures, and failure modes.	The paper does not present any type of risk estimation or evaluation for the identified failure modes.	The paper presents a decision tree to support the selection of an appropriate failure management policy for each failure mode.	The paper does not specifically mention periodic review procedures review procedures such as reviewing input information and decisions made.
Lopez and Kolios (2022) [39]	RBM	The paper provides a systematic study of the items, including the identification of failure modes, effects, and causes.	The paper presents risk estimation and evaluation for each failure mode based on risk assessment through a risk matrix.	The paper presents a decision tree to support the selection of an appropriate failure management policy for each failure mode.	The paper does not specifically mention periodic review procedures for re-estimating or re-classifying risk.
Masud, Chattopadhyay, and Gunawan (2019) [40]	RBM	The paper provides a study of the items, including the identification of fault events and consequences.	The paper presents risk estimation and evaluation for each failure mode based on risk assessment through a risk matrix.	The paper does not present a support tool to select an appropriate failure management policy for each failure mode.	The paper does not specifically mention periodic review procedures for re-estimating or re-classifying risk.

Table 9. *Cont.*

Authors	Method	Item Study	Risk Estimation and Evaluation	Maintenance Planning	Periodic Review
Hu et al. (2009) [41]	RBM	The paper provides a study of the items, including the identification of fault events and consequences.	The paper presents risk estimation and evaluation for each failure mode based on probabilistic risk assessment.	The paper does not present a support tool to select an appropriate failure management policy for each failure mode.	The paper does not specifically mention periodic review procedures for re-estimating or re-classifying risk.
Dong, Gu, and Chen (2008) [42]	RBM	The paper provides a study of the items, including the identification of fault events and consequences.	The paper presents risk estimation and evaluation for each failure mode based on probabilistic risk assessment.	The paper does not present a support tool to select an appropriate failure management policy for each failure mode.	The paper presents an iterative method that re-evaluates risk after developing a maintenance plan.
Khan and Haddara (2004) [43]	RBM	The paper provides a study of the items, including the identification of fault events and consequences.	The paper presents risk estimation and evaluation for each failure mode based on probabilistic risk assessment.	The paper does not present a support tool to select an appropriate failure management policy for each failure mode.	The paper presents an iterative method that re-evaluates risk after developing a maintenance plan.
Proposed method	RRCM	The proposed RRCM includes a broad study of the items, including their functions, functional failures, failure modes, failure effects, and FCC.	The proposed RRCM incorporates the FMRL for the classification of the risk associated with each identified failure mode based on risk assessment.	The proposed RRCM includes different decision trees to support the selection of an appropriate failure management policy according to the FMRL of each failure mode.	The proposed RRCM includes the Risk Review and Assessment of Maintenance Plans' Effectiveness as necessary processes, which periodically reassess the risks and outcomes of the method.

Finally, although the RBM method provides in-depth risk estimation and evaluation of items and their failure scenarios, it lacks a comprehensive examination of the functions, failure modes, and functional failure effects of these items. As a consequence, the RBM does not provide sufficient guidance for maintenance planning decision-making and usually is not supported by guidelines or decision diagrams for the selection of failure management policies [40–43]. Such limitation is addressed through the implementation of the proposed RRCM method that not only specifies a broad item study as in the RCM method [13,25,37] but also enhances it with more detailed diagrams and guidance that ensures reliability and incorporates risk and cost considerations in maintenance planning.

5. Conclusions

Traditional maintenance strategies based on reliability (RCM) or risk (RBM) should no longer be seen separately in the face of a current scenario in which equipment and processes are increasingly complex and the concern for the safety of workers and the environment is higher. In this context, this paper proposed a novel method that integrates RCM and RBM methods to support maintenance management.

The proposed Reliability and Risk Centered Maintenance (RRCM) combined the study of the system and the cost-effectiveness reasoning of the RCM with risk estimation and evaluation of RBM to determine maintenance plans oriented to reliability, risk, and cost. The case study results showed the RRCM method can assist organizations in the development and implementation of maintenance plans for physical assets through a detailed and dynamic method. Furthermore, the features of the RRCM method expand the capabilities of the RCM or RBM as they incorporate tasks that are not present when applied individually.

Nevertheless, it is worth mentioning that two of the main perceived limitations of RRCM are consistent with those found in both RCM and RBM. Firstly, the proposed method depends on the availability of in-depth technical knowledge and data regarding the items under analysis. For instance, insufficient and inaccurate information input for RRCM may impact the proper identification of the item’s functions, functional failure effects, and potential failure modes and classification of the FMRL. Secondly, although RRCM shows promise, it requires proper planning and a significant amount of time to effectively derive the maintenance plans.

As an additional limitation of RRCM, although the decision diagrams support the decision-making in the selection of the appropriate failure management policy based on the FMRL, they may involve subjective judgments and introduce epistemic bias during the reasoning process.

Finally, it is expected that the findings of this paper will contribute to maintenance professionals and researchers by introducing a novel method to determine maintenance plans considering reliability, risk, and cost-effectiveness at once. As opportunities for future work, the authors suggest further exploration of the processes of Risk Review and Assessment of Maintenance Plans’ Effectiveness as they are critical for the continuous improvement of the maintenance plans to support maintenance management.

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