An overview of reliability centered maintenance using failure mode and effect analysis

Un aperçu de la maintenance centrée sur la fiabilité à l'aide de l'analyse des modes de défaillance et de leurs effets

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ABSTRACT. In certain industries, the different operations are very complex, and a small error may lead to a catastrophe. So, there is a strong need to establish an effective maintenance program to avoid any possible error. A concept called Reliability-Centered Maintenance (RCM) was found in the 1960s and initially oriented towards maintaining aircrafts. The objective of this overview is to present the different difficulties when implementing RCM strategy in other industrial fields. So, we first present some RCM concepts and next deal with the most used assessment methods such as Risk Priority Number (RPN) method and Military Standard one. Failure Mode and Effect Analysis (FMEA) as a structured approach is used next to discover potential failures that may exist within a product design or production process. Far away from aviation industry, a coffee maker is considered as an illustrative example to provide the newcomers with a simplified way to implement the RCM concepts in different industrial sectors. Several failure modes considering MSG-3 standard are presented to provide the suitable preventive maintenance actions. Finally, a discussion and future perspective section provides some critical points and future propositions when implementing this strategy in other industrial fields such as additive manufacturing.
KEYWORDS. Maintenance strategy, Reliability Centred Maintenance (RCM), Failure Modes and Effect Analysis (FMEA), MSG-3 standard.

1. Introduction

Reliability-Centered Maintenance (RCM) is a strategy for maintenance planning which has been first developed within the aircraft industry and later extended to other industries (Ahmadi (2010)). This concept belongs to the third generation of maintenance (after mid 70's), while the first and the second generations (pre and post second world war) are related to corrective maintenance and preventive one, respectively. The initial report of RCM was written by Nowlan and Heap of United Airlines in 1978 (Nowlan and Heap (1978)). Since this report, the RCM methodology has been widely used by different industries, such as military, nuclear power generation, offshore, oil and gas, maritime, solar receiving plant, grain terminal, and coal mining and paper mills. It is a well structured, logical decision process, used to identify the policies which must be implemented to manage the failure modes, which could cause the functional failure of any physical asset in a given operating context. The objective is here to increase the reliability levels of industrial systems. This strategy is used to ensure several objectives (quality, safety, economy ...) of a given component function of an operating system (Piechnicki et al. (2021)). In general, the RCM can be considered as a step before carrying out the Preventive Maintenance (PM) where Failure Mode Effect and Criticality Analysis (FMECA) should be performed as a first step (Blanchard (2008)). FMECA is a developed version of FMEA which was introduced in 1949 by US Army to study problems that might arise from malfunctions of military systems (Spreafico et al. (2017)). FMECA is often used in product design phase to assess the impact of potential faults on equipment functions, reliability, maintainability, maintenance personnel and environment, and hence to prevent, or minimize, the criticality of equipment faults (Zhou et al. (2015)).

The use of the RCM strategy aims to prevent some failures to occur or at least to reduce them. The RCM concept can be applied to several areas. For example, Mokashi et al. (2002) mentioned the maintenance differences between the aviation and maritime industries. They proposed a subjective qualitative approach to overcome the definitive logic limitations and used a fuel oil purification system as a test case. Next, van Jaarsveld and Dekker (2011) used RCM to control spare part stock for redundant systems. They proposed an approximative, analytic method to determine minimum stock quantities in case of redundancy and multiple systems. It had been shown that including redundancy information in the stocking decision led to significant cost benefits. In nuclear energy, Huang et al. (2013) presented RCM applications with the object of improving the reliability levels of systems and equipment in new nuclear power plants. In deregulated power industry, Heo et al. (2014) applied an RCM model to a transmission system where degradation can be classified according to the aging severity. Particle Swarm Optimization (PSO) is utilized to extract the optimal RCM strategy from a large class of possible maintenance modes. Zhou et al. (2016) developed a dynamic RCM approach for natural gas compressor stations and validated it on three application cases. In solar energy, Roa et al. (2016) presented an intelligent approach for fault diagnostics of a solar micro grid with battery back-up for an RCM approach with object of improving upon preventive maintenance strategy. After that, Catelani et al. (2020) proposed a customized decision-making diagram inside the RCM assessment and applied it to an onshore wind turbine to save costs by optimizing maintenance decisions. Recently, Kharmanda et al. (2022) established a comparison of four RCM standards considering four comparison criteria are: 1) Categories of failure consequences, 2) Treatment of hidden failures, 3) Management of different consequences, and 4) Decision diagrams. Three of them are related to reliability improvement and the last one is related to the RCM process it-self. After having discussed the similarities and differences, NAVAIR was selected to be the most suitable standard to determine the significant functional failures in terms of safety, operations, environment, and economy.

In this work, some available RCM standards are first presented in order to select MSG-3. After that, some basic principles about FMEA are presented and the most used methods to carry out the criticality assessment are treated. A coffee maker machine is selected as an illustrative example to perform the RCM using FMEA where the different RCM steps are detailed. Finally, a discussion and future perspective section is established to provide the different difficulties and some propositions to solve them with focus on additive manufacturing technology.

2. Selected RCM standard (MSG-3)

In general, maintenance standards are established criteria for carrying out different maintenance tasks such as cleaning, lubrication, repairs, parts replacement, and maintenance data collection. Stakeholders in the maintenance industry create RCM standards for different purposes, including reduced safety risks, increased asset reliability, and enhanced efficiency. The maintenance industry uses several standards to maintain safe, efficient, and reliable operations. Figure 1 shows a simplified RCM roadmap where in the analysis stage, several criteria can be selected (for more details, see NAVAIR 00-25-403 (2016)). The scope of this stage is to meet the different objectives such as safety, quality ... Another optimization RCM loops can be found in literature (i.e., Heo et al. (2014)).

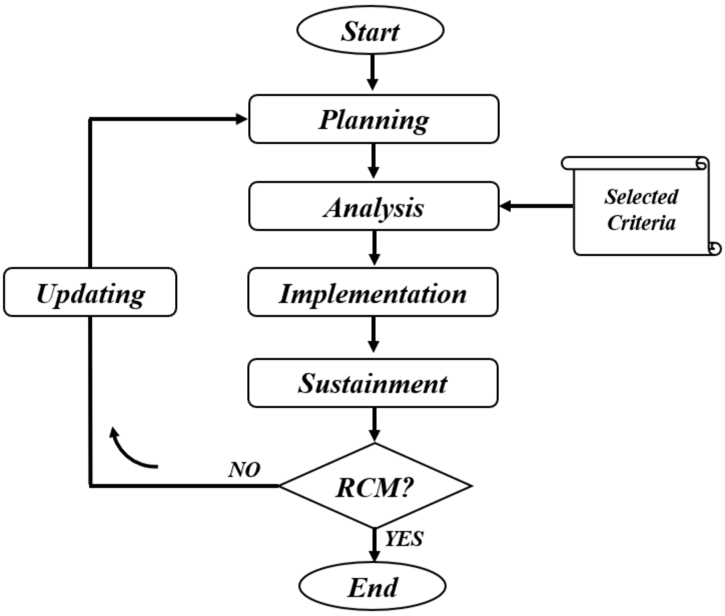


Figure 1. *RCM roadmap/loop (Kharmanda et al. (2022))*

Regarding the RCM concept, a big number of standards have been elaborated where the RCM strategy is customized to different application areas (Rausand and Vatn (2008)). In literature, several RCM standards can be found such as MIL-STD-2173 (1986), IEC 60300-3-11 (IEC 1999), USACERL TR 99/41 (USACERL 1999), NASA (2000), DEF-STD 02-45 (DEF 2000), SAE JA 1012 (SAE 2002), ABS (2003, 2004), NAVAIR 00-25-403 (NAVAIR 2005), MSG-3 (2007) ... Each one of these standards is related to specific industrial challenges in order to enhance the capability of making effective and efficient decisions during the development of maintenance tasks (Ahmadi (2010)). These standards are always evolving. A maintenance department must continually adapt their strategies in order to determine which standards are most applicable to their unique needs. In Ahmadi (2010) and Ahmadi et al. (2010), the RCM by MSG-3 was chosen with the aim of providing information for aviation industry. The primary purpose of using this standard is to develop a proposal to assist the Regulatory Authority in establishing initial scheduled maintenance tasks and intervals for new types of aircraft and/or powerplant. The intent is to maintain the inherent safety and reliability levels of the aircraft. These tasks and intervals become the basis for the first issue of each airline's maintenance requirements to govern its initial maintenance policy. Initial adjustments may be necessary to address operational and/or environmental conditions unique to the operator. As operating experience is accumulated, additional adjustments may be made by the operator to maintain efficient scheduled maintenance. The different issues and challenges of scheduled maintenance task development were presented within the maintenance review board process in order to find potential areas of improvement in the application of the MSG-3 methodology for aircraft systems. In this work, we use this standard to apply it to an illustrative example to provide the newcomers with a pedagogical implementation way. The application of RCM steps is generally related to the used standard. When dealing with different RCM standards, the reader can find totally different steps in the previous published works.

3. FMEA concept

The failure can be identified by using several components such as failure mode, failure cause, failure mechanism, failure detection and failure effect (or consequence). Regarding the failure mode, it can be defined as the manner in which an item fails. In other words, it is the specific physical condition or state that causes a particular functional failure. The failure cause(s) is(are) the reason(s) for the failure mode to occur. The failure mechanism which is related to the failure cause, can be physical, chemical, or other process which leads failure such as human errors, aging, poor maintenance, improper installation, fatigue, creep, over loading or can be multiple roots. And the failure detection is the description of the existing means and methods by which the effects can be detected. The consequence of failure (failure effect) is related to the result of a functional failure on surrounding items, the functional capability of the end item. Effects of failure can be noise, instability, inoperability, impaired control, impaired operation, roughness, unpleasant or unusual odour ... In literature, FMEA is considered as a systematic approach to identify all possible ways in which failure of a system can occur together with its causes and thus the failure's potential effect on system. The objective is to identify and document, within established ground rules, the functions, functional failures, and failure modes of an item. In addition, we can identify potential failures in a system or a process and determine how each item in the system is likely to fail and what will happen if it does. So, it consisted of first mapping the whole traceability process from gamete procurement to final disposition (Rienzi et al. (2015)). Each step was described, responsibilities identified, and a flow diagram produced (Figure 1). Any possible source of error (real or potential) was discussed. The analysis focused on elucidating the reasons why failure might occur, and estimating likelihood of incidence, severity of the consequences and chance of detection. A score was then calculated for each phase of the process to prioritize and quantify the potential risks of failures. In addition to FMEA, we have the concept FMECA (Failure Mode, Effects and Criticality Analysis) which was introduced shortly after it (it is considered as an extension of FMEA). FMECA includes basic FMEA and also a criticality analysis, which is used to chart the probability of failure modes against the severity of their consequences. In a recent review of von Ahsen et al. (2022), it is shown that the FMEA is increasingly modified in order to additionally align decisions in companies with ecological and social criteria. Their review focuses on sustainability oriented FMEA, while the previous reviews focus on the FMEA modifications and applications during the last few decades (Prajapati (2012); Spreafico et al. (2017); Sharma and Srivastava (2018); Liu et al. (2020); Wu et al. (2021)).

4. Assessment with FMEA

To assess a risk (Smith (2017)), there are several methodologies such as Failure Mode and Effects Analysis (FMEA) (Sharma and Srivastava (2018)), Failure Mode, Effects and Criticality Analysis (FMECA) (Spreafico et al. (2017)), Fault Tree Analysis (FTA) (Yazdi et al. (2022)), Event Tree Analysis (ETA) (Singh et al. (2022)) and Hazard and Operability analysis (HAZOP) (Mocellin el al. (2022)). In this work, the criticality assessment is presented by two methods: Risk Priority Number (RPN) method and Military Standard one.

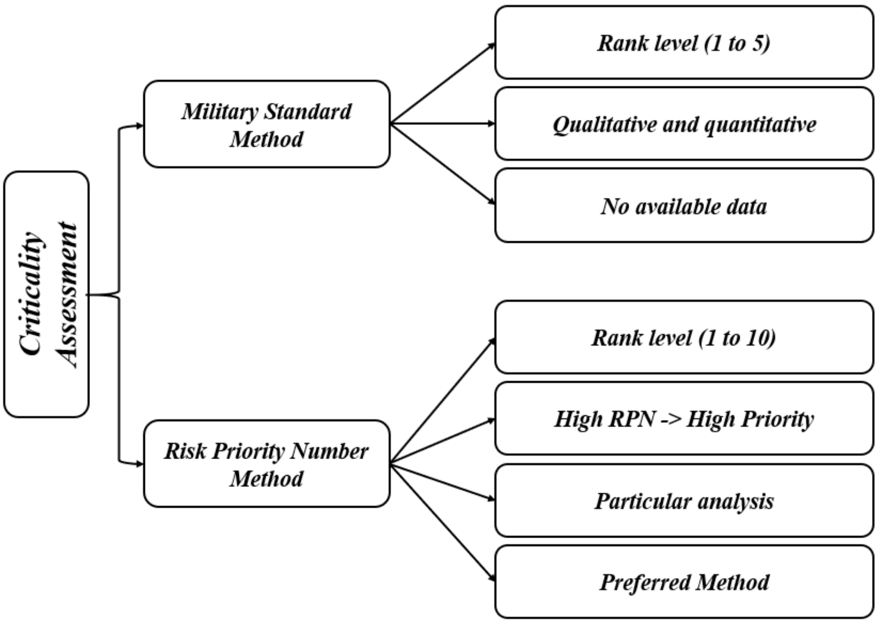


Figure 2. *Criticality assessment methods*

4.1. *RPN Method*

In order to verify the existence of a failure mode, several criteria should be tested (Porter 2004). For example, the severity can be represented by the consequence of the failure. The occurrence corresponds to the likelihood of failure and the detectability is how to detect a failure mode if it exists. This method is based on the RPN (Risk Priority Number):

$$RPN = S \times O \times D \quad (1)$$

where S is the severity of the effect of failure, O is the probability of occurrence, and D is the ease of detection. The rank levels vary between 1 and 10. RPN may not play an important role in the choice of an action against failure modes but will help in indicating the threshold values for determining the areas of greatest concentration. In other words, a failure mode with a high RPN number should be given the highest priority in the analysis and corrective action.

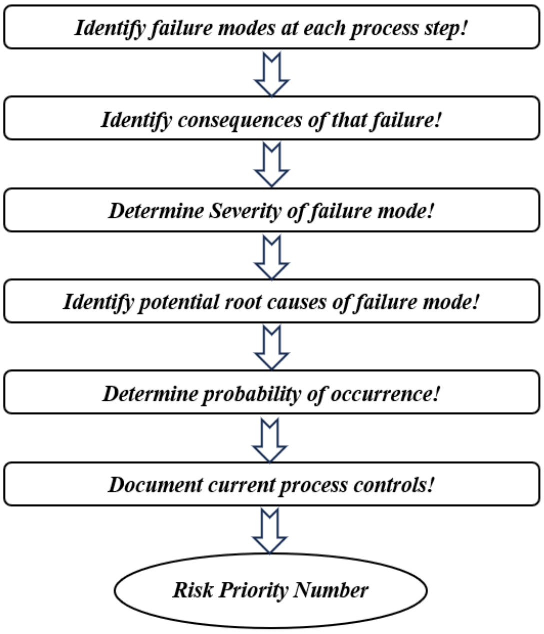


Figure 3. *Criticality assessment methods*

4.2. *Military Standard Method*

This method is based on the CN (Criticality Number) which represented by the multiplication of severity number (SN) and the probability number (PN):

$$CN = SN \times PN \quad (2)$$

The rank levels vary between 1 and 5 (Dhillon 1999). It is a qualitative and quantitative approach and can be used where there is not enough data (for example, nuclear and aerospace industries).

In this next section, a combination of two selected assessment methods is carried out to provide the reader with the advantages of both methods to overcome difficulties in several industrial sectors whether there is enough data or not.

5. Illustrative application of a coffee maker machine

5.1. *Problem description*

The studied coffee maker is designed to perform the following seven functions: 1) To brew coffee, 2) To maintain coffee at 120°f (±) 5°f, 3) To contain coffee in carafe 4) To brew coffee at not less than one cup per minute, 5) To automatically brew coffee at a time specified by user +15 minutes, 6) To automatically shut down coffee maker four hours after brew cycle is completed, 7) To contain one carafe of water in reservoir. The item breakdown of the coffee maker is shown in Figure 4 where the coffee maker (Unit 1) is divided into two main systems: brewing and electrical systems (1A & 1B). Each system is also divided into several subsystems. The brewing system is divided into three subsystems: Water Reservoir Subsystem (1A1), Filtration Subsystem (1A2) and Carafe Subsystem (1A3). And the electrical system is divided into four subsystems: Power Switch Subsystem (1B1), Clock Programmer Subsystem (1B2), Water Heating Subsystem (1B3), and Hot Plate Subsystem (1B4). The objective is to detect any errors of this process and to study next the consequences of those failures.

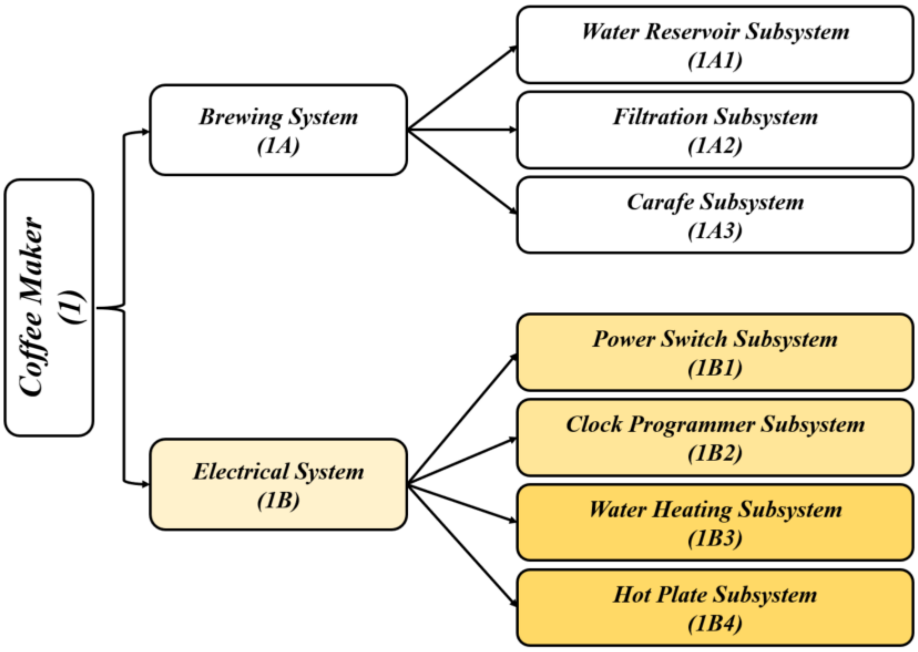


Figure 4. *Subsystems of coffee maker*

5.2. *Functional failures*

For the studied coffee maker, we determine the functional failures as follows: The first function is represented by brewing coffee. The functional failure is represented by failing to brew coffee (Problem in Brewing System (1A)). In this case, we have four failure modes:

- Failure Mode 1: Inoperative heating element due to excessive calcium build-up: (Failure Effect => No Coffee),
- Failure Mode 2: Clogged heating chamber tubing due to excessive calcium build-up: (Failure Effect => No Coffee),
- Failure Mode 3: Shorted wiring due to overheating: (Failure Effect => No Coffee),
- Failure Mode 4: Open On/Off switch due to corrosion: (Failure Effect => No Coffee).

However, the second function is represented by maintaining coffee temperature at 120°f. Here, we have three functional failures:

- Functional failure A: Unable to heat coffee (Problems in Power Switch Subsystem (1B1) or/and Water Heating Subsystem (1B3)),
- Functional failure B: Coffee temperature greater than 125°f (Problems in Clock Programmer Subsystem (1B2) or/and Water Heating Subsystem (1B3)),
- Functional failure C: Coffee temperature less than 115°f (Problems in Clock Programmer Subsystem (1B2) or/and Water Heating subsystem (1B3)).

In a similar way, we analyse the different functional failures and failure modes of the studied coffee maker machine in the next sections.

Coffee Maker			FMEA							
ID	**Item**	**Function**	**Functional Failure**	**Failure Mode**	**Failure Effect**	**P**	**S**	**D**	**RPN = P*S*D**	**Proposed actions**
						1 to 10	1 to 10	1 to 10	**1 to 1000**	proposed solutions to avoid the failure mode or to avoid the efects
1A1	Water Reservoir Subsystem	Contain 1 carafe of water in reservoir	Fails to contain 1 carafe of water	Leaking reservoir due to corrosion,	No coffee	2	4	2	**16**	Replace
1A2	Filtration Subsystem	Brew coffee	Fails to brew coffee	clogged valve due to excessive calcium build-up.	No coffee	3	4	9	**108**	Cleaning the valve
1A3	Carafe Subsystem	Contain coffee in carafe	Fails to contain coffee	Leaking carafe due to a crack.	No coffee	2	5	2	**20**	Replace
1B1	Power Switch Subsystem	Automatically shut down coffee maker 4 hours after brew cycle is completed	Fails to switch on the power	Open On/Off switch due to corrosion.	No coffee	2	4	9	**72**	Cleaning the switch or replace it.
1B2	Clock Programmer Subsystem	Automatically brew coffee at a time specified by user within 15 minutes	Does not brew coffee at all.	Inoperative Clock due to internal failure	No coffee	2	4	5	**40**	Drying the circuit or replace it.
			Brew coffee more than 15 minutes earlier than specified.	Clock operate too fast due to internal failure.	Old, bitter coffee	2	2	5	**20**	Replace
			Brew coffee more than 15 minutes after the time specified by user.	Slow clock operation due to internal failure.	No coffee until more than 15 minutes time specified.	2	4	5	**40**	Replace
1B3	Water Heating Subsystem	Brew coffee at not less than one cup per minute	Fails to brew coffee	Inoperative heating element due to excessive calcium build-up.	No coffee	8	4	9	**288**	Cleaning
				clogged heating chamber tubing due to excessive calcium build-up.	No coffee	2	4	8	**64**	Cleaning
				shorted wiring due to overheating.	No coffee. Possible fire	3	9	10	**270**	Replace
1B4	Hot Plate Subsystem	Maintain coffee at 120°f ± 5°f	Fails to heat coffee (< 100°f)	Broken supply wire to heating element conection.	Cold coffee	2	2	9	**36**	Replace
				Heating plate thermostat internal failure.	Cold coffee	3	2	9	**54**	Replace
			Heating coffee too hot (>125°f)	Corroded heating plate thermostat.	Possible damage to coffee maker. Possible fire.	3	10	10	**300**	Replace
			Partially warm coffee (>100°f, but <115°f)	Corroded heating plate thermostat.	Lukewarm coffee.	2	2	9	**36**	Replace

Table 1. *FMEA of a Coffee Maker*

5.3. *FMEA of the studied coffee maker machine*

The failure occurrence of the studied coffee maker can be divided into two modes as shown in Figure 4. When considering the Water Heating Subsystem (1B4), the effect of calcium plays an important role in this element (brewing system). This affects the operation and leads to prevention of coffee flow. However, the second case corresponds to the electrical system. The most dangerous state corresponds to the component 1B4 (Hot Plate Subsystem). The function is to maintain the coffee at 120°f, and the functional failure is that the coffee is too hot (>125°f). After that we have a failure mode 'corroded heating thermostat'. Here, the effect represents a problem where it is possible to damage the coffee maker and a possible fire consequence occurs. So, the severity equals to 10, the probability of occurrence 3 and 10 to the detectability. So, the risk priority number is 300. During the evaluation, we should not consider the severity as a single criterion evaluation. The RPN should be considered. In this case, we have to replace this part. This evaluation should be carried out to all failure modes as shown in Table 1. The most dangerous case at the RPN equals to 300.

5.4. *Risk analysis of coffee maker*

In order to form the risk matrix, we have to determine the criticality number (CN) which should be determined for all failure modes. In this case, we need to determine the severity and probability numbers. In Table 2, the failure effects are classified according to the severity categories. The severity number is distributed according to these categories. These are qualitative measures used to categorize potential effects of each failure mode on the end item.

Severity Category	***Failure Effect***	***Severity Number (SN)***
Catastrophic	i.e. Loss of life Loss of facilities Long-term environmental effect	4
Critical	i.e. Loss of mission Temporarily disabling Major damage to other system Short-term environmental effect	3
Major	i.e. Mission degradation Degradation of functionality	2
Negligible	i.e. Five minutes delay	1

Table 2. *Severity categories*

However, in Table 3, the probability numbers are determined according to different occurrence probability levels. Both numbers vary from 1 to 4. So, probability level estimation is a qualitative approach which shall be used if specific failure rate data are not available.

Level	***Limits***	***Probability Number (PN)***
Probable	$P > 10^{-2}$	4
Occasional	$10^{-4} < P \leq 10^{-2}$	3
Remote	$10^{-5} < P \leq 10^{-4}$	2
Extremely Remote	$P \leq 10^{-5}$	1

Table 3. *Occurrence levels*

Figure 5 shows the risk matrix considering a discrete relationship between probability and severity. It is a combined measure of the severity of failure mode and its probability of occurrence (or frequency of occurrence). The risk increased when increasing the severity and/or probability numbers (SN and/or PN). The criticality becomes high when the criticality number equals to eight or bigger ($CN \geq 8$).

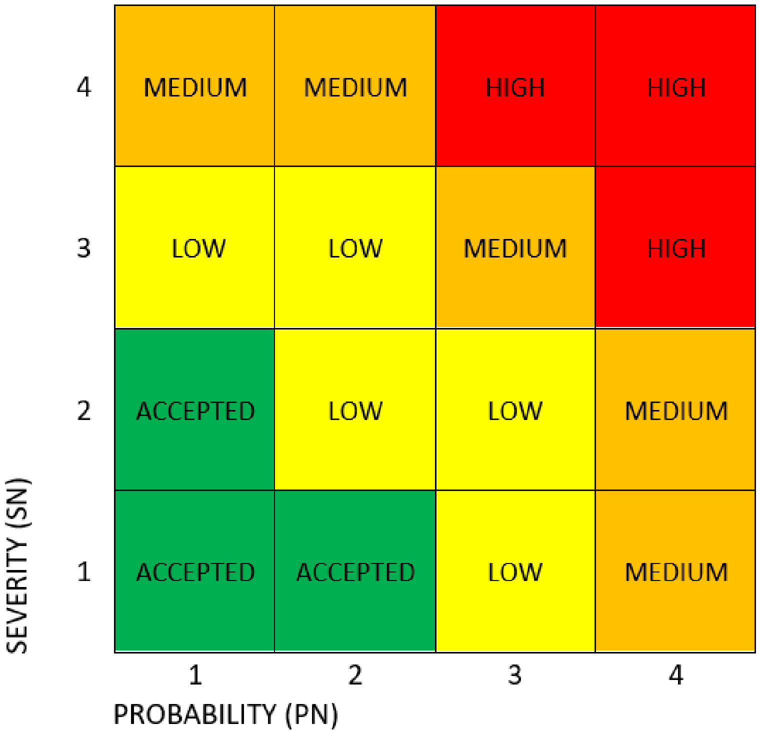


Figure 5. *Risk matrix*

According to Table 4, we have the maximum value of the criticality number equals to 8. In order to select the dangerous cases, we have also to compare the RPN. When CN=8, three failure modes can be considered: Inoperative heating element due to excessive calcium build-up, Shorted wiring due to overheating and Corroded heating plate thermostat. We perform the analysis strategy on two cases where RPN equals to 288 and 300 (green fields in Table 4).

After having answered the applicable questions (as shown in Table 5), it should be directed to one of the five effect categories:

- Evident Safety (Category 5),

- Evident Operational (Category 6),

- Evident Economic (Category 7),

- Hidden Safety (Category 8),

- Hidden Non-Safety (Category 9).

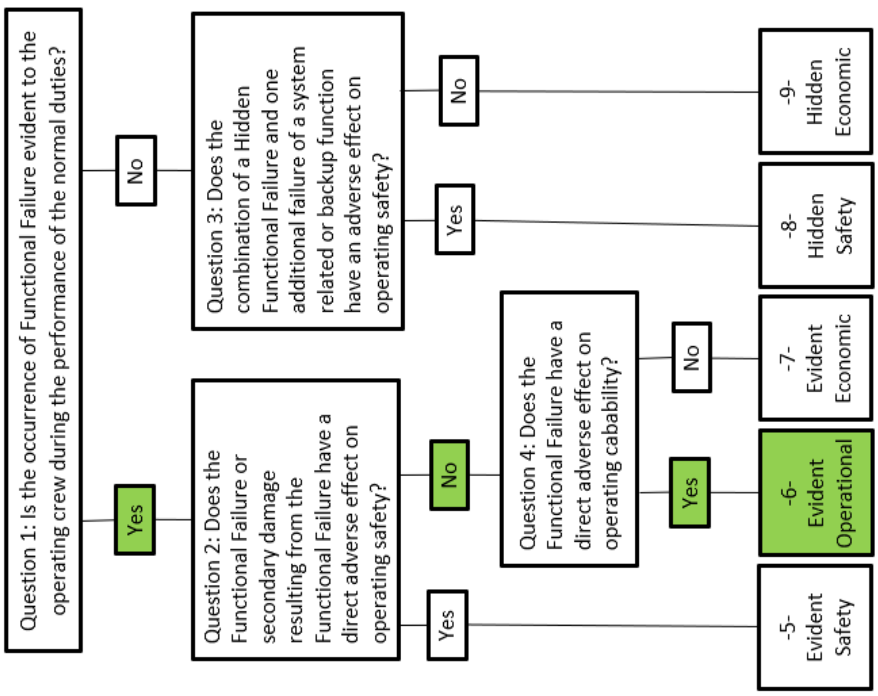
RISK ANALYSIS								
Failure Mode	**Failure Effect**	**P**	**S**	**D**	**RPN = P*S*D**	**PN**	**SN**	**PN*SN**
Slow clock operation due to internal failure.	No coffee until more than 15 minutes time specified.	2	4	5	**40**	**1**	**2**	**2**
Inoperative heating element due to excessive calcium build-up.	No coffee	8	4	9	**288**	**4**	**2**	**8**
clogged heating chamber tubing due to excessive calcium build-up.	No coffee	2	4	8	**64**	**1**	**2**	**2**
shorted wiring due to overheating.	No coffee. Possible fire	3	9	10	**270**	**2**	**4**	**8**
Broken supply wire to heating element conection.	Cold coffee	2	2	9	**36**	**1**	**1**	**1**
Heating plate thermostat internal failure.	Cold coffee	3	2	9	**54**	**2**	**1**	**2**
Corroded heating plate thermostat.	Possible damage to coffee maker. Possible fire.	3	10	10	**300**	**2**	**4**	**8**
Corroded heating plate thermostat.	Lukewarm coffee.	2	2	9	**36**	**1**	**1**	**1**

Table 4. *Risk analysis*

So, Table 5 shows a detailed analysis for 1B3 item (Water Heating System). The failure mode is identified by failure to brew coffee. Several questions should be answered in order to identify the category of each failure. As shown in Table 5, considering the green road, we obtain an event operational mode.

Analysis Sheet		FAILURE EFFECT CATEGORY
Coffee Maker	1B3	Function: Brew coffee at not less than one cup per minute Failure: Fails to brew coffee Mode: Inoperative heating element due to excessive calcium build-up. Effect: No coffee

FAILURE EFFECT QUESTIONS	QUESTION		ANSWER



1	Yes	Functional Failure will be evident to the operating crew.
2	No	No direct adverse effect on operating safety.
3	N/A	Not applicable.
4	Yes	The Functional Failure have a direct adverse effect on operating cabability.
Category		Evident operational
Remarks:		

Table 5. *Failure effect category for Water Heating System (1B3 item)*

Task development is handled in a similar manner for each of the five Effect categories. In Table 6, we continue the process in order to select the task to be performed. In this case, we can perform cleaning task, which corresponds to category number 6 (evident operational category). The selection of FEC (Failure Effect Category) which is related the used standard (MGS-3), is carried out as a combination with Table 5 where A, B, C, D, E and F are the failure managements.

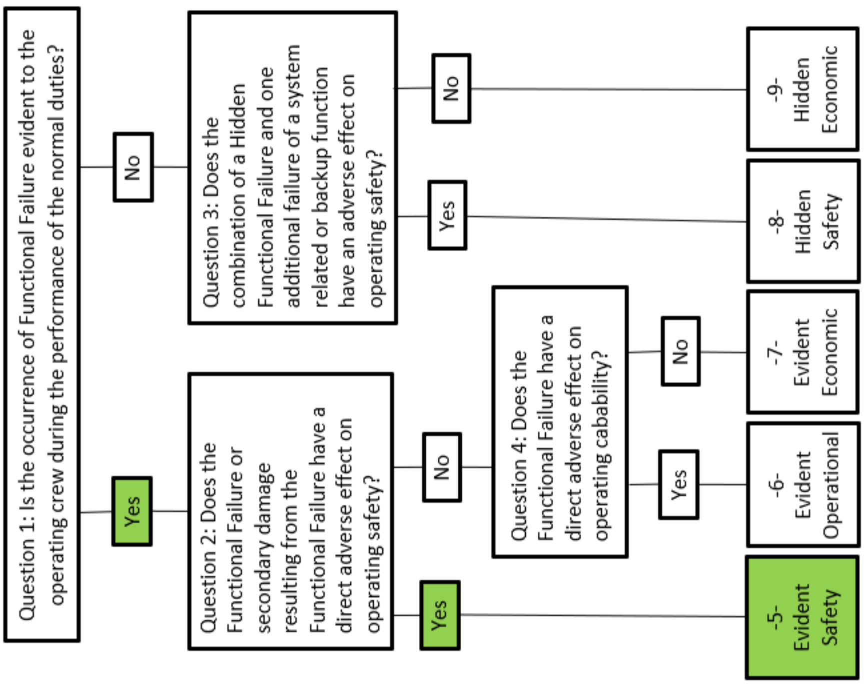
Analysis Sheet					TASK SELECTION QUESTIONS				
Coffee Maker					IB3	Item Description: Water Heating Subsystem			
FAILURE EFFECT CATEGORY					Function: Failure: Mode: Effect:	Brew coffee at not less than one cup per minute Fails to brew coffee Inoperative heating element due to excessive calcium build-up. No coffee			
5	6	7	8	9	TASK SELECTION QUESTIONS	Yes	No	N/A	Answer & Explanation
A	A	A	A	A	Is the lubrication or servicing task applicable and effective?	X			Cleaning is effective in this case.
			B	B	Is a check to verify operation applicable and effective?			X	Question not applicable for Category 6.
B	B	B	C	C	Is an inspection or functional check to detect degradation of the function (potential failure) applicable and effective?		X		Task is not applicable.
C	C	C	D	D	Is a restoration task to reduce the failure rate applicable and effective?		X		Task is not applicable.
D	D	D	E	E	Is a discard task to avoid failures or to reduce the failure rate applicable and effective?		X		Task is not applicable.
E			F		Is there a task or combination of tasks that are applicable and effective?			X	Question not applicable for Category 6.

TASK NO.	TYPE	TASK DESCRIPTION	FEC	INTERVAL	REMARKS / EFFECTIVITY	ZONAL
		Clean out the excessive calcium build-up.	6			

Table 6. *Task selection for Water Heating System (1B3 item)*

Table 7 shows an analysis for 1B4 item (Hot Plate Subsystem). The failure mode is identified by overheating of coffee (>125°f). Several questions should be answered in order to identify the category of each failure. As shown in Table 7, considering the green road, we obtain an event safety mode.

Analysis Sheet		FAILURE EFFECT CATEGORY		
Coffee Maker	1B4	Function: Maintain coffee at 120°f ± 5°f Failure: Heating coffee too hot (>125°f) Mode: Corroded heating plate thermostat. Effect: Possible damage to coffee maker. Possible fire.		
FAILURE EFFECT QUESTIONS			QUESTION	ANSWER



1	Yes	Functional Failure will be evident to the operating crew.
2	Yes	The secondary damage resulting from the Functional Failure have a direct adverse effect on operating safety.
3	N/A	Not applicable.
4	N/A	Not applicable.
Category		Evident Safety
Remarks:		

Table 7. *Failure effect category for Hot Plate Subsystem (1B4 item)*

In Table 8, we continue the process in order to select the task to be performed. In this case, we have to replace the Hote Plate Subsystem, which concerns category number 5 (evident safety category). The selection of this number is related to the used standard (MSG-3).

Analysis Sheet									TASK SELECTION QUESTIONS
Coffee Maker					IB4	Item Description: Hot Plate Subsystem			
FAILURE EFFECT CATEGORY					Function: Maintain coffee at 120°f ± 5°f Failure: Heating coffee too hot (>125°f) Mode: Corroded heating plate thermostat. Effect: Possible damage to coffee maker. Possible fire.				
5	6	7	8	9	TASK SELECTION QUESTIONS	Yes	No	N/A	Answer & Explanation
A	A	A	A	A	Is the lubrication or servicing task applicable and effective?		X		Task is not applicable.
			B	B	Is a check to verify operation applicable and effective?			X	Question not applicable for Category 5.
B	B	B	C	C	Is an inspection or functional check to detect degradation of the function (potential failure) applicable and effective?		X		Task is not applicable.
C	C	C	D	D	Is a restoration task to reduce the failure rate applicable and effective?	X			Replace a new Hot Plate Subsystem is applicable and effective.
D	D	D	E	E	Is a discard task to avoid failures or to reduce the failure rate applicable and effective?		X		Task is not applicable.
E			F		Is there a task or combination of tasks that are applicable and effective?		X		Task is not applicable.

TASK NO.	TYPE	TASK DESCRIPTION	FEC	INTERVAL	REMARKS / EFFECTIVITY	ZONAL
		Replace a new Hot Plate Subsystem.	5			

Table 8. *Task selection for Hot Plate Subsystem (1B4 item)*

To conclude this section, we recommend adding the different failure cases and to provide to the customer how to avoid the failure cases. In addition, it is better to use different standard in order to compare the results. So, we summarize here some principles and advantages of RCM:

- System level instead of component level,
- Top-down instead of bottom-up approach,
- Concentration on the function and not on the system hardware,
- Function preservation instead of failure prevention,
- Task-oriented instead of maintenance process oriented,
- Consequence driven approach instead of concentration on failure mode.

6. Discussion and future perspectives

In this work, we deal with FMEA for process (P-FMEA), however, when extending to design (D-FMEA), we can increase the reliability level. So, the objective is to find the optimum design that leads to a reduction of probability of failure. Development of new criticality measures (ex. new formulation for criticality number) is important and needs mathematical developments. The criticality method has an important advantage when creating a new model or product where data is insufficient (even no data in certain cases). For RPN method, several improvements can be carried out to minimize the highest RPN value (Rienzi et al. 2015). For example, integration of advanced optimization technology into maintenance management to select optimal strategy can be one of a future perspective of this method. Here, we can use several kinds of optimization strategies for continuous and discrete models. For the current studied case, we have discrete models where it is possible to use neural networks in order to select automatically the best strategy. FMEA model and failure data may be affected by several kinds of uncertainty. Therefore, robustness assessment against these the different uncertainties should be conducted (Ouyang et al. (2022)). In addition, Six Sigma concepts can be used to determine if the output parameters satisfy the Six Sigma quality criteria or not (Shorky et al. 2023). In our future works, we focus on the application of this interesting strategy to the additive manufacturing technology in order to reduce the failure likelihood with the object of reducing material and operating time wastes. For example, when performing additive manufacturing using Fused Filament Fabrication (FFF), or also known as Fused Deposition Modelling (FDM), several failure modes can appear regarding design and manufacturing parameters which lead to failure of manufacturing process. In addition, the manufacturing process can continue to the end, but the product quality will be affected. Furthermore, Polylactic acid (PLA) is one of the most frequently used materials in additive manufacturing because it is considered as a nontoxic, biodegradable, and biocompatible material (Kharmanda (2022)). When using FFF to manufacture PLA, additional failure modes can appear regarding the different properties of PLA materials (pure and composite) (Kharmanda (2023a)). So, it is recommended to use RCM using FMEA to overcome several problems when manufacturing PLA materials by FFF technique in different areas, especially medical ones where complex geometry description is needed (Kharmanda (2023b)).

7. Conclusion

In this work, RCM technology using FMEA is presented as an analytical process to determine the appropriate failure management strategies to ensure safe operations and cost-wise readiness. An illustrative application on a coffee maker is carried out in detail to show the applicability of this technology using MSG-3 standard. The benefits of FMEA are to reduce costs, improve quality, increase reliability .... In order to obtain these benefits, evaluation of customer's feedback (information) is needed to improve this process. In addition, it is important to integrate new regulations to this process. It is also important to optimize the design considering the potential risks in order to reduce the likelihood of failures. Furthermore, there is also a need to some information to start considering the mathematical description in order to perform the required tasks.

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