NAVAIR as an Effective Standard of Reliability Centered Maintenance for Determining Significant Functional Failures

NAVAIR en tant que norme efficace de maintenance centrée sur la fiabilité pour déterminer les défaillances fonctionnelles importantes

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ABSTRACT. In certain industries such as aviation, the different operations are very complex, and a small error may lead to a catastrophe. So, there is a strong motivation to establish an effective maintenance program to avoid any probable error. A concept called Reliability-Centered Maintenance (RCM) was found in the 1960s and initially oriented towards maintaining airplanes. In this work, we first present some existing RCM standards since standardization is considered as an important element of maintainability. Four significant criteria are next selected in order to establish a comparison of four RCM standards. These 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. Here, we present and discuss the similarities and differences considering the selected criteria. In addition, we add new diagrams to combine between the different RCM standards which paves the way to establish a generalized RCM standard in the future works. As a result, NAVAIR is selected to be the most suitable standard to determine the significant functional failures in terms of safety, operations, environment, and economy.
KEYWORDS. Reliability of Operating Systems, Maintenance strategy, Reliability Centred Maintenance (RCM), Preventive Maintenance (PM).

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 several other industries and military branches (Ahmadi 2010). It is the objective to increase the reliability levels of industrial systems. This strategy is utilized 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) as shown in Figure 1 where Failure Mode Effect and Criticality Analysis (FMECA) should be performed as a first step (Blanchard 2008). The goal of the RCM strategy is to prevent some failures to occur or to reduce them.

Figure 1. *Relationship between FMECA/RCM/PM*

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. Recently, 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.

A big number of standards have been elaborated where the RCM strategy is customized to different application areas (Rausand and Vatn 2008). 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 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, some available RCM standards are first presented. After that, four standards are selected to carry out a comparison according to four criteria which are common in the selected standards. Some new diagrams are added to combine between several RCM standards with the object of elaborating a generalized RCM standard. Next, 'NAVAIR 00-25-403 (2005)' is selected among these four standards for aviation industry. A discussion section is included to show the different advantages and disadvantages. Finally, a conclusion section is established to show the suitable selection way and its application steps.

2. Some available RCM standards

In general, maintenance standards are established criteria for carrying out different maintenance tasks such as cleaning, repairs, lubrication, parts replacement, and maintenance data collection. Stakeholders in the maintenance industry create RCM standards for different reasons, including reduced safety risks, increased asset reliability, and enhanced efficiency. The maintenance industry uses several standards to maintain safe, efficient, and reliable operations. Figure 2 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 objective such as safety, quality ... Additional criteria more than the selected ones should be added. Another optimization RCM loops can be found in literature (i.e. Heo et al. (2014)).

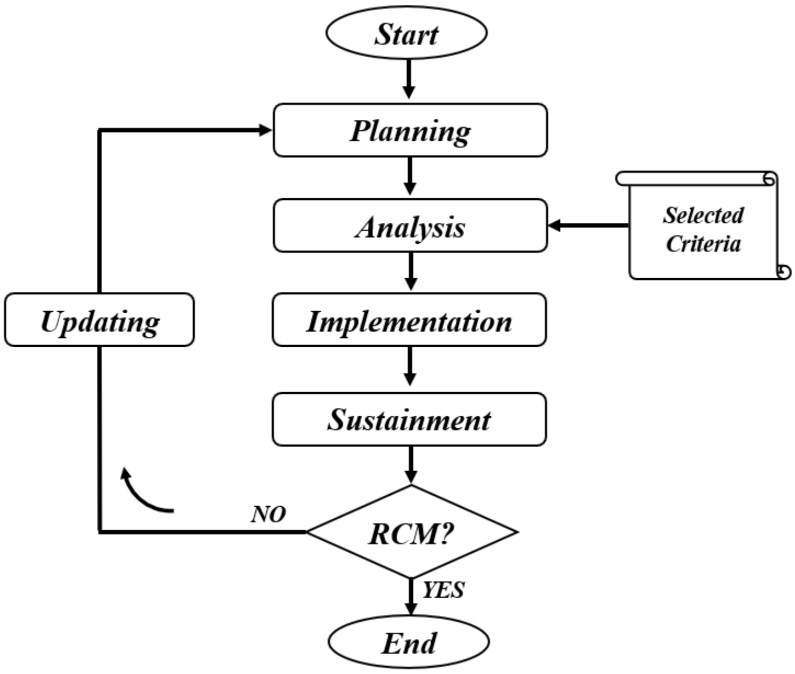

Figure 2. *RCM roadmap/loop*

In literature, several RCM standards can be found: 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 this work, we select four criteria which common in the four following standards: MIL–STD-2173 (1986), SAE JA1011 (1999), SAE JA1012 (2002) and NAVAIR 00-25-403 (2005). According to a comparison of these standard regarding the four selected criteria, the most suitable standard will be selected.

3. Selected criteria for comparison

The selected four criteria are related to the definition of the RCM which is considered as a well-structured logical decision process. It is used to recognize the maintenance policies that should be implemented to manage the failure scenarios, that may cause a functional failure of a physical asset in a certain operating context (Ahmadi 2010). These criteria are: 1) Categories of failure consequences, 2) Treatment of hidden failures, 3) Management of different consequences, and 4) Decision diagrams. The first three are related to reliability improvement, while the last one is related to the RCM process it-self.

3.1. *Categories of failure consequences*

The failure consequences are the main driver in the different maintenance decisions. They dictate the maintenance task objectives. The different consequences of failure can be divided to certain categories such as safety, operational, economic, ... This classification can help to prioritize the failure modes (Mokashi et al. 2002). When dealing with RCM standards, the failure consequences are classified in different ways. In Figure 3, we divide here the failure consequences into two main categories: Economic and environmental failure consequences. These main categories are next divided into sub-categories according to the nature of failure. The different studied RCM standards consider almost the same keywords with different classification ways. However, in our proposed diagram, we consider that the failure consequences essentially lead to problem at the economic and/or environmental levels.

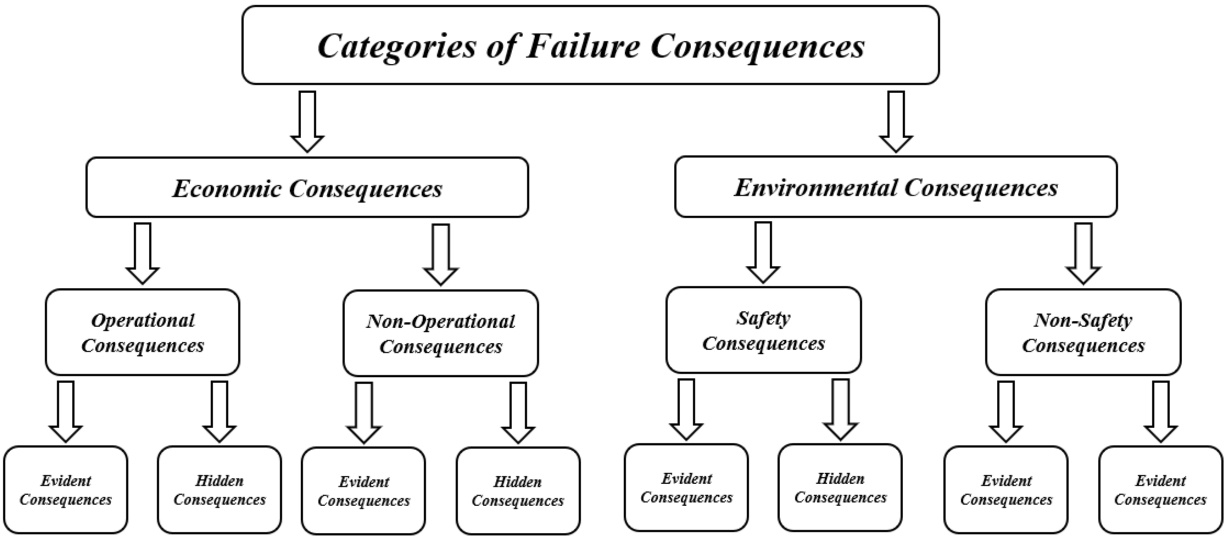

Figure 3. *Categories of failure consequences*

According to MIL–STD-2173 (1986), four types of failure consequences are considered: 1) Safety consequences, 2) Economic/operational consequences, 3) Non-safety hidden failure consequences, and 4) Safety-hidden failure consequences. The type of failure consequence identifies the degree of urgency to perform a preventive maintenance task and the criteria for determining its effectiveness.

In SAE JA1011 (1999) and SAE JA1012 (2002), similar types of consequences can be found. They are divided into four categories in two stages. The first stage separates hidden failures from evident failures where the relationship between hidden failures and protection is explained. And the concept of a “multiple failure” is introduced. The second stage separates safety and/or environmental consequences from economic consequences (operational and non-operational consequences).

For NAVAIR 00-25-403 (2005), the failure consequence evaluation is a two-step process. First, functional failures are separated into two categories: those that are evident to the operator/operating crew and those that are not. Second, the effects of the failure are evaluated to identify those that affect safety or environmental compliance. Therefore, there are four types of failure consequences: Evident Safety/Environmental Consequences, Evident Economic/Operational Consequences, Hidden Economic/Operational Consequences, and Hidden Safety/Environmental Consequences.

3.2. *Treatment of hidden failures*

The failure functions can be classified in several categories: Essential, auxiliary, information, protective, interface, evident and hidden functions as shown in Figure 4. In this section, we deal with the hidden failure functions. These functions are divided into two sub-categories: active and inactive functions as shown in Figure 4. A normally active function gives no indication to the operating crew if it ceases, while for a normally inactive function, the crew cannot know whether it will available when it is needed. When using RCM methodology, it is the objective to deal with the availability of certain hidden functions which are not evident to the operating crew during normal duties performance (Ahmadi et al. 2014).

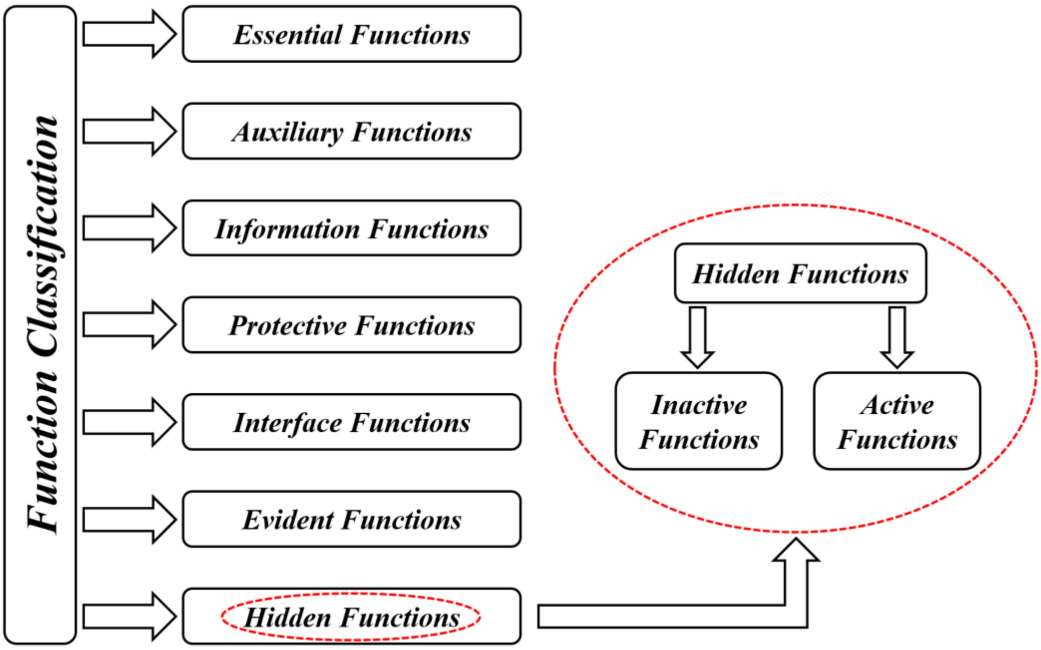

Figure 4. *Function classification*

According to MIL–STD-2173 (1986), the hidden failure is divided into two types with focus on its safety consequences criterion more than other criteria. Therefore, the hidden failure is divided into safety hidden failure and non-safety hidden failure consequences.

According to SAE JA1011 (1999), the basic information of the hidden failure such as the definition, effect, consequences, is provided in brief. However, in SAE JA1012 (2002), the RCM hidden failure analyses are described in detail. In addition, the failure finding task is defined as the task to fulfill four criteria, and these criteria focus on:

a. The basis upon which the task interval is selected, shall consider the need to reduce the probability of the multiple failure of the associated protected system to a level that is tolerable to the owner or user of the asset.

b. The task shall confirm that all components covered by the failure mode description are functional.

c. The failure-finding task and associated interval selection process should take into account any probability that the task itself might leave the hidden function in a failed state.

d. It shall be physically possible to do the task at the specified intervals.

According to NAVAIR 00-25-403 (2005), the hidden failure is defined as functional failure whose effects are not apparent to the operating crew under normal circumstances if the failure mode occurs on its own. In addition, the failure finding task is defined as a preventive maintenance task performed at a specified interval to determine whether a hidden failure has occurred where one of the main roles of the scheduled maintenance tasks, according to this standard, is to prevent the problems associated to the intrusion of failures.

3.3. *Management of different consequences*

RCM allows us to decide which maintenance activities are needed (Moubray 1997). This way, we can choose the most suitable tasks to manage the different consequences with objective of reducing the probability of failure and/or to decrease the consequences of failures. The maintenance strategies found in the different RCM standards are very various. It is difficult for the moment to propose a generalized diagram. So, we present here the different tasks proposed in each studied RCM.

According to MIL–STD-2173 (1986), several strategies for failure effect management can be used: Condition-directed tasks, Discard tasks, Effective tasks, Failure-finding tasks, Lubrication tasks, Servicing tasks, and Time-directed tasks.

According to SAE JA1011 (1999) and SAE JA1012 (2002), several strategies for failure effect management can be utilized: Scheduled tasks, On-condition tasks, Scheduled discard tasks, Scheduled restoration tasks, and Failure-finding tasks.

According to NAVAIR 00-25-403 (2005), several strategies for failure effect management can be used: Servicing Task, Lubrication Task, Corrosion Preventive Compounds, Servicing/Lubrication Task Cost Analysis, On Condition Task, Hard Time Task, Failure Finding Task, No PM, and Age Exploration. This standard has additional tasks to perform more maintenance activities to manage the different failure effects.

3.4. *Decision diagrams*

The decision diagrams of RCM generally contain failure consequences and the maintenance tasks which are determined whether it must use proactive tasks (Rahmadhanty et al. 2019). An optimization process can be integrated to these diagrams to select the best combination between the failure consequences and the maintenance tasks. According to different RCM standards, several questions should be answered (Ahmadi 2010), while we select in this work, four main questions to answer. As shown in Figure 5, if the answer to the first question ‘Failure Effect?’ affects for example the safety level, it may be needed to change the design, not only to schedule maintenance tasks. For the second question ‘Hidden Failure?’, if the hidden failure from crew for example may occur, there is a need to check operations and then schedule maintenance tasks. For the third question ‘Degradation?’, if it leads for example to failure detectable by maintenance, it is recommended to perform periodic inspections or tests and then schedule maintenance tasks. For the last question ‘Age?’, if the equipment/component’s age is known regarding its reliability level for example, it is recommended to fix a time for replacement and then schedule maintenance tasks.

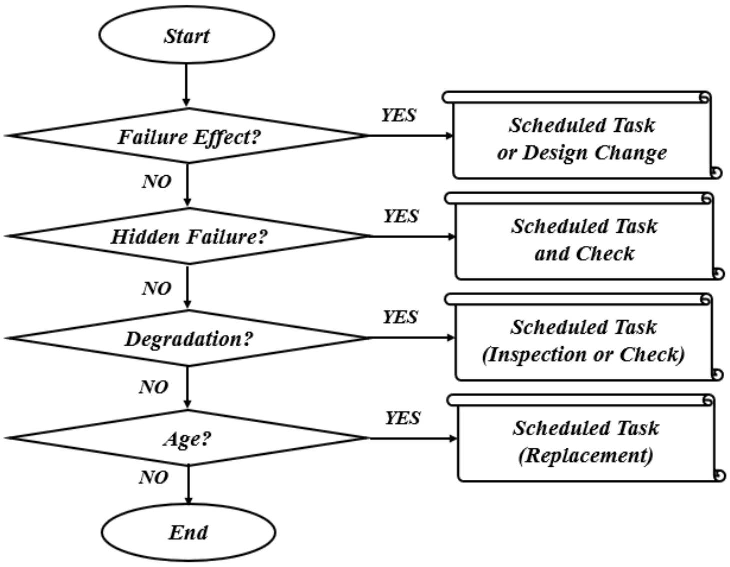

Figure 5. *Simplified version of decision logic tree*

According to MIL–STD-2173 (1986), the RCM decision logic is considered as a part of RCM analyses process and the input to the RCM decision logic comes from two different parts, the first one from design characteristic as the FMEA (Failure Modes and Effect Analysis) and the second one from the age exploration as program change and order improvement.

According to SAE JA1011 (1999) and SAE JA1012 (2002), decision diagrams are typically applied in three stages, as follows:

- Working from the top, using the decision diagram to determine the category of consequences that apply to the failure mode under consideration.

- Working down the relevant consequence column, using the technical feasibility criteria discussed in to assess the technical feasibility of possible failure management policies in each category.

- Selecting a failure management policy from the first category that satisfies the technical feasibility criteria and that will deal effectively with the consequences of the failure mode under consideration.

According to NAVAIR 00-25-403 (2005), the major output of the RCM decision logic divide into two sub-logic sequence either required preventive maintenance or non-required preventive maintenance. Inside the RCM decision logic, the process is divided into two major sub-logic according to the failure visibility evident or hidden failure. Then, these two sub-logic sequences divided into four sub sequences according to their safety, environment, and operational effect. In the final stage the last four logic sub-subsequence ended with four options to analyze the error and select one appropriate solution.

4. Discussions

The selected four standards generally differentiate in several essential points taking the needs and the industrial developments into account. Some of them can be considered as newer versions of others. For example, Standards SAE JA1011 (1999) and SAE JA1012 (2002) contains same RCM standard and procedure. SAE JA 1011 is the older version of this standard and it was issued in 1999. This document contains the basic details about the RCM, while the second one, called SAE JA 1012, was issued in 2002. In this newer version, more details about the RCM procedures and implementations are included. This discussion is established according to only four criteria presented previously.

Regarding the first criterion ‘Categories of failure consequences’, the definitions of categories of failure consequences in all standards are almost similar, which consider two factors, one is evident or hidden, another is safety or non-safety. In other words, categories of failure consequences are basically divided into four types: evident safety, evident non-safety, hidden safety, and hidden non-safety. However, different standards focus on different points in terms of failure consequences. For example, unlike the other two standards, MIL–STD-2173 (1986) does not take environmental impacts into account in their categorizing failure consequences. In SAE JA1012 (2002), hidden failures are treated by explaining the relationship between hidden failures and protection. Furthermore, it is also introduced the concept “multiple failure” in the standard where the protected function fails while the protection is in a failed state.

Regarding the second criterion ‘Treatment of hidden failures’, Standard MIL–STD-2173 (1986) provides a simple approach to define the hidden failure in RCM analyses. It is approved that Fixed Time Maintenance (FTM) approach is considered as the most suitable approach to diagnosis and fix the hidden failure. Standard SAE JA1012 (2002) describes the RCM hidden failure analyses in details, while SAE JA1011 (1999) provides only the basic information of the hidden failure such as the definition, effect, consequences. For NAVAIR 00-25-403 (2005), the hidden failure is defined as functional failure whose effects are not apparent to the operating crew undergoing normal circumstances if the failure mode occurs on its own. So, it does not mention the failure consequences, as Standard SAE JA1012 (2002) does. Another important difference between the above-mentioned standards is to avoid the hidden failure. In Standard JA1012 (2002), it is mentioned that it is necessary to have an additional system to detect the hidden failure, while in NAVAIR 00-25-403 (2005), it relays more on perform preventive maintenance in fixed interval. NAVAIR 00-25-403 (2005) defines the Preventive Maintenance (PM) – Actions performed prior to functional failure (multiple failures or demand requirements for hidden failures) to achieve the desired level of safety and reliability for an item. Similarly, to MIL–STD-2173 (1986), NAVAIR 00-25-403 (2005) approves Fixed Time Maintenance (FTM) approach to be the most suitable approach to diagnosis and fix the hidden failure.

Regarding the third criterion 'Management of different consequences', in MIL–STD-2173 (1986), the different mentioned tasks are based on the reliability characteristics of the equipment. They are either inspections or removals at a scheduled time period and can be accomplished at any maintenance level. According to SAE JA1011 (1999) and SAE JA1012 (2002), the newer version presents a detailed description of the different strategies for failure effect management. In NAVAIR 00-25-403 (2005), when comparing with previous standards, additional tasks are added to be achieved such Lubrication Task, Corrosion Preventive Compounds, Hard Time Task, Age Exploration... However, not all these additional tasks can be applied to all systems. For example, the Lubrication task is appropriate only if the lubricant to be used is a non-permanent type and needs to be reapplied periodically.

Regarding the fourth criterion 'Decision diagrams', in Standard MIL–STD-2173 (1986), the output of the RCM design logic preventive or non-preventive maintenance is feedback to the design. The RCM decision logic starts by dividing the failure into evident and hidden failures. Then, each part of them is divided into two logic sub-sequences. The first evident logic subsequence is categorized according to the safety effect of the failure, and it ends with redesign requirements or task combination. The second evident logic subsequence is categorized according to the environment effect, and it ends with either PM task or no PM task and recommendation for redesign. In SAE JA1011 (1999) and SAE JA1012 (2002), the decision logic is divided according to the failure detection into two major parts: evident and hidden failures. Then, the evident failure is divided into three sub-logic sequences according based on the effect of the failure on the safety, environment, and operational capability. The first sub-logic sequence ends with either mandate unit redesign or task combination. The second and third sub-logic sequence end with recommendation for unit redesign. In NAVAIR 00-25-403 (2005), the RCM decision logic is considered as a part of RCM based maintenance process which is the bigger picture/framework for all maintenance tasks. The RCM decision logic gets input from the FMECA, send feedback on the failure process to the FMECA, too. Another input to the RCM decision logic comes from the feedback process from the reliability and maintainability data analyses.

Figure 6 shows the selection process where four RCM standards are chosen considering four criteria. In addition to its detailed description and various maintenance activities, the NAVAIR 00-25-403 (2005) is selected considering its different advantages regarding safety, environmental, operational, and economic objectives. More details about NAVAIR processes and tools can be found in (Leverette 2006, NAVAIR 00-25-403 (2016)).

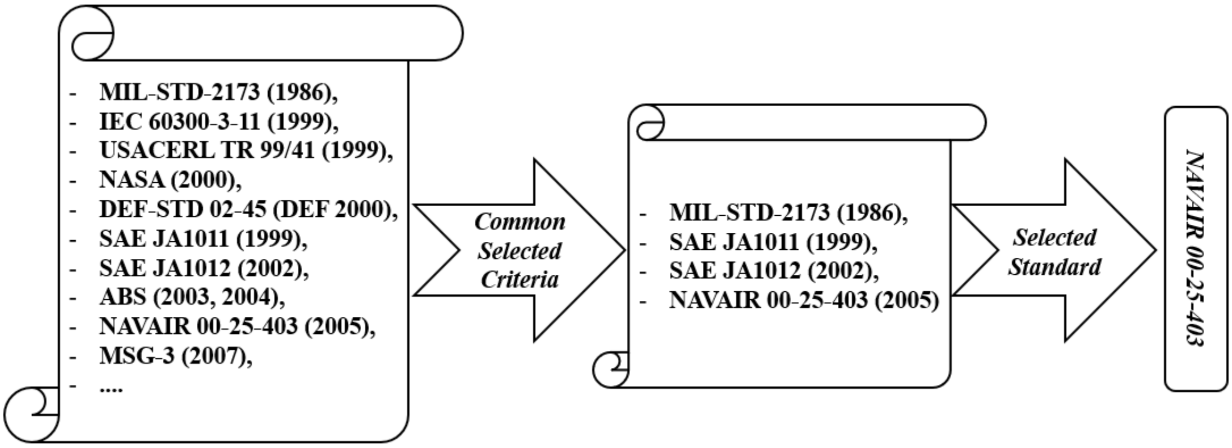

Figure 6. *Selection process of RCM standards*

5. Conclusions

The choice of the standard to follow depends on the industry field since the requirements differ from one industry to another. In this work, four RCM standards are compared in order to select the most suitable one. Four criteria are chosen for comparison: 1) Categories of failure consequences, 2) Treatment of hidden failures, 3) Management of different consequences, and 4) Decision diagrams. In addition, some new diagrams are added as simple/generalized versions of the different presented criteria, except for the third one entitled 'Management of different consequences' since the maintenance strategies in the different RCM standards are very various. It is concluded that among the chosen standards, NAVAIR seems to be the best for the maintenance in naval aviation industry when regarding to the identification of the most significant functional failures. Furthermore, NAVAIR can be a valuable guide to learn more about the RCM strategy and allows us determining maintenance task intervals based on the methods described in it (in detail). It doesn't only present the different RCM processes and analysis, but also provides information about FMECA which is a pre-step before the RCM to determine the failure rate values. In aviation industry, the safety plays a very important role to realize the compliance of regulations and to avoid any probable risk, however in certain industries, the economic needs can affect the selection of the RCM standards. So, from economy viewpoint, another RCM standard can be selected.

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