A DYNAMIC MAINTENANCE FMEA TO SUPPORT A RELIABILITY CENTERED MAINTENANCE IMPLEMENTATION OF CRITICAL SYSTEMS IN NUCLEAR FACILITIES

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Abstract. *Reliability Centered Maintenance (RCM) was originated on aeronautical industry and was adopted by worldwide nuclear industry, as an effort to improve plant safety, reliability and availability, and reduce maintenance costs. Failure Mode and Effects Analysis (FMEA) is extensively used to support RCM, providing a way for identifying the component failure modes leading to functional failures and assessing the impact of each component failure mode on the system or plant performance. The nuclear industry has stringent requirements on safety and reliability, mainly because of potential catastrophic failure and public opinion about nuclear risks. The purpose of maintenance is to prevent or mitigate the consequences of failure, and RCM is a method that allows achieving this goal in an effective way. It defines the maintenance requirements of the identified critical systems (safety systems and systems that are important for the operation of the facility) in the current operating context. Identical systems can have completely different strategies, depending on operating contexts. RCM includes reactive, time-based, condition-based, and proactive-based tasks. In addition, a user should understand system boundaries, system/equipment functions, functional failures, and failure modes of all critical components of the facility. Applying the concept of RCM as a strategy for performing maintenance involves several time-consuming and complex tasks that can often postpones the implementation of obvious condition-monitoring tasks. The classical RCM has been based on FMEA with little analysis of historical performance data. Especially in cases in which the systems or equipments are new to the facility and the facility maintenance and operational knowledge on functions and functional failures are insufficient, there is a need of a flexible but standardized approach to facilitate this task. The purpose of this paper is to present a methodology and a computer implementation of a maintenance FMEA that can be adjusted to support the conduction of a RCM program of critical systems of nuclear facilities. As RCM should be a living system, it should gather data from the results achieved and feed these data back to improve design and future maintenance. This feedback is an important part of the proactive-based task of the RCM program. This resource was provided by a dynamic FMEA in which the severity, occurrence and detection indexes are annually reevaluated considering the failures that have occurred in the period. Specifically to support NRC's Maintenance Rule compliance, it is expected that this approach could provide a continued and standardized monitoring and recording of the maintenance program effectiveness. The software was implemented using Visual Basic for Applications (VBA) which is an implementation of Visual Basic language and associated Integrated Development Environment (IDE) into Microsoft™ Office Applications.*

Keywords: *reliability centered maintenance, nuclear facilities, FMEA, critical systems*

1. INTRODUCTION

Reliability Centered Maintenance – RCM was developed in the aeronautical industry in the late 1960s as an alternative to the traditional maintenance programs to improve the management of aircraft reliability (Mobley, 2002). Because of their similarities with the aeronautic sector regarding requirements of safety, availability and maintenance costs, the nuclear worldwide industry was one of the first sectors to use RCM methodology. The safety rules and the availability requirements of the nuclear industry are very strict mainly because the public opinion about risks and the high costs involved both in maintenance and shutdown of nuclear facilities. The application of RCM is a strategy toward reaching these goals in a cost-effective way. RCM can be used for guiding the shift from traditional time-based maintenance to risk- and reliability-driven approaches, meeting regulatory requirements like Maintenance Rule in nuclear industry (Kadak and Matsuo, 2007).

The Failure Mode and Effects Analysis – FMEA provides a format for identifying the dominant failure modes leading to functional failure on systems or on the whole facility. It is extensively used on implementation of RCM methodologies. The purpose of this paper is to present an approach of implementation of RCM using a set of spreadsheet templates and FMEA indexes that are continuously updated according to events and failures that have occurred over a period of time. This could not only speed up the analysis process, but also improve the maintenance strategies and, as a result, the safety and the availability of the plant.

2. MAINTENANCE OF CRITICAL SYSTEMS

The nuclear industry has stringent requirements on safety and reliability because the potential catastrophic failures. One of the main concerns of this industry is to improve the availability of its safety-related systems to achieve high safety levels (CNEN, 2002, and USNRC, 1991). The development of efficient maintenance methodologies has been traditionally one of the different ways to assure high levels of critical systems availability.

According to Cotaina et al. (2000), the critical systems that should be prioritized regarding maintenance are defined by estimating the consequences of failure modes for each system, equipment or component. Failures modes could have consequences on:

- Main safety functions;
- Plant availability;
- Repair and mitigation costs.

Moreover, the operation of a nuclear facility may be dependent on support from outside resources to supply necessary utilities or services, such power, air and water (IAEA, 2008). Facilities involved in waste management and fuel supply can also affect plant availability, reliability and safety, and shall be considered critical when defining maintenance policies. The definition of such critical systems for nuclear industry can be carried out with the aid of systematic methodologies as FMEA.

Specifically for nuclear power plants, Nuclear Regulatory Commission establishes through the Maintenance Rule (USNRC, 1991) that companies should monitor their safety-related structures, systems and components (SSCs) to ensure that they are capable of fulfilling their intended functions. Licensees should consider the following SSCs to be within the scope of Maintenance Rule (USNRC, 1997):

- SSCs whose failure has caused a reactor scram or actuation of a safety related system at their site or at a site with similar configuration;
- SSCs identified in the licensee’s analysis whose failure would cause a reactor scram or actuation of a safety-related system.

2.1. Types of maintenance

According to NBR 5462 standard (ABNT, 1994) maintenance is a combination of all technical and administrative actions, including supervision ones, intended to retain an item or to restore it to a state in which it can perform a required function. It can also include the modification of an item. In this work it will be adopted the following concepts:

a) ***Preventive maintenance (PM).*** It is maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the failure probability or the degradation of the functioning of an item.
b) ***Corrective maintenance (CM).*** It is maintenance carried out after the fault occurrence and intended to put an item into a state in which it can perform a required function.
c) ***Controlled/predictive maintenance.*** It is maintenance that provides a means of assuring the required service quality, using systematic analysis tools and/or centralized supervisory and sampling techniques in order to minimize the preventive maintenance and reduce the corrective maintenance.
d) ***Condition-based maintenance.*** It is a specialized form of checking that ascertains the presence of a failure mode within a system, equipment or component. The restoring or replacing of such items is based on measured conditions compared to standards.
e) ***Scheduled maintenance.*** It is a preventive maintenance carried out according to preplanned actions.
f) ***Nonscheduled maintenance.*** It is a preventive maintenance that is not carried out according to preplanned actions, but after receiving information regarding the state of a system, equipment or component.

2.2. Maintenance policies

There are many systems to effectively improve systems reliability and plant availability through the choice of the adequate maintenance policy. Among several maintenance policies, the most applied everywhere in the world are the Total Productive Maintenance – TPM and Reliability Centered Maintenance – RCM (Mobley et al., 2008).

TPM comes from Japan and was first developed in manufacturing industry, where poor maintenance practices were applied, based on fixing after equipment had broken down. In these cases, preventive actions were not carried out at all. TPM rests on “five pillars” stated by Mr. Nakajima in the eighties (Mobley et al., 2008):

- Maximizing overall equipment effectiveness;
- Establishing a thorough system of preventive maintenance;
- Implementing TPM by involving all departments of the plant;

- Involving every single employee, from top management to workers on the floor;
- Promoting TPM through motivational management.

RCM methodology is based on understanding of how systems function, how they fail and how are the consequences of failures to select the most appropriate maintenance actions to prevent them. This approach reduces operational delays, consequently saving time and other valuable resources. Traditionally, maintenance strategies have been derived from manufacturer specifications, as an effort to prevent recurrence of costly failures, or using past experiences which can be ineffective when working with new complex systems or unexpected failure modes. On the other hand, RCM addressed elements include process and risk analysis to define spare parts requirements for the plant maintenance plans and other measures to keep the maintenance plans updated according to equipment ages and plant modifications (NASA, 2000).

3. RELIABILITY CENTERED MAINTENANCE

Mid 60s studies have shown that schedule overhaul of complex equipments has little or no effect on in-service reliability. RCM had its beginning in the commercial airline sector in 1970´s. At that time, the commercial airline industry was experiencing high number of crashes in the take-offs, which majority of them were related to equipment failures. It has proved to be highly successful the application of RCM. The number of crashes was significantly reduced, as well as the equipment related crashes (Backlund, 2003).

Reliability Centered Maintenance is a process that systematically identifies all of the functions and functional failures of systems, equipments or components, as well as all likely causes for these failures. It then proceeds to identify the effects of the likely failure modes and also in what way those effects matter. Once it has gathered this information, the RCM process then selects the most appropriate maintenance policy. As a result, the maintenance intervention and tactics are optimized to meet the predetermined reliability, availability and safety goals. According to Moubray (1997) seven questions should be answered in order to prioritize the maintenance activities:

1) What are the functions and associated desired performance of an item in its present operating context (functions)?
2) In what ways can an item fail to fulfill its functions (functional failures)?
3) What causes each functional failure (failure modes)?
4) What happens when each failure occurs (failure effects)?
5) In what way does each failure matter (failure consequences)?
6) What can be done to predict or prevent each failure (proactive tasks and task intervals)?
7) What can be done if proactive tasks are not possible (default actions)?

A “failure-finding task” is a scheduled task used to define whether a specific hidden failure has occurred (Mobley *et al.,* 2008). It usually applies to protective devices that fails without notice and represents a transition from the Moubray’s sixth question (proactive task) to the seventh one (action taken in the absence of proactive task). Failure-finding tasks are scheduled like the proactive tasks, but they are not proactive because they do not predict or prevent failures. In fact, they detect failures that have already happened, reducing the likelihood of a multiple failure and the failure of a protected function while a protective device is already in a failed state.

If the RCM process offers the option to let systems, equipments or components “run-to-failure”, care must be taken about safety and environmental consequences before taking that decision. The process must not allow its users to select “run-to-failure” if the failure mode or (in the case of hidden failure) the associated multiple failure, has safety or environmental consequences.

3.1. Types of RCM

There are many different processes and ways to perform RCM, but there are only few forms of RCM. They are based on the so-called P-F (or potential failure – functional failure) curve, that is illustrated in Figure 1. On this Figure is illustrated the relationship between resistance to failure and operating age for an item from the point of initial introduction into service (point A) to the point of actual failure (point F). If a new bearing is placed in service, for example, with an initial resistance to failure near 100%, as the operating age of the bearing increases, its resistance to failure gradually decreases; that is, it experiences *age degradation* (point B). At some point in the operating life of the bearing, in this hypothetical example, the reduction in resistance to failure becomes evident, for instance, as an increase in level of vibration, a temperature increase, an evidence of particulate matter, or a change of chemical or physical properties of lubricating oil. The bearing continues in service with increasing degradation and steadily decreasing resistance to failure until it reaches a point of potential failure (point P), that is, at which point a preventive maintenance action should be performed (NAVSEA, 2007).

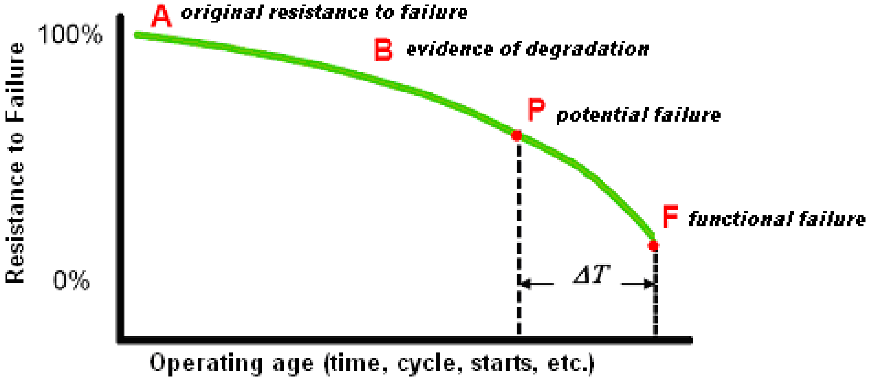

Figure 1. P-F curve (adapted from NAVSEA (2007))

According to Nowlan and Heap (Keeter and Plucknette, 2008) there are two types of failures: the functional failures and potential failures. Functional failures are usually found by operators, and potential failures are usually found by maintenance personnel. Considering a failure as an unsatisfactory condition, the equipment can be operated continuously until fail. Many maintenance programs often try to run the equipments as long as possible or until they get closer to the F of the P-F curve. Other maintenance programs manage to the P, meaning that they take action as soon as the unsatisfactory condition is recognized. The further it is gone along the P-F curve the higher is the accepted level of plant risk. According to Mather (2009), there are two basic approaches to RCM:

- ***The Moubray approach***. Based on classical Moubray's seven questions and it is heavy on P-F intervals with a consistent use of decision diagrams;
- ***The Anthony Smith approach.*** Based on Age Exploration (AE) process, it is not so heavy on decision diagrams and reliance on the P-F interval. AE is an option to address situations where sufficient maintenance data does not exist (Martin, 2006).

Every other method is an adaptation of one of these two fundamental ones. Overall RCM is the optimum mix of reactive, time- or interval-based, condition-based, and proactive maintenance practices (NASA, 2000). The basic application of each strategy is shown in Figure 2. These main maintenance strategies are integrated to take advantage of their respective strengths in order to maximize facility and equipment reliability and minimize costs.

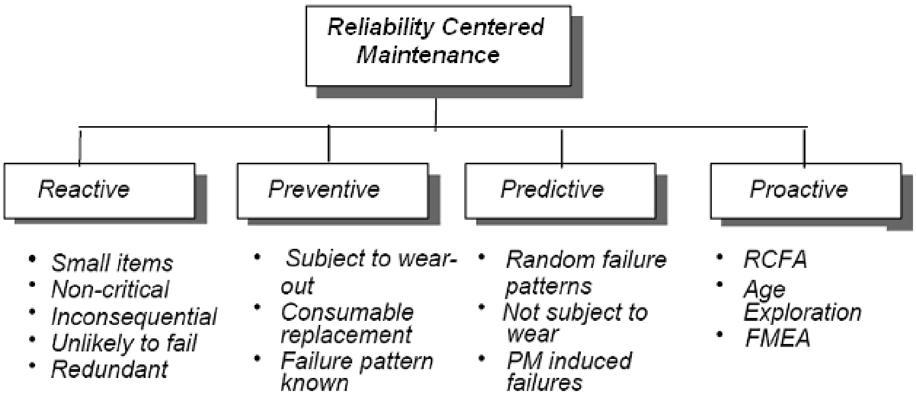

Figure 2. Components of an RCM program (NASA, 2000)

As can be seen, RCM includes reactive, time-based, condition-based, and proactive tasks. In addition, systematic analysis tools like RCFA (Root-Cause Failure Analysis) and FMEA are intensively used.

3.2. Root-Cause Failure Analysis (RCFA)

In some cases, plant equipments fail repeatedly, and there are recurrent problems such as short bearing life, frequent seal fracture, and structural cracking that are symptoms of more severe problems. However, maintenance programs often fix only the symptomatic problems and continue with the frequent repairs. Repeated failures result in high costs and resource consuming tasks, as well as may result in unacceptable environment and industrial risks (NASA, 2000).

While Predictive Testing and Inspection (PT&I) programs can identify most equipment faults at early stages that they do not lead to an equipment failure, this type of program often does not include discovering the underlying reason for the faults. For example, a bearing may fail repeatedly because of excessive bearing loads caused by an underlying misalignment problem. PT&I would most likely predict a bearing failure and thus allow the bearing to be replaced before it fails, but if no one recognizes the misalignment and eliminates it, for example, the conditions causing the failure will remain and failures will recur and continue to require unnecessary corrective work and downtime.

RCFA is a tool that proactively seeks the fundamental causes that lead to facility and equipment failure. It is used together with FMEA, supporting RCM program and its goals are to:

- Find the causes of a problem quickly, efficiently, and economically;
- Correct the causes of the problems, not just their effects;
- Provide information that can help prevent the problem from recurring;
- Create a culture of definitively solve the problems through the elimination of the fundamental causes of them.

3.3. Failure Mode and Effects Analysis (FMEA)

FMEA is one of the most efficient tools for preventing problems and for identifying more adequate solutions, in order to prevent such problems (Mobley et al., 2008). It is a deductive technique that consists on identifying the possible failures in each component, their causes and consequences on equipments and on the whole system. FMEA can easily and objectively help the user to answer those questions related to RCM implementation and mentioned in the beginning of section 3 of this paper.

To develop a FMEA, it is initially done a survey on the functions of each component, as well as on its failure modes and effects (DOE, 1980). It is used, as support for this analysis, the system textual description, contained in the operational technical instructions, the fault records in the service orders for maintenance of the plant, the maintenance plans currently used and the instrumentation descriptions of the equipments and components. It is also sometimes needed to perform a brainstorming with the plant operators, in order to get more details about the description of the possible failures of each component. The documentation of FMEA application is reported according to a standardized form shown in the Table 1.

Table 1. Standardized form for FMEA analysis (adapted from DOE (1980) and Dyadem (2003))

SYSTEM IDENTIFICATION					
Function	**Description of system function**				
Component	**Component function**	**Functional failure**	**Failure mode**	**Failure Cause**	**Failure Effect**

The meaning of each column is as follow (DOE, 1980 and Dyadem, 2003):

- ***Function:*** Action which the user desires that the item or system performs in a specified performance standard;
- ***Component function***: Description of the functions and associated desired performance of the component;
- ***Functional failure***: Description of the possible failures to fulfill the component function;
- ***Failure mode***: Description of the form as the failure is observed by the operation team;
- ***Failure cause***: Description of the cause that can origin the considered type of failure;
- ***Failure effect***: Consequence of the occurrence of the failure, perceived or not by the final user.

They are established indexes for evaluation of the importance of each failure mode for the analyzed system. The most common parameters used to evaluate the risk priority are severity, occurrence and detection indexes. The severity index quantifies the magnitude of the failure consequences. The occurrence index in the case of FMEA applied to RCM is defined as function of the number of failure occurrences reported in the administrative orders of maintenance. In this paper, it was adopted the period of 3 years, as suggested by Souza and Tavares (2008). Such indexes are measured in a scale of 1 to 10: the number 1 indicates a lesser importance of the failure, in the point of view of determined parameter, and the number 10 indicates that the biggest importance must be attributed to the failure. The detection index is based on the probability estimative that a failure can be detected, assuming that it has occurred. This index can assume values of 1, 3, 5 and 7, depending on ability of controls on detecting the failure. The classifications criteria of each one of these parameters adopted in this work are presented in Table 2 were based on Souza and Tavares (2008), Dyadem (2003), and Dhillon (2002). These criteria were adapted in order to take into account specific features of nuclear facilities. The Risk Priority Number – RPN is calculated by the product of the three defined indexes (*Severity x Occurrence x Detection*) and it is used as a practical way to prioritize certain failures and to evaluate which steps have to be carried out first.

Table 2. Criteria for failure modes evaluation (adapted from Souza and Tavares (2008), Dyadem (2003), and Dhillon (2002))

Severity		**Occurrence**	
Index	**Classification Criteria**	**Index**	**Classification Criteria**
1	Very insignificant effect, corrected immediately by the operational team.	1	Without failure registry in the last 3 years.
2	Impact on system mission is negligible, insignificant effect, and defects can be corrected immediately by the maintenance team.	2	1 failure in the last 3 years.
3	Minor effect, gradual degradation of the system, but there is an insignificant impact on system mission because the use of redundancy.	3	2 failures in the last 3 years.
4	Local or downstream processes might be affected, some processes might be delayed, but the maintenance does not demand the system trip.	4	3 failures in the last 3 years.
5	Moderate effect, which causes the reduction of the performance level of the facility, and whose maintenance does not demand to stop the facility.	5	4 or 5 failures in the last 3 years.
6	Moderate effect, which causes the reduction of the performance level of the facility and whose maintenance demands to stop the facility during one day or less.	6	6 failures in the last 3 years.
7	Critical effect that causes loss of primary function of the facility, and whose maintenance demands to stop the facility for more than one day.	7	7 failures in the last 3 years.
8	Significant downtime and financial impacts, brusquely interrupting facility functioning, but without safety, health, or environmental issues.	8	8 failures in the last 3 years.
9	Very critical effect that causes significant downtime of the facility with potential safety, health, or environmental issues, and involving noncompliance with regulatory requirements.	9	9 failures in the last 3 years.
10	Catastrophic effect that can harm people, properties or environment.	10	10 failures in the last 3 years.

Detection	
Index	**Classification Criteria**
1	Failure indicated directly by the instrumentation
3	Failure identified by the operational team through daily inspections.
5	Failure identified directly through abnormal noises, or indirectly by the instrumentation.
7	Hidden failure, impossible to be identified by the operator. Failure will occur without warning.

4. RCM IMPLEMENTATION METHODOLOGY

4.1. Approach for RCM application

Looking for the answers to the seven questions about the system under review (adopting the Moubray approach), the implementation of RCM analysis can be divided into ten steps, as shown in Figure 3.

In step 1, the system under analysis is defined as a user-defined group of components, equipments, or facilities that support an operational requirement. In this paper the critical systems of nuclear facilities of interest are selected. Most systems can be divided into sub-systems, according to their complexities, facilitating the analysis.

In step 2, the operating context and performance standards are determined. The operational requirements include environmental, health, safety, regulatory, quality, or other requirements stated by regulatory bodies, and performance standards. The operating context is the circumstance in which the system is operated. The same hardware does not always require the same failure management policy in different facilities. For instance, a single pump in a system will usually need a different failure management policy compared to a pump that is one of several redundant units in a system. A pump moving corrosive fluids will usually need a different policy compared to a pump moving non-corrosive ones. The user shall dictate the performance level that the maintenance program shall be designed to sustain.

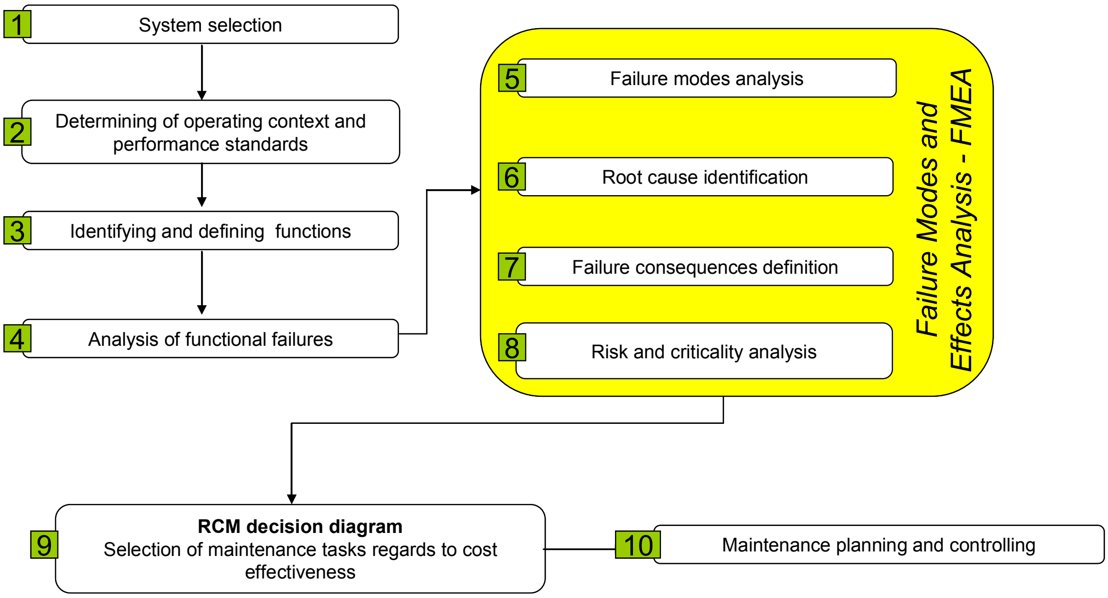

Figure 3. Flowchart for implementing the Moubray approach for RCM analysis

In step 3, all primary and secondary functions of the system shall be identified, including the functions of all protective devices. The performance standards shall be incorporated in all function statements, that is, the performance level desired by the user of the system in its operating context.

In step 4, the functional failures shall be analyzed. All the failed states related to each function shall be identified. If the functions are defined, the identification of functional failures is easily carried out. For example, if a function is "to keep the temperature of a system between 50°C and 70°C", then the functional failure might be "unable to keep system temperature above 50°C" or "unable to keep system temperature below 70°C".

The steps 5, 6, 7 and 8 are implemented through a FMEA. In the context of a RCM, the term failure mode refers to the event that causes functional failure. At the implementation of FMEA in the scope of this work, the occurrence index is dynamic and must be reevaluated annually considering the number of failures in the 3 last years. Therefore, the FMEA analysis is dynamic and has its values annually modified. The index values are defined according to Table 2. FMEA shall be applied to each critical identified in the boundary definition. For every function identified, there can be multiple failure modes. The FMEA addresses each system function (and, since failure is the loss of function, all possible failures) and the dominant failure modes associated with each failure, and then examines the consequences of the failure. Even though there are multiple failure modes, often the effects of the failure are the same or very similar in nature. That is, from a system function perspective, the outcome of any component failure may result in the system function being degraded. Likewise, similar systems, equipments or components will often have the same failure modes. Then, the use of a set of worksheet templates and FMEA indexes that are continuously updated according to events and failures that have occurred over a period of time, both speeds up the analysis process, and improve the maintenance strategies and, as a result, the safety and the availability of the plant.

In step 9, the selection of maintenance tasks is carried out using the decision diagram shown in Figure 4. Note that the analysis process, as depicted in this Figure, has four possible outcomes: perform condition-based actions; perform interval (time- or cycle-) based actions; assume that redesign will solve the problem or accept the failure risk, or assume that no maintenance action will reduce the probability of failure and install redundancy; or perform no action and choose to repair following failure (run-to-failure).

In step 10, maintenance planning is concerned with preparing work to be done in the future, based on RCM analysis. Specific tasks include, among others: job plans and cost estimates; work schedules by priority; coordination of availability of manpower, parts, materials, and equipments for work execution; maintenance of records, indexes and charts; and reports on performance versus goals. Maintenance controlling is primarily concerned with diary maintenance tasks. Specific responsibilities include, among others: quality control; duration, cost, and completeness of work; time lost between jobs and at breaks and shift changes; training and motivation; report of time to repair of the critical systems; act upon requests for support and help; and assure reasonably accurate distribution of time and materials to specific jobs.

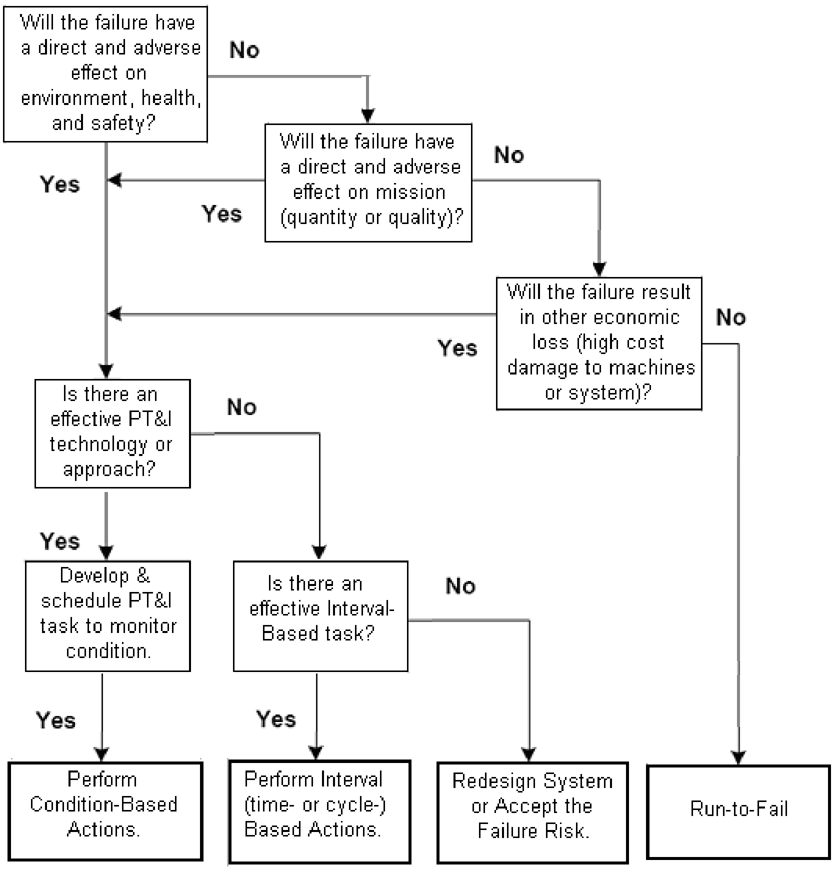

Figure 4. RCM decision diagram (adapted from NASA (2000))

4.2. Implementation of the dynamic maintenance FMEA

The main screen of the software that implements the dynamic maintenance FMEA methodology is shown in Figure 5. The software was implemented using Visual Basic for Applications (VBA), which is an implementation of Visual Basic language and associated Integrated Development Environment (IDE) into Microsoft™ Office Applications (Schmalz, 2006). The developed software has resources to streamline the required processes of RCM steps 5, 6, 7 and 8, for instance, for creating new FMEA, editing existing FMEA, and editing FMEA library, through the use of the buttons named “Criar Nova FMEA”, “Editar” and “Editar Biblioteca”, respectively. The creation of a new FMEA is streamlined through the use of templates, editing an existing FMEA, or using an existing library of processes, systems, failure modes, effects, causes, etc. On the other hand, this library can be edited, introducing new elements or periodically updating the tables of occurrence, severity and detection indexes, according to recorded performance, failure and maintenance data. Different formats of FMEA can be exported and imported through the use of the “Exportar” and “Importar” buttons, respectively. The other buttons guides the whole FMEA application.

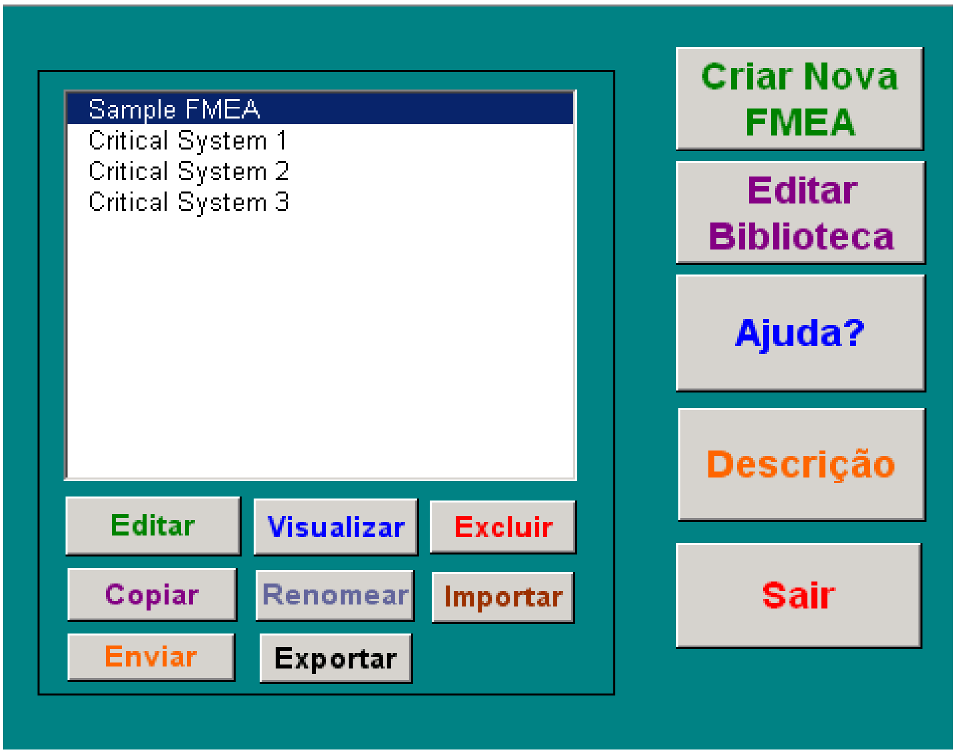

Figure 5. Main screen of the computer implementation of FMEA

5. RESULTS AND DISCUSSION

The implementation of RCM proposed in this paper is a process to continually improve and update the reliability knowledge database created by the RCM process in order to enable better analyses and understanding of failure information. Therefore, the maintenance strategies are continuously refined. Whenever a failure occurs and maintenance work is done, the failure data captured in the work order system will be checked and the reliability knowledge database is updated. As RCM should be a living system, it should gather data from the results achieved and feed these data back to improve design and future maintenance. This feedback is an important part of the proactive-based tasks of a RCM program. This resource was provided in this work by a dynamic FMEA in which the severity, occurrence and detection indexes are annually reevaluated considering the failures that have occurred in the period. The intended benefits of such living RCM process applied to critical systems of nuclear facilities are: faster problem solving; improved validity of failure information; enable better reliability analyses; and faster improvement to safety, reliability and availability in the long term. Despite a case study using the proposed approach has not been yet carried out, it is expected that its use would facilitate the compliance with Maintenance Rule, that is NRC's attempt to uniformly introduce the notion of risk into the process of assessing which system has high safety significance and establishing appropriate maintenance policy.

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