ELEMENTS OF MAINTENANCE SYSTEMS AND TOOLS FOR IMPLEMENTATION WITHIN THE FRAMEWORK OF RELIABILITY CENTRED MAINTENANCE- A REVIEW

Ikuobase Emovon[1*], Rosemary A. Norman[2] and Alan J. Murphy[2]

[1] Department of Marine Engineering, Federal University of Petroleum Resources, Effurun, Nigeria

[2] School of Marine Science and Technology, Newcastle University, Newcastle upon Tyne, NE1 7RU, UK

ABSTRACT

For plant systems to remain reliable and safe they must be effectively maintained through a sound maintenance management system. The three major elements of maintenance management systems are; risk assessment, maintenance strategy selection and maintenance task interval determination. The implementation of these elements will generally determine the level of plant system safety and reliability. Reliability Centred Maintenance (RCM) is one method that can be used to optimise maintenance management systems. This paper discusses the three major elements of a maintenance system, tools utilised within the framework of RCM for performing these tasks and some of the limitations of the various tools. Each of the three elements of the maintenance management system has been considered in turn. The information will equip maintenance practitioners with basic knowledge of tools for maintenance optimisation and stimulate researchers with respect to developing alternative tools for application to plant systems for improved safety and reliability. The research findings revealed that there is a need for researchers to develop alternative tools within the framework of RCM which are efficient in terms of processing and avoid the limitations of existing methodologies in order to have a safer and more reliable plant system.

KEYWORDS: *Plant systems; Reliability centred maintenance; Risk assessment; Maintenance strategy selection.*

1.0 INTRODUCTION

Dhillon (2002) defined maintenance as the combination of activities undertaken to restore a component or machine to a state in which it can continue to perform its designated functions. Maintenance usually involves repair in the event of a failure (a corrective action) or a preventive action. On the other hand the British Standard defines maintenance as (BS 1993) "*the combination of all technical and administrative actions,*

*Corresponding author e-mail: ikuoy2k@yahoo.com

intended to retain an item in, or restore it to, a state in which it can perform a required action". The costs incurred in this are normally a major percentage of the total operating cost in most industries including the maritime sector. Vavra (2007) reported that wasted energy as a result of poorly maintained compressed air systems collectively cost US industry up to $3.2 billion annually. This can be attributed to the general perception in the past that maintenance is an evil that plant managers cannot do without and that it is impossible to minimise maintenance cost (Mobley, 2004). However in order to minimize cost of plant system maintenance without compromising the system safety and reliability there is a need to have an effective maintenance system in place.

There are three major elements that make up a maintenance system; risk assessment, maintenance strategy selection and maintenance task interval determination. These elements must be performed optimally in the maintenance management of a plant system in order to have a safe and reliable system at reasonable cost. Different maintenance methodologies have been applied in optimizing these elements of maintenance. One of the most notable is Reliability Centered Maintenance (RCM). Within this maintenance framework, different tools/methods are used to perform these three elements of a maintenance system. The paper discusses an overview the RCM methodology, tools utilised within the framework in carrying out the three major elements of a maintenance system, advances and associated limitations. The rest of the paper is organized as follows: An overview of RCM is presented in section 2. This is then followed by a discussion of the three elements of a maintenance system in turn in sections 3, 4 and 5. Finally the conclusion is presented in section 6.

2.0 RCM OVERVIEW

Moubray (1991) defined RCM as "*a process used to determine what must be done to ensure that any physical asset continues to function in order to fulfil its intended functions in its present operating context*." From this definition it is obvious that RCM focuses, not on the system hardware itself rather, on the system function. Maintenance practitioners are faced with challenges with respect to maintaining their asset and some of these challenges are; difficulty in selecting the most appropriate maintenance strategy for each equipment item, difficulty in prioritizing the risk of component failure modes of the system, difficulty in ascertaining the most cost effective approach and difficulty in getting the best support from the workforce. All of these challenges are addressed by the RCM frame-work in a systematic manner. In fact, Moubray (1991) categorically stated that no maintenance technique has proven to be more successful in preserving the function of a system than RCM.

The development of the RCM technique can be traced to the aviation industry where the Maintenance Steering Groups (MSG) formed within the industry developed a maintenance methodology which was reported in three documents referred to as MSG1 MSG2 and MSG3, released in the years 1968, 1970 and 1980 respectively (Dhillon, 2002). This technique evolved into classical RCM which has since been embraced by industries ranging from manufacturing to the marine sectors and has proven to be successful in all these industries.

The first step to the successful implementation of the RCM technique is to ask seven basic questions about the asset that the methodology is intended to be applied on. These seven questions are as follows, (Moubray, 1991):

1) What are the intended functions and performance standards of the asset or machinery in its current operating situation?
2) How does it fail to fulfil these intended functions?
3) What are the causes of each failure?
4) What are the corresponding consequences?
5) In what way does each failure matter?
6) What task should be performed in order to avert each failure?
7) What should be done if no preventive task is found to be applicable?

The basic steps of the RCM analysis are reviewed as follows (Rausand & Vatn, 1998, Dhillon, 2002, Selvik & Aven, 2011):

(1) Preparatory stage: RCM is generally performed by a team and, as such, the first step in the RCM analysis is to set up the RCM team. The team should consist of experts with adequate knowledge of the system to be investigated. Generally the team should have a minimum of one person each from the maintenance and the operational units. The team should also have a member with a vast knowledge of the RCM methodology and who could serve as the facilitator. The RCM team have the responsibility for determining; the scope of the study, the level of the assembly to be investigated (i.e. plant, system, sub-system) and the equipment or asset to be investigated. They also have the responsibility, among others, of data gathering for the analysis.

(2) Maintenance significant items (MSI) identification: Failure Mode and Effect Analysis (FMEA) is generally applied here in determining the maintenance significant items. FMEA methodology is discussed in detail in Sections 3.1.1 and 3.1.2 below. These items are then used to populate the RCM decision diagram in order to determine the most appropriate maintenance task. For a very simple system, MSI can easily be identified without resorting to any specialized tools. For the non-MSI items, the items are generally allowed to fail before repair or replacement can be implemented. However for the MSI items, preventive maintenance tasks are usually more appropriate but in some cases they are allowed to fail before repair or replacement activities are performed and these are dependent on the MSI item failure characteristics, the impact of the failure and maintenance costs.

(3) Maintenance strategy classification: The maintenance strategy for addressing crucial failure modes of the critical components of an asset have been classified in different ways. Rausand and Vatn (1998) considered five distinct maintenance strategies namely continuous predictive maintenance, scheduled predictive maintenance, scheduled overhaul, scheduled replacement and scheduled function testing for preventing or mitigating the effects of failures. Dhillon (2002) presented the following four maintenance strategies for use in the RCM methodology; reactive maintenance, preventive maintenance, predictive testing and inspection and proactive maintenance. Nevertheless both the five maintenance strategy types considered by Rausand and Vatn (1998) and the four maintenance strategies considered by Dhillon (2002) fall within the

three basic main maintenance strategies: corrective maintenance, preventive maintenance and condition/predictive maintenance.

(4) Maintenance task selection: Here the RCM logic is designed and applied in selecting the appropriate maintenance task for the crucial failure mode of each of the critical components of the asset. The RCM logic is expressed in decision diagram form which, through a series of YES and NO questions, enables the RCM facilitator to arrive at an optimal maintenance strategy for the particular failure mode/component in question. There are various versions of the decision RCM logic tree and a sample is shown in Figure 1. However all of the versions are based on the basic decision criteria of the RCM for selecting the maintenance task which are; cost effectiveness, applicability and failure characteristics. The term applicability, with respect to selecting the maintenance task, means a maintenance preventive task that is capable of mitigating or preventing failure and in the case of a potentially hidden failure is capable of discovering it. The term cost-effectiveness is a decision criterion for determining the maintenance task, from different alternatives, that is the most cost effective. If there is no applicable preventive maintenance task available, then the only alternative is to select Run– To–Failure. In the case of cost effectiveness; the cost of the applicable preventive maintenance task to mitigate or prevent failure must be greater than the aggregate cost related to the failure itself, otherwise Run–To–Failure will be more appropriate except with a safety-related issue or a failure situation where redesign may be compulsory.

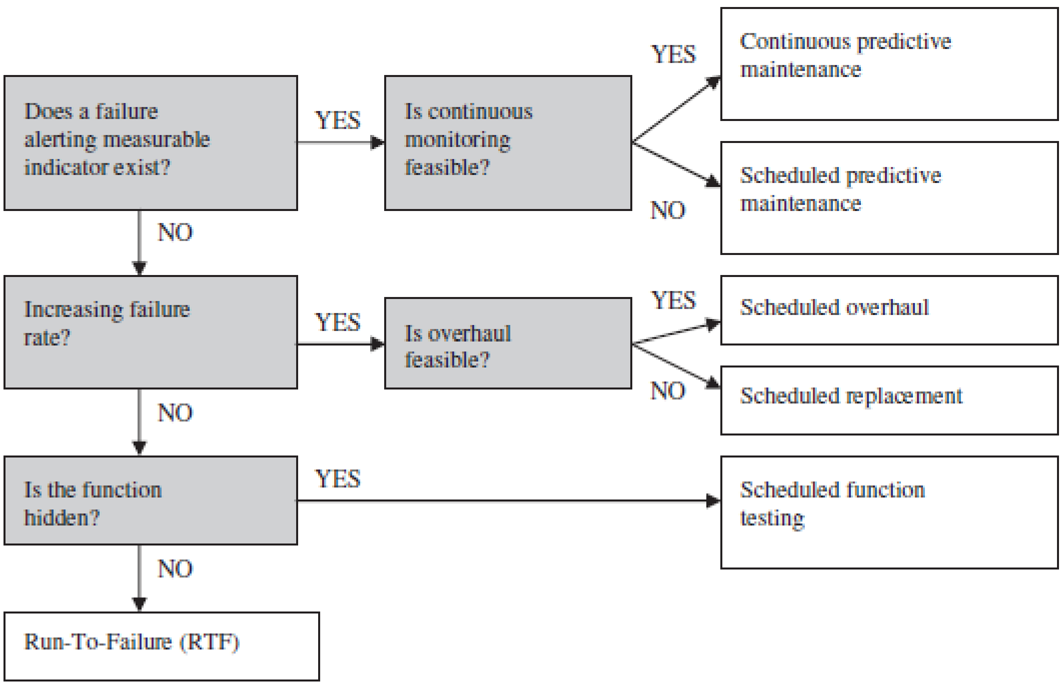

Figure 1. A sample of RCM logic adapted from (Rausand and Vatn, 1998)

(5) Maintenance planning: Here the optimal intervals are determined for the preventive maintenance tasks assigned for the crucial failure modes of the critical components of the asset. Some of the failure modes are assigned scheduled predictive maintenance and some scheduled overhaul, etc. using the RCM logic. The process of determining the interval for a preventive maintenance task is, in many instances, very challenging and, in general, mathematical models are applied in obtaining these intervals. However in some cases mathematical models are not applied and preventive maintenance task intervals are not optimized but are determined based on experts' opinions, operational experience and manufacturers' recommendation. It is worth mentioning that in the traditional RCM process there is no provision for tools for use in the determination of preventive maintenance task intervals.

(6) Implementation and update: Here the managerial procedures, with respect to how the results of the RCM analysis that is performed by the RCM team are applied, is described. This step includes among others; communication of the RCM analysis results from the RCM team to the management, results documentation and undertaking updating from time to time which is generally subject to availability of new, relevant data.

From the RCM discussion it can be seen that there are three key elements of maintenance that the methodology is used to optimize; (1) risk assessment, (2) maintenance strategy selection from different alternatives, and (3) maintenance task interval determination. The three elements of a maintenance system and the advances of the tools utilised for performing them within the frame work of RCM together with the limitations of the tools, are discussed next.

3.0 RISK ASSESSMENT

The American Bureau of Shipping (2000) defined risk as the product of the probability of the occurrence of a failure and consequence of the failure. While risk assessment, according to Cross and Ballesio (2003), is defined as being a systematic method that combines diverse aspects of design and operation in assessing risk. Arendt (1990) described risk assessment as activities involving hazard identification, chances of the occurrence of failure estimation and the consequences of the failure estimation.

With the advent of risk-based inspection and maintenance in the 1990s in conjuction with reliability maintenance, risk assessment has gained popularity in the maintenance world and it is worth noting that risk assessment is clearly the most critical phase of risk-based maintenance since maintenance decisions to be taken will be based on the assessed level of risk (Arunraj & Maiti, 2007). Risk assessment is also a very important aspect of Reliability-Centred Maintenance (RCM) though RCM is mainly intended for preserving the reliability of plant equipment and systems. The risk assessment in the RCM process involves assessing the risk of failure of equipment items and, based on the assessed risk, an appropriate maintenance strategy will be recommended. However the acceptable level of risk must be defined, possibly through a retrospective study of earlier successful items etc.

Some of the factors that affect the quality of the output from a risk analysis are; data sources, human factors, methods and tools for performing the analysis itself, and the ability and experience of the analyst.

3.1 Risk Assessment Tool

An analyst has the option of choosing from a variety of tools for performing risk analysis in each of the three major phases of risk assessment; hazard identification, risk estimation and risk evaluation. The commonly used tool/method within the framework of RCM for prioritising risk is FMEA.

3.1.1 FMEA

Siddiqui and Ben-Daya (2009) defined Failure Mode and Effect Analysis (FMEA) "as a systematic failure analysis technique that is used to identify the failure modes, their causes and consequently their fallouts on the system function". The methodology was developed by the United States Army in 1947 and in the 1970s industries such as the automotive, aerospace and manufacturing embraced the use of the technique in the maintenance of their asset (Scipioni et al., 2002). Nowadays FMEA is a popular risk assessment tool in the production of hardware such as mechanical and electronic components (Scipioni et al., 2002). The technique has also become a popular tool for performing risk assessment for ship systems. When FMEA is combined with criticality analysis (CA) it is referred to as Failure Mode Effect and Criticality Analysis (FMECA) and its essence is to rank the impact of each of the failure modes for the various components that make up the entire system (Headquarters Department of the Army, 2006, Sachdeva et al., 2009a). According to Ben-Daya (2009) FMEA basically performs three functions. These are:

(1) To identify and recognize potential failures including their causes and effects.
(2) To evaluate and prioritize identified failure modes.
(3) To identify and suggest actions to either eliminate or reduce the chance of the potential failures from occurring.

The technique can be applied to any well-defined system but it is best suited to the risk assessment of mechanical and electrical systems (e.g. fire suppression systems, propulsion systems) and the approach can either be quantitative or qualitative, (American Bureau of Shipping, 2000, Headquarters Department of the Army, 2006). The availability or non-availability of failure data will determine, to a large extent, the approach that is used in carrying out FMEA risk assessment. A quantitative approach is used when variables such as failure rate (λ_i), failure mode ratios (α_i), failure effect probability (β_i) and its operating time (t) are known and are used to generate the criticality number (CN) which can then be used to rank the ith failure mode (Headquarters Department of the Army, 2006, Braglia, 2000). This can be represented mathematically as:

$$CN_i = \alpha_i \, x \, \beta i \, x \, \lambda_i \, x \, t \tag{1}$$

In applying the qualitative method each failure mode is rated or ranked by developing a risk priority number (RPN) which is computed by multiplying the severity rating (*S*) by both the occurrence probability (*O*) and the detection rating (*D*):

$$RPN = S \times O \times D \quad (2)$$

Qualitative terms are used to determine these three parameters, usually on a numerical scale of 1 to 10 having been determined based on collective expert opinion (Sachdeva et al., 2009b, Siddiqui & Ben-Daya, 2009, Ling et al., 2012, Kahrobaee & Asgarpoor, 2011, Zammori & Gabbrielli, 2012, Braglia, 2000). Typically values are assigned to O, S and D by a team of experts using an ordinal scale, an example of which is shown in Table 1. In performing FMEA for any assets a series of steps are followed and are represented diagrammatically in Figure 2.

3.1.2 FMEA based on MCDM technique

Multi-Criteria Decision Making (MCDM) tools have been applied in literature to an extent in addressing some of the challenges of the conventional FMEA. This is due to their ability to judge different alternatives based on certain decision criteria. Braglia (2000) utilised the Analytic Hierarchy Process (AHP) technique in aggregating the decision criteria (O, S and D) in the conventional FMEA system together with an economic cost criterion in prioritising possible causes of failure of a refrigerator manufacturing plant. The decision problem was structured in a three-level hierarchy, with the top level signifying the goal, the intermediate level signifying the four decision criteria; O, S, D and economic cost and the bottom level signifying the alternative causes of failure of the plant. Pairwise comparison judgements were obtained and evaluated to produce weights of decision criteria and local priorities of possible causes of failure for every decision criterion. The decision criteria weights were then synthesized with the local priorities of causes of failure to produce overall weights of the possible causes of failure. Carmignani (2009) used the Braglia (2000) methodology in prioritising the risk of failure modes of an electro-injector, a fuel system component. The author however developed a new mathematical model for evaluating the economic cost criterion. However the use of AHP has been criticised due to its use of an unbalanced scale of judgement and its inadequacy in addressing risk criteria rating that may be uncertain and imprecise in the pairwise comparison process (Deng, 1999, Ilangkumaran & Kumanan, 2009). Additionally, the use of AHP methodology limits risk prioritisation to the use of a maximum of 15 decision criteria in order to reduce the number of pairwise comparison judgements and evaluation complexity (Vidal et al., 2011).

Table 1. Ratings for occurrence (O), severity (S) and Detectability (D) in a marine engine system, adapted from (Yang et al., 2011, Pillay & Wang, 2003, Cicek & Celik, 2013, Emovon et al., 2015)

Rating	Linguistic term	Occurrence (O) (failure rate measured in operating days)	Severity (S)	Likelihood of non-detection (D)
10	Very high	>1 in 2	Engine failure resulting in hazardous effects is almost certain	Very high chance control system will not and /or cannot detect a potential cause and subsequent failure mode
9		1 in 3	Engine failure resulting in hazardous effects highly probable	
8	High	1 in 8	Engine inoperable but safe	High chance control system will not detect a potential cause and subsequent failure mode
7		1 in 20	Engine performance severely affected	
6	Moderate	1 in 80	Engine operable and safe but performance degraded	Moderate chance the control system will not detect a potential cause and subsequent failure mode
5		1 in 400	Reduced performance with gradual performance degradation	
4		1 in 2000	Minor effect on engine performance	
3	Low	1 in 15,000	Slight effect on engine performance. Non-vital faults will be noticed most of the time	Low chance the control system will not detect a potential cause and subsequent failure mode
2		1 in 150,000	Negligible effect on engine performance	
1	Remote	<1 in 1,500,000	No effect	Remote chance control system will not detect a potential cause and subsequent failure mode

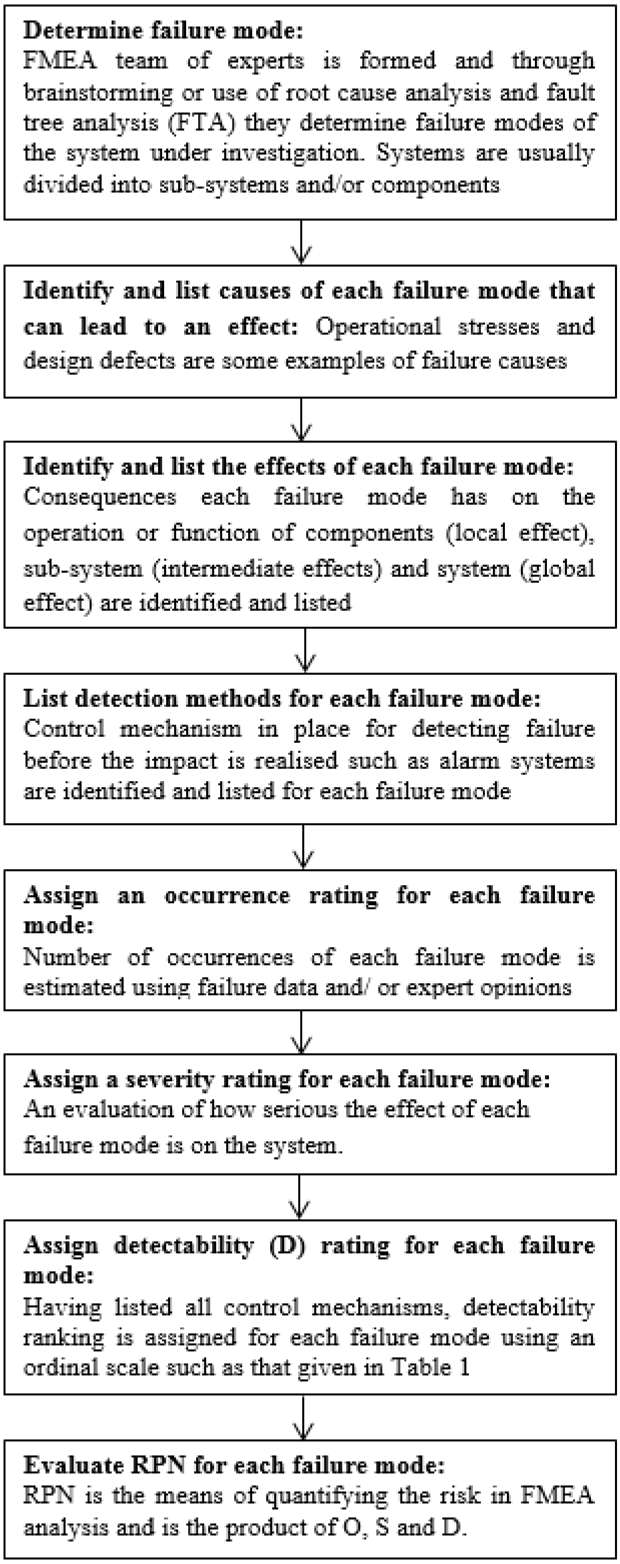

Figure 2. FMEA methodology, adapted from (Cicek & Celik, 2013, Emovon et al., 2015)

Maheswaran and Loganathan (2013) proposed an integrated AHP and Preference Ranking Organisation METHod for Enrichment Evaluation (PROMETHEE) as an alternative to RPN in the traditional FMEA system for prioritising failure modes of a boiler system in the tyre manufacturing industry. The AHP was applied in determining weights of decision criteria while PROMETHEE was used in the ranking of risk of failure modes of the system. Other authors have also used PROMETHEE for prioritising risk of failure modes. Ayadi et al., (2013) applied PROMETHEE for prioritising risk of failure modes of a gas treatment plant. Moreira et al., (2009) utilised PROMETHEE in the ranking of failure modes of equipment items of a power transformer. The main limitation of the PROMETHEE technique is that it results in poor structuring of decision problems and when more than seven decision criteria are used, it becomes difficult to have a clear view of the problem thereby making the evaluation process very complex (Macharis et al., 2004). Seyed-Hosseini et al., (2006) proposed Decision Making Trial and Evaluation Laboratory (DEMATEL) as an alternative tool to the RPN of the conventional FMEA for prioritisation of risk of failure modes. With this approach alternative failure modes are prioritised based on severity of effect and direct/indirect relationships between them. However the major demerit of the approach is that a lot of computational effort is required. Furthermore, the technique cannot address the limitations of the conventional RPN method in systems where each cause of failure is linked to a single failure mode and for such systems the results obtained by both methods are the same (Shaghaghi & Rezaie, 2012).

Sachdeva et al., (2009b) proposed the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) as an alternative to the RPN of the conventional FMEA for risk prioritisation. The author applied six decision criteria of O, D, maintainability, spare parts availability, economic safety and economic cost upon which the risk of failure modes were ranked. A case study of the digester of a paper manufacturing plant in India was used to demonstrate the applicability of the method. Braglia et al., (2003) used TOPSIS under a FUZZY environment for risk prioritisation of a foaming machine of a refrigerator production line. Emovon et al., (2014) proposed a technique referred to as AVTOPSIS for risk prioritisation of marine machinery systems. The approach is based on a combination of an averaging technique with TOPSIS. The technique allows the use of imprecise information from experts in the decision making process and that is made possible with the averaging technique which aggregates the information and the result is used as input to the TOPSIS methodology which executes the ranking of the failure modes of the system. The technique was demonstrated with a case study of the marine diesel engine of a ship. The TOPSIS technique basic concept is that the best alternative is the one closest to the positive ideal solution and farthest from the negative ideal solution. One major limitation of the technique is the lack of measure of the relative distance between positive ideal and negative ideal in the evaluation process which seems to negatively affect the outcome. In a similar study Emovon et al., (2015) proposed an integrated VIKOR and Compromise Programming (CP) method with averaging technique as an alternative to the standard RPN calculation of the FMEA system for prioritising risk of failure mode of marine machinery systems. While the averaging technique was use for imprecise data aggregation, the CP and VIKOR methods were used for ranking of risk of failure modes.

4.0 MAINTENANCE STRATEGY SELECTION

One of the main challenges of maintenance management is the selection of the appropriate maintenance strategy for each equipment item in the system because not all maintenance strategies are applicable and cost effective for different components. Hence choosing the right maintenance strategy for the system will help maintain a balance between the system availability and cost of performing the maintenance. However when choosing the type of maintenance strategy for plant systems, several conflicting decision criteria must be taken into consideration such as cost, reliability, availability and safety. These make maintenance strategy selection analysis critical and complex and the investigation fundamental and justifiable (Bevilacqua & Braglia, 2000). Despite the significance of the subject, only a few studies have dealt with the maintainance selection policy problem (Bertolini & Bevilacqua, 2006).

There are different maintenance strategies that can be used for mitigating the different failure modes of a plant system. Generally there are three types of maintenance strategy that are available for maintenance practitioners to choose from. The three maintenance strategies and a review of the methods utilised for the selection of the optimum strategy for each of the different component/failure mode of the system are discussed next.

4.1 Maintenance Strategies

According to Pintelon et al., (2006) a maintenance strategy is generally viewed from the perspective of maintenance policies such as breakdown maintenance, preventive maintenance and predictive maintenance and sometimes RCM or TPM. It is worth noting that the maintenance strategy is one of the most influential factor affecting the effectiveness of a maintenance system (Stanojevic et al., 2000, Stanojevic et al., 2004) and the process of estimating the optimal combination of maintenance strategies for different plant system equipment items is a very hard and complex task as the maintenance program must combine both technical and management requirements (Sachdeva et al., 2009b, Bertolini and Bevilacqua, 2006, Bevilacqua et al., 2000). The selections usually require a vast amount of information relating to the following decision criteria (Bertolini & Bevilacqua, 2006): manpower utilization, cost and budget constraints, safety factors, environment factors and Mean Time Between Failure (MTBF) for each piece of equipment.

4.1.1 Run-to-Failure

The rationale of the run-to-failure management approach is simple and straightforward. When an equipment item fails it is fixed. That is to say equipment is allowed to fail before any maintenance (repair or replacement) is carried out and, as such, resources are not deployed until equipment breaks down. It is, in fact, a no-maintenance approach to maintenance management of an asset and it is generally the least cost effective technique of maintenance management, since the maintenance costs are higher and plant availability is lower. In fact maintenance cost analysis revealed that repair carried out in reactive mode is nearly three times higher in cost than that carried out in preventative mode (Mobley, 2001).

This type of maintenance is usually effective for non-critical and low cost components and equipment in a system (Pride, 2008). For the plant manager to know that a component is non-critical, criticality analysis is carried out and, based on the result, an appropriate maintenance strategy is recommended for the plant equipment.

4.1.2 Preventive Maintenance

Preventive maintenance (PM) is defined as maintenance actions performed on plant systems at a definite interval with the aim of preventing wear and functional degradation, extending the useful life and mitigating the risk of catastrophic failure (Sullivan et al., 2004) and it concerns itself with such activities as the replacement and renewal of components, inspections, testing and checking of working parts during their operation (Ebrahimipour et al., 2015). In utilising this approach for maintenance management, equipment repairs or replacement are performed at pre-established intervals. The length of the intervals is usually based on equipment items' industrial average-life such as Mean Time Between Failures (MTBF). However some plant managers rely on machine or component manufacturer's recommendation to schedule preventive maintenance activities.

For the shipping industry, IMO in 1993 set the foundation for preventive maintenance implementation by releasing the International Safety Management (ISM) code (IMO 1993). Chapter 10 of it clearly states the procedure and the duties of the shipping industry for preventive maintenance implementation in such a way that international regulations are adhered to strictly.

The major merit of PM is its ability to increase the average life of equipment items and to reduce the risk of catastrophic failure (Sullivan et al., 2004). However despite the numerous benefits of PM, the major limitation is that it often results in unnecessary repair or replacement. Another limitation is the difficulty in evaluating the optimum interval of performing the maintenance task as this may take years of data collection and analysis (Chen, 1997).
The time based preventive maintenance approach can further be divided into two categories as follows:
(1) Scheduled overhaul: In this type of time based preventive maintenance, equipment overhaul or repair is performed on a definite time interval. The strategy is suitable to equipment with identifiable age when failure rate function rapidly increases and large units of the equipment can survive to that age. Furthermore, where reworking can restore the equipment to its normal operating condition (Rausand, 1998).
(2) Scheduled replacement: The application of this type of time based preventive maintenance approach, requires an equipment item or a unit of it being replaced at a specific time interval. This strategy is generally best for equipment that is exposed to critical failure and where the majority of the items of the equipment must survive to the minimum replacement time. Additionally, the equipment failure type must be of prime economic consequences (Rausand, 1998).

4.1.3 Condition Based Maintenance

This refers to the maintenance strategy in which the condition of an equipment item is monitored in order to detect potential failure and recommend appropriate corrective action. Basically there are two types of Condition Based Maintenance (CBM); the continuous on-condition task and the scheduled on-condition task (Rausand and Vatn, 1998). The continuous on-condition task is the approach where equipment item condition is monitored uninterruptedly using diagnostics devices. The main shortcoming of this approach is that it is expensive (Jardine et al., 2006). The scheduled on-condition task is a CBM strategy in which the condition of an equipment item is monitored at regular time intervals with the objective of detecting potential failure (Rausand and Vatn, 1998). The check carried out on an equipment item is implemented by maintenance practitioners or operators with or without the use of diagnostic tools. This approach is nowadays more commonly used by most industries than the continuous on-condition task because it’s less expensive and yet effective. However the main challenge of the scheduled on-condition task is the difficulty in determining the appropriate interval for carrying out the task (Jardine et al., 2006).

In designing a condition monitoring program for ship systems the general procedure to follow has been put in place by BSI/ISO 17359 (2003). The standard includes procedures for equipment auditing, criticality assessment and overview of the condition monitoring procedure and the determination of the maintenance action to be used.

The technique for scheduling maintenance tasks is the major difference between time based preventive maintenance and condition based maintenance. While the time based preventive maintenance activity is scheduled based on average life evaluated using historical data of the particular piece of equipment, the condition based maintenance activity is scheduled in response to a performance degradation observed from diagnostic device readings and/or human sensing which deviate from standard equipment operating conditions (Noemi & William, 1994).

4.2 Maintenance Strategy Selection Methods

The Reliability Centered Maintenance (RCM) technique has been used extensively for maintenance strategy selection (Bevilacqua & Braglia, 2000, Mohan et al., 2004). “*RCM represents a method for preserving functional integrity and it is designed to minimise overall maintenance costs by balancing the higher cost of corrective maintenance against the cost of preventive maintenance*” (Crocker & Kumar, 2000). Within the RCM framework the RCM logic diagram is the tool used for selecting the most appropriate maintenance strategy for different failure modes of a system (Conachey, 2005, American Bureau of Shipping, 2004). However the use of RCM is a very time consuming exercise (Waeyenbergh & Pintelon, 2004) and this may be attributed to the excessive time that may elapsed for decision makers or maintenance practitioners to reach a consensus decision on every failure mode. Furthermore, the use of the RCM logic tree does not allow for ranking of maintenance strategy alternatives such that the optimum solution can easily be determined.

The use of different Multi-Criteria Decision Making (MCDM) tools such as AHP, Analytical Network Process (ANP) and TOPSIS has been reported in literature for addressing maintenance strategy selection problems for various industries. These techniques have either been applied individually or in combination with one another or they have been integrated with other tools such as fuzzy set theory and mathematical programming. Bevilacqua and Braglia (2000) used AHP in conjunction with Failure Mode Effect and Criticality Analysis (FMECA) principles to select the optimum maintenance strategy for each equipment item of an integrated gasification and combined cycle plant. The five possible maintenance strategy alternatives considered were; preventive, predictive, condition-based, corrective and opportunistic maintenance. Goossens and Basten (2015) used AHP in the selection of the optimum maintenance strategy for naval ship systems. The authors involved three different groups in the ranking of three maintenance strategies; corrective, time/use-based maintenance and condition based maintenance based on some decision criteria. The different groups within the maritime industry from which pairwise comparison judgements were obtained for the prioritisation of maintenance strategy alternatives were; shipbuilders, the owners/operators and the Original Equipment Manufacturers (OEM). The authors structured the decision problem in five levels. The first level (top) representing the goal (best maintenance strategy for naval ship), the second, third and fourth levels, representing decision criteria, consisted of two, eight and 29 decision criteria respectively while the fifth level (bottom) representing the three maintenance strategy alternatives. The optimum maintenance strategy as determined based on data from shipbuilder, owner/operator and the OEM was condition based maintenance.

Resobowo et al., (2014) presented the AHP technique in the ranking of the factors that affect military ship maintenance management. The factors the authors considered are; cost, availability, reliability, safety, human resource, operations, types of ship and ship characteristics. These factors were prioritised based on three decision criteria consisting of planned maintenance, preventive maintenance and routine maintenance. From the analysis, human resource was considered as the most important factor that affects military ship maintenance management. Other examples of the use of AHP for maintenance strategy selection are: Triantaphyllou et al. (1997) presented an AHP technique for the selection of an optimum maintenance strategy taking into consideration four maintenance decision criteria, Nyström and Söderholm (2010) proposed a procedure based on AHP for prioritising diverse maintenance strategies in railway infrastructure, and Labib et al. (1998) developed a methodology based on AHP for selecting the optimum maintenance strategy for an integrated manufacturing system. The limitations of AHP in addressing multiple criteria decision problems have been described in Section 3.1.2.

Bertolini and Bevilacqua (2006) presented a model which combines AHP with the Goal Programming (GP) technique for the selection of maintenance strategies for centrifugal pumps in an oil refinery. The methodology takes into consideration decision criteria such as account budget and number of man-hour constraints in selecting the optimum strategy from among three alternative maintenance strategies (corrective, preventive and predictive). The authors concluded that the methodology proved to be a viable tool for minimization of maintenance cost (Bertolini & Bevilacqua, 2006). In a similar study, Arunraj and Maiti (2010) used AHP and GP methods for the selection of the optimum maintenance strategy for a benzene extraction unit within a chemical plant. The decision criteria, on the basis of which optimum maintenance strategy was selected, are equipment failure risk and the cost of performing maintenance. The authors used AHP to determine decision criteria weights and the GP considered the assigned weights to rank the alternative maintenance strategies (corrective, time based, condition based and shutdown maintenance). The major improvement to the work of Bertolini and Bevilacqua (2006) was the use of the Fussell-Vesely (F-V) importance measure by the authors to calculate the different equipment items risk contributions to the plant. The introduction of goal programming increases the computation complexity of the decision making process as the decision makers or maintenance practitioners will require knowledge of programming. Zaim et al., (2012) reported the use of an hybrid MCDM approach based on the integration of AHP and ANP techniques for selection of an optimum maintenance strategy for a newspaper printing facility located in Turkey. From the comparative study, the two techniques yielded almost the same results.

The use of MCDM within the fuzzy environment has also been reported in literature for addressing maintenance strategy decision problem. Lazakis et al., (2012) presented a methodology based on a combination of fuzzy set theory and TOPSIS for the selection of the optimum maintenance strategy for a diesel generator in a cruise ship. The author ranked three maintenance strategy alternatives; corrective, preventive and predictive maintenance based on eight decision criteria; maintenance cost, efficiency/effectiveness, system reliability, management commitment, crew training, company investment, spare parts inventories and operation loss. Condition based maintenance (CBM) was considered as the optimum maintenance strategy for the cruise ship diesel generator from the analysis. In an attempt to improve the fuzzy-TOPSIS methodology, Lazakis and Olcer (2015) integrated AHP into it. The use of AHP was for the determination of decision criteria weights. The result of the AHP-Fuzzy-TOPSIS yielded preventive maintenance as the best strategy for the ship diesel generator maintenance. Al-Najjar and Alsyouf (2003) presented integrated fuzzy logic and AHP methods for solving pump station maintenance strategy selection decision problem. Wang et al., (2007) also used an integrated fuzzy logic and AHP technique to select optimal maintenance strategies for different equipment items in a manufacturing firm. However some doubts remain with regard to the practical use of the fuzzy approach because of the difficulty in testing and developing extensive sets of fuzzy rules (Zammori and Gabbrielli, 2012, Braglia, 2000).

5.0 MAINTENANCE INTERVAL DETERMINATION

After determining the type of maintenance strategy for each of the failure modes/components of an asset or plant system, the next assignment is to determine the interval for carrying out the maintenance task. This process is an essential phase of RCM. Different maintenance strategies have been discussed earlier for preventing or mitigating the effects of failure and these strategies are; corrective maintenance, scheduled overhaul, scheduled replacement, scheduled on-condition task (inspection) and continuous on-condition task. For the preventative maintenance approaches, different models have been developed by researchers for determining the interval for performing them and they have been applied in different fields with variations to suit specific industrial needs. However the basic principle for the determination of the interval is to have a balance between the cost of achieving the highest reliability and the cost of unexpected failure. In the subsequent sections the different models that have been developed by different researchers for determining intervals for (1) scheduled replacement and (2) scheduled on-condition task (inspection) are discussed.

5.1 Scheduled Replacement Interval Determination

Preventive maintenance involves repair or replacement activities being performed at regular intervals and, as such, scheduled replacement is one of the strategies used within the framework to recover the functions of an equipment item. Bahrami-G et al., (2000) defined scheduled replacement as a practice that involves making decisions, on the optimal time to replace an equipment item with respect to certain criteria with the aim of reducing or eliminating a sudden breakdown. Optimization techniques are used to define the appropriate interval for the replacement of an equipment item in order to have a balance between availability of the equipment item and the cost of the related maintenance. To justify the use of the technique, two conditions must be met. The conditions are: (1) the value of Weibull shape parameter β of the equipment statistical variability must be greater than 1 and (2) the cost of performing a replacement task as a result of failure must be greater than the cost of replacement under preventative mode. It therefore means that data on the failures of the equipment and related cost information are essential in order to ascertain whether or not there is the need for scheduled replacement to be carried out. This information is also required as an input into the replacement model in order to determine the optimum interval for the task. Once it is ascertained that scheduled replacement is the optimum option for performing the recovery or sustainment of items of equipment, the most appropriate interval is then determined. In the determination of the optimum interval for performing scheduled replacement tasks, two models are prominent and these are; the Age Replacement Model (ARM) and the Block Replacement Model (BRM) (Aven & Jensen, 1999).

In the application of the ARM, an equipment item is replaced at a predetermined age (t_p) or at failure. The implication is that if failure occurs before, t_p, replacement will be performed at failure otherwise replacement is carried out at a predetermined age. Additionally if an equipment item is replaced as a result of system failure, the replacement equipment is assumed to be as good as new and as such the maintenance practitioner would have to wait for another t_p to elapse before performing the next replacement. The universal ARM mathematical model, which is generally used for determining the appropriate time interval (t_p) for scheduled replacement, is the one that was proposed by Barlow and Hunter (1960) and it is represented as follows:

$$C(t_p) = \frac{C_a\left(1 - R(t_p)\right) + C_b R(t_p)}{\int_0^{t_p} t f(t)dt} \quad (3)$$

Where:
$C(t_p)$ is the cost function per unit time
C_a is the cost of unit failure replacement
C_b is the cost of unit scheduled replacement

t_p is the given scheduled replacement interval and
$f(t)$ is the probability density function
$R(t_p)$ is the Reliability function

The essence of this age replacement model is to evaluate cost of equipment replacement for different values of 't_p'. The value of $t_p$with the lowest cost is then chosen as the optimum replacement interval. Hence the main purpose of this model is to minimise the cost of replacement of equipment.

For the block replacement model however, equipment/components are replaced at constant time intervals and in the case of failure before the constant time interval has elapsed the equipment/components are replaced and will be replaced again once the constant time interval is attained. This type of replacement model can then result in unnecessary replacement of equipment/components. Hence the generally accepted perception is that the ARM is more cost effective than the BRM. Nevertheless the BRM can be applied for less expensive equipment items whose replacement can be carried out in a group. The only advantage of BRM over ARM is that BRM is easier to apply and manage since replacement is performed at regular intervals as opposed to ARM where the maintenance practitioner would have to consider the time for replacement at failure before knowing the exact date that the next preventative replacement will be performed. The general BRM mathematical model is the one developed by Barlow and Hunter (1960) represented as follows (Ahmad & Kamaruddin, 2012):

$$C(t_p) = \frac{C_b + C_a \,.\, N(t_p)}{t_p} \tag{4}$$

Where $N(t_p)$ is the number of failures expected in an interval of 0 to t_p. As in the case of ARM, the main purpose of this model is to obtain an optimum replacement interval at the least cost.

These models (ARM and BRM) and variations have been applied in solving replacement problems for both single unit and multi-unit systems in different industries.

5.1.1 ARM and BRM applications and improvement

Huang et al., (1995) proposed a standard solution for the ARM developed by Barlow and Hunter (1960). The standard solution was organised in the form of tables and charts for ease of use. Another novel idea for the solution is the reduction of input parameters by applying a cost ratio (ratio of C_a to C_b) in place of failure replacement cost (C_a) and preventative replacement cost (C_b). To demonstrate the suitability of the approach, various hypothetical examples were used. Cheng and Tsao (2010) applied the Huang et al., (1995) standard solution to obtain optimum replacement intervals for a rolling stock component. Das and Acharya (2004) presented two alternative techniques based on ARM for optimum replacement of equipment items which indicated signs of performance degradation but operated in that state for some random time before failure. Since the equipment item the authors investigated had a delay time which is the time between the point of equipment item failure initiation and the point at which the equipment item eventually failed, the concept was taken into consideration in the development of two replacement methods. The first technique recommends that replacement of equipment items whether at failure or in preventative mode is performed after a fixed time during its delay time. The second technique, which extend the first policy to opportunistic age replacement, recommends that a failing equipment item should be replaced at the next available maintenance opportunity. According the authors, the two policies although designed for a single unit system are capable of addressing a multi-unit system when there is difficulty in tracking the whole life of each individual equipment item. Jiang et al., (2006) examined the connection between the preventative effect associated with various replacement intervals and equivalent cost savings. The replacement models that the authors studied were ARM and BRM. The result obtained from the study shows that reasonable cost savings can be made if the equipment item is replaced when it has reached satisfactory age. The authors also opined that the often increasing failure rate of equipment or components does not necessarily translate to representing ‘satisfactory age’ and this has to be determined by the maintenance practitioners based on the maintenance goal.

Ahmad et al., (2011) used the basic ARM developed by Hunter and Barlow in evaluating the optimum replacement interval for a production machine. The significant feature of the approach was the consideration of the covariate effect on the life of the machine, in arriving at the optimum solution. The authors compared the result they obtained with the result of the existing model which did not consider covariate effect. From the comparative analysis, the replacement interval with covariate effect and the existing replacement interval without the covariate effect were at variance. While the replacement interval with covariate effect produced a 21 day interval for replacement of the production machine, the replacement interval without the covariate effect produced a 35 day interval for the replacement of the production machine. Bahrami-G et al., (2000) proposed a novel model for the scheduled replacement of an equipment item with an increasing failure rate. The technique proposed is a simplified version of the BRM developed by Hunter and Barlow. To demonstrate the applicability of the technique a case study of an equipment item whose failure rate followed a normal distribution was applied. The result the authors obtained from the model was almost exactly the same as the result from the method of Hunter and Barlow. They concluded that the proposed model will support maintenance practitioners to easily define optimum replacement intervals for plant systems for better productivity and cost minimisation.

From the above discussion, the majority of the methods for defining optimum replacement intervals for most systems, published in the literature are based on a single criterion. Furthermore, a number of them are too abstract requiring a high level of programming, mathematical and statistical skills which can limit their use in real life situations (Vatn et al., 1996, Duarte et al., 2006, Huang et al., 1995). Additionally, approaches based on a single criterion are neither reliable nor flexible for appropriate interval selection decision making (Gopalaswamy et al., 1993).

The essence of undertaking preventive maintenance is to reduce the chances of failure of plant equipment such that plant reliability and availability is optimised. The reliability of a system is dependent on the reliability of the individual components/equipment items that collectively make up the system and in order to achieve this aim, a suitable preventive maintenance and inspection programme should be in place (Duarte et al., 2006). A multi-criteria decision making method which combines numerous decision criteria may be more appropriate for solving a preventive replacement interval selection decision problem that involves a number of multiple conflicting decision criteria.

5.2 Inspection Interval Determination

One of the strategies used in Condition Based Maintenance for monitoring system performance degradation is the scheduled on-condition task and the inspection is carried out on plant systems with the aim of detecting potential failure and eliminating the failure to prevent further system degradation. The inspection task is performed on equipment items by maintenance practitioners or operators, basically with the use of handheld diagnostic tools and human intelligence. This technique nowadays is more commonly used by most industries for monitoring the condition of plant systems because it is less expensive than online monitoring or the continuous on-condition task. However the main challenge of the scheduled on-condition task is the difficult in determining the appropriate interval for performing the inspection task. This is generally due to the possibility of failure occurring between inspections if the interval is not properly timed (Jardine et al., 2006) which may result in irreversible damage to the image of the company. This makes the subject of inspection interval determination important and worthy of investigation. Traditionally, maintenance practitioners determined appropriate inspection intervals for their systems by relying merely on experience and/ or on the equipment manufacturers' recommendation and in most cases the results are far from being optimal (Christer et al., 1997).

The inspection task, as an alternative maintenance approach for equipment item maintenance, can only be beneficial if there is a sufficient period between the time that a potential defect is observed and the actual time of failure of the equipment. Hence the time that elapses between point of failure initiation, P, and the point of failure, F, is vital in estimating the appropriate inspection interval. The time that elapses between points P and F is referred to as the P-F interval (T_{PF}) within the RCM frame work and is illustrated in Figure 3.

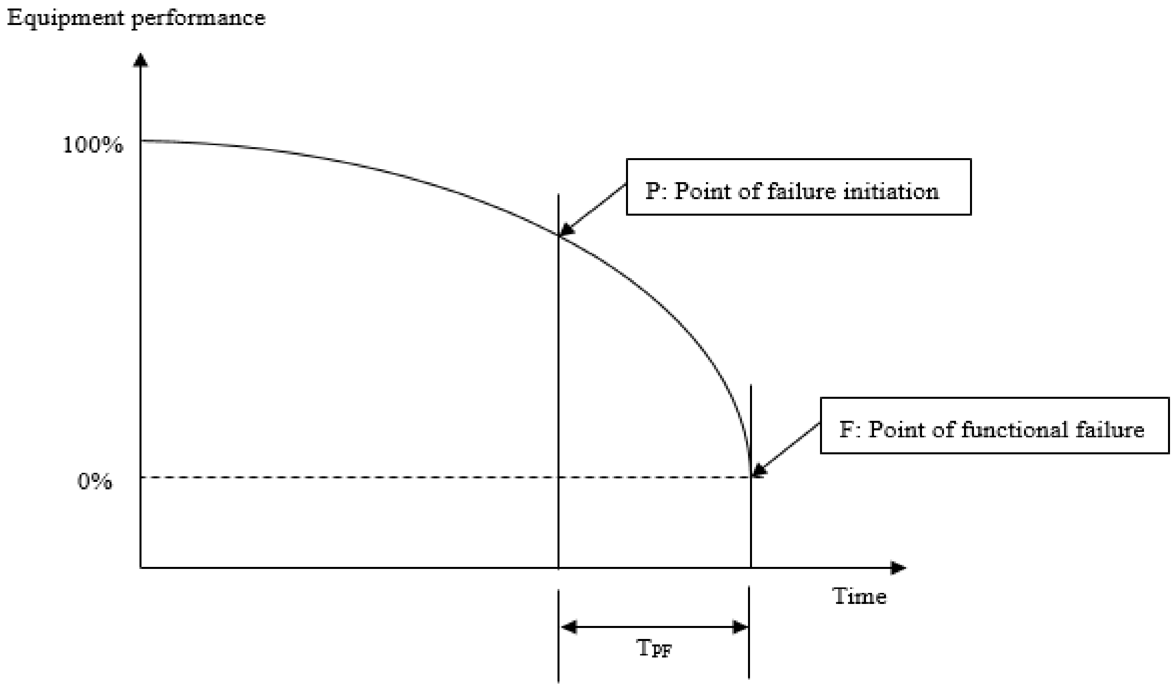

Figure 3. P-F interval (Rausand, 1998)

In RCM, the P-F interval principle is applied in determining the frequency of the condition monitoring of equipment and it was suggested that an inspection interval (T) be set at $T \leq T_{PF}/2$ (Arthur, 2005). The author however stated that one major challenge of the use of the P-F approach is that there is usually no data to evaluate the P-F interval (T_{PF}) and in most cases the evaluation is based on experts' opinion. Moubray (1991), on the other hand, suggested five ways of determining the inspection interval based on P-F but the author concluded that: "*it is either impossible, impractical or too expensive to try to determine P-F intervals on an empirical basis*".

Apart from this approach that is used in the conventional RCM, other approaches have been described in the literature for determining inspection intervals. In the majority of these methods, cost optimization is the main decision criterion for determining the inspection interval. Christer et al., (1997) proposed the Delay Time (DT) concept and this concept has been applied by many researchers in the modelling of the problem of inspection intervals. This approach has surpassed alternative techniques developed by other researchers for enhancing inspection intervals under different situations (Wang et al., 2010). The DT concept and its application in the modelling of inspection programmes is discussed next.

5.2.1 Inspection interval determination based on delay time

In the delay time concept the failure processes of plant systems are divided into two phases; the first phase is the time period from when the plant system is new, to the time that it starts displaying signs of performance degradation. The second phase commences when the system starts showing some sign of degradation and runs until the system finally fails.

The time that elapsed between when the plant system initially shows signs of degradation and when it eventually fails is denoted as the delay time of the system.
The Delay Time concept is essentially the same as the P-F interval principle described previously. The main difference between the two concepts is in the mathematical model used in determining the optimum solution for the inspection interval decision problem. The delay time concept is illustrated in figure 4.

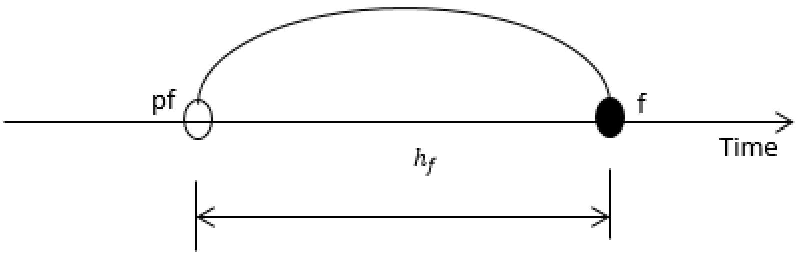

Figure 4. The Delay Time concept

In Figure 4, h_f denotes the delay time; pf denotes the time of plant system performance degradation initiation and, f, denotes the time that the plant system fails. The best time to carry out inspection tasks is during the delay time of the plant system.

The delay time concept was introduced by Christer (1982) and has been applied by many researchers for the determination of optimum maintenance inspection intervals for different industrial systems. Christer (1982) applied the delay time concept in the development of a cost model for building inspection maintenance. The model was utilised in determining an appropriate inspection maintenance plan for a complex building as an alternative maintenance strategy to the reactive approach. The following assumptions were made; (1) the cost function varied within the delay time period and (2) inspection is perfect. In determining the probability density function of the delay time a subjective method was proposed. On that basis the author suggested that information such as time of failure initiation and delay time of system parts should be obtained based on experts' (that is engineers and inspectors) estimates. A questionnaire developed for obtaining information from experts asked questions such as:
(1) For how long has it been since the fault was first observed (=HLA)?
(2) If repair or replacement is not performed, what duration of time could the fault stay before parts may or will eventually fail (=HML)?

The delay time is then evaluated for each fault as, h_f = HLA+HML. The distribution function $f(h_f)$ is therefore then obtained by observing a sufficient number of faults or defects.

Christer and Waller (1984a) developed two models based on the delay time concept for inspection interval determination for a complex industrial system. The two models; cost and downtime, were firstly developed with the assumption that inspection is perfect and secondly with the assumption that inspection is imperfect. The suitability of the models was demonstrated with some numerical examples. The limitation of the work is that only a single criterion is used to determine inspection interval.

Christer and Waller (1984b) then presented an inspection interval determination technique based on a combination of a delay time model and a snapshot model. The proposed technique was used to evaluate downtime consequences for every inspection interval such that the interval with the lowest downtime is selected for the system. To demonstrate the applicability and suitability of the method, a case study of a canning-line plant in a production company was used and data for the analysis was obtained subjectively through the administering of questionnaires. The method again is limited to the use of a single criterion in the determination of inspection interval.

Wang (1997) proposed a unique delay time methodology for determining optimum inspection interval for use in the face of insufficient data either in quantity or quality. This was achieved by developing a new technique for estimating delay time distribution from a combination of experts' judgements rather than using actual failure data. The proposed methodology was demonstrated through two case studies. From the results of the analysis it was concluded that the technique produces similar results to the existing method that uses actual failure data. In a similar study, Wang and Jia (2007) developed a method based on a combination of an empirical Bayesian-based technique with a delay time concept for determining the optimum inspection interval for an industrial boiler. The introduction of the empirical Bayesian model was to make it possible for the proposed technique to utilise both subjective and objective data. However only a single criterion was used to determine the inspection interval.

Arthur (2005) presented a delay time model for the determination of the optimum inspection interval for condition monitoring of an offshore oil and gas water injection pumping system. The purpose of the study was to produce a more cost effective inspection plan for the system than the current inspection regime of a one month cycle. From the comparative analysis it was revealed that the proposed delay time model produced an inspection interval of 5 months against the current interval of 1 month with annual cost savings of £21,000.

Tang et al., (2014) proposed a model based on the delay time concept for inspection interval determination for a system subjected to wear whilst taking into consideration the wearing characteristics of the system. A blowout preventer core and a filter element of an oil and gas drilling system were used to demonstrate the suitability of the proposed model. For the delay time concept based model, parameters were obtained from failure and maintenance data relevant to both components.

Pillay et al., (2001) used an expected downtime model based on the delay time concept for determination of optimum inspection interval for a fishing vessel. The technique was applied with the objective of reducing vessel downtime due to machinery failure that could occur between discharge ports. The suitability of the approach was demonstrated with a case study of the winch system. Reliability data was gathered to complement the with experts' opinions and used as input into the proposed model. The result of the analysis shows that an inspection period of 12 hours was optimum for the system. In the authors' approach, only a single criterion was utilised in the determination of inspection interval. The main highlights of this review paper are presented in Table 2.

Table 2. Summary of review

RCM major elements	Tools	Users/Authors	Merits	Demerits
Risk assessment	FMEA	Cicek and Celik (2013)	Computationally easy	Limited to use of only three criteria, allow only use of precise data, result may not be reliable
Risk assessment	AHP	Braglia (2000), Carmignani (2009)	Allows use of both quantitative and qualitative data	Unbalanced scale, limited to use of precise information
Risk assessment	PROMETHEE	Maheswara and Loganathan (2013), Ayadi et al., (2013), Moreira et al., (2009)	Allows use of multiple criteria	Challenges of determining preference function for each criterion, poor problem structuring
Risk assessment	DEMATEL	Seyed-Hosseini et al., (2006)	Failure mode severity effects & relationship between them are considered	Requires a lot of computational effort
Risk assessment	TOPSIS	Sachdeva et al., (2009)	Allows use of multiple criteria	
Risk assessment	FUZZY TOPSIS	Braglia et al., (2003)	Allows the use of multiple criteria	Computational complexity due to FUZZY logic
Risk assessment	AVTOPSIS	Emovon et al., (2014)	Allow both use of precise and imprecise information, allows the use of more than three criteria	
Risk assessment	VIKOR/CP	Emovon et al., (2015)	Use of more than three criteria	

Maintenance strategy selection	RCM logic tree	Crocker and Kumar (2000), Conachey (2005)		Time consuming, does not allowing ranking of alternatives
Maintenance strategy selection	AHP	Braglia (2000), Goosen and Basten (2015), Resobowo et al., (2014), Triantaphyllou et al., (1997), Nystrom ad Soderholm (2010)	Allows use of both quantitative and qualitative data	Unbalanced scale, limited to use of precise information
Maintenance strategy selection	AHP-GP	Bertolini and Bevilacqua (2006), Aruraj and Maiti (2010)	Allows use of multiple criteria	Requires high level of programming skills, computational complexity
Maintenance strategy selection	AHP-ANP	Zaim et al., (2012)	The ANP allows interrelationship between criteria to be considered	Computational complexity due to ANP
Maintenance strategy selection	FUZZY TOPSIS	Lazaklis et al., (2012)	Criteria weights methods determination not considered	Computational complexity due to FUZZY logic
Maintenance strategy selection	AHP-FUZZY TOPSIS	Lazaklis and Olcer (2015)	Allows use of both quantitative and qualitative data, criteria weights not assumed.	Computational complexity due to FUZZY logic
Maintenance strategy selection	FUZZY-AHP	Najjar and Alsyouf (2003), Wang et al., (2007)	Allows use of both quantitative and qualitative data	Computational complexity due to FUZZY logic,
Scheduled replacement interval determination	ARM	Huang et al., (1995), Barlow and Hunter (1960), Cheng and	More cost effective than BRM.	Only a Single criterion is considered, More costly to implement

		Tsao (2010), Jiang et al., (2006), Ahmad et al., (2011)		than BRM
Scheduled replacement determination	BRM	Barlow and Hunter (1960), Bahrami-G et al., (2000), Jiang et al., (2006)	Easier to determine and implement	Only a single criterion is considered, approach is not cost effective
Inspection interval determination	P-F interval principle	Rausand (1998)		Impractical to determine P-F interval, Not possible to consider multiple criteria simultaneously
Inspection interval determination	DTM	Christer (1982), Christer and Waller (1984a), Christer and Waller (1984b), Christer et al., (1997), Wang and Jia (2007),Wang et al., (2010), Arthur (2015), Tang et al., (2014), Pillay (2001)	Result more reliable than of the P-F approach	Not possible to consider multiple criteria simultaneously

From Table 2 it is obvious that the approaches used by the different authors in solving maintenance problems within the framework of RCM all have one limitation or another. Hence there is a need for researchers to develop alternative approaches that avoid the limitations of the current approaches. For example, approaches used in the determination of scheduled replacement intervals and inspection interval determination mainly use single criteria however in real-world situations multiple-criteria are generally involved in the decision making process. These criteria are in conflict with one another in most cases and in such circumstances, the use of MCDM tools such as MAUT or PROMETHEE may become imperative for simultaneously prioritising maintenance interval alternatives.

6.0 CONCLUSIONS

In this paper a thorough literature survey was conducted with respect to providing relevant information pertaining to the need for researchers to develop more efficient tools within an RCM framework for application to plant systems in order to make the systems safer and more reliable. To achieve this aim, the three major elements of maintenance systems; risk assessment, maintenance strategy selection and maintenance interval determination were discussed in detail and for the risk assessment a particular focus was on FMEA, its variants and their corresponding limitations. For the maintenance strategy selection, the three types of maintenance strategies; corrective maintenance, preventive maintenance and condition based maintenance were presented. A survey of methods used by previous researchers for the selection of the appropriate maintenance techniques was considered together with associated limitations. For the maintenance interval determination, the discussion was centred on scheduled replacement and scheduled inspection types of maintenance with respect to current approaches and limitations of these approaches. From the review it was obvious that some of the tools and the variants utilised within the framework of RCM for the optimisation of the three main elements of maintenance systems have limitations and there is a need for researchers to develop alternative approaches that avoid such limitations.

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