Chapter 1: Prologue

1.1. Introduction

With the advent of the Reliability Centred Maintenance (RCM) methodology, a new chapter in the history of preventive maintenance strategy setting began. One could now develop a scientifically based and highly successful maintenance program for a complex system, such as an aeroplane. The success of the application of RCM can be seen in the relatively low incidence of critical failures in modern day passenger aircraft. Part of the success is of course attributable to better design, but even that was influenced considerably by the RCM analyses that took place. This success story was and is being repeated in the design of maintenance programs in general industry.

The initial success of RCM led to the further development of the technique. The original MSG-1, which was the version applied first in the airline industry, was soon replaced by MSG-2. Nowlan and Heap (1978) was later commissioned by the US Department of Defence to publish a full user manual based on this version under the name Reliability Centred Maintenance. The airlines' version was subsequently updated to MSG-3, which is now in its second revised form [MSG-3 (1993)]. Moubray (1991) introduced a version called RCM II, which is being marketed world-wide. Others are simplifying the technique to make it more palatable, whilst some firms are selling software based on the principles of RCM, not all of which results in correct RCM analyses [Moubray (2000)].

In academic circles right across the globe there is dissatisfaction with the technique [Pintelon et al (1999)]. A part of this dissatisfaction stems from the bad image RCM consultants have given the technique by watering down its scientific basis to suit their own marketing ends [Moubray (2000)]. Even respected RCM practitioners like Moubray (1991) and Smith (1993) are guilty of this practice, as is expounded further on in this thesis. On the other hand, at least part of the dissatisfaction is based on perceived inherent scientific weaknesses in the methodology itself. This dissatisfaction led to Ph.D. theses such as 'On the maintenance concept for a technical system - a framework for design' [Gits (1984)] and 'On the selection of elementary maintenance rules' [Geurts (1986)].

The premise of this thesis is thus to do fundamental research into the RCM methodology and related techniques, with the purpose to develop a methodology without the shortcomings of present day RCM.

1.2. Mission

Historically, the RCM methodology has developed as a result of the reliability problems and cost of maintenance of aircraft during the late 50's and early

60's. The result was a methodology called MSG-1, which soon evolved into the improved MSG-2. Through the contractual use of MSG-2 for the United States Department of Defence, the present definition of Reliability Centred Maintenance (RCM) evolved.

There is a marked difference between the application area, for which RCM was originally developed and general industry. It was originally intended for use with equipment (aircraft and military machinery) that are developed using stringent user specifications, and which undergoes strenuous testing. The requirements in general industry, where equipment are developed and installed expeditiously and problem areas often has to be resolved later, necessitates certain changes in the application of the technique.

Problem areas, which are identified in chapter 2, include the perception that the technique does not have a proper scientific base, problems in the application of the technique, problems in the definition of RCM and the fact that other techniques are developed by opponents of RCM. All of these and the ensuing debates cause confusion amongst maintenance practitioners, which should be resolved in the interest of suitable maintenance results.

RCM has also not developed much since its conception [Nowlan and Heap (1978)], apart from a few RCM textbooks with relatively small detailed changes to the technique [Moubray (1991), Smith (1993) and Coetzee (1997/2)]. Changes that are more fundamental have been proposed by MSG-3 (1993), but these have not been carried through into the main body of RCM. There is consequently a great need for the consolidation of the contributions of different authors, as well as some further development of the technique to resolve most of its shortcomings.

1.3. Framework

The number of publications that only mentions RCM as a very agreeable reference is quite numerous. On the other hand, the number of publications that specifically addresses the development and use of RCM is limited.

The major and groundbreaking work in the introduction of RCM was the report commissioned by the United States Department of Defence under contract from United Airlines. This work was called Reliability Centered Maintenance [Nowlan and Heap (1978)], in line with the name given to the technique by the Department of Defence.

This introduction to the methodology, followed by presentations at maintenance conferences world-wide, led to a number of early adopters of the technique and eventually led to RCM texts that were more user friendly towards the typical industrial user. These include Moubray (1991), Smith (1993) and Coetzee (1997/2).

In the meantime, other authors for various reasons developed alternatives to RCM. These ranged from the belief that RCM is too complex to problems with the scientific base of the method. These include Gits (1984), Jones (1995) and Kelly (1997).

Developments and research in RCM was limited to the changes suggested in MSG-3 (but not implemented in RCM) and the suggestions in some of the publications mentioned in the previous two paragraphs. The only exception to this rule is the work of Harris (1985), which suggested some fundamental changes that were not taken note of by the maintenance community.

Another important development was the introduction of the SAE standard for the application of RCM [SAE JA1011 (1999)].

1.4. Outline

This thesis follows the somewhat familiar scheme of *firstly* defining the problem area(s) to be addressed, *then* studying the literature on RCM and related techniques, *followed by* the development of the methodology to alleviate as much as possible of its limitations and the problems encountered in its application. The improved methodology is *then* tested on a typical industrial problem and compared to the outcome of 'classical' RCM. *Lastly*, the proposed methodology is evaluated, some conclusions drawn and follow-up research recommended.

Chapter 2 is devoted to the identification of the limitations and shortcomings of RCM and the definition of the scope of the task at hand. This was elucidated in paragraph 1.2.

The literature survey, which is done in chapter 3, follows the general structure of the methodology as proposed by Nowlan and Heap (1978) and which was followed by most authors on the subject [e.g. Moubray (1991) and Coetzee (1997/2)]. The structure is:

i. The principle behind RCM: preserve function or preserve equipment?
ii. The selection of application areas for RCM
iii. Information Assembly
iv. Identification of Failure Modes
v. Prioritisation of Failure Modes
vi. Classification of Failure Modes
vii. Task Selection
viii. Task Frequencies
ix. Task Packaging
x. Critical assessment of the resulting program

The new proposed RCM methodology is developed in chapter 4. It *firstly* studies the technique from the viewpoint of the different authors on the subject, using the same ten component structure introduced above in the outline of chapter 3. *Secondly,* these components are integrated into a single methodology and *thirdly*, the way of using the methodology to the benefit of the typical industrial organisation is addressed.

In the development of the proposed model's components, use is made of the best work of sources such as Nowlan and Heap (1978), Moubray (1991), Smith (1993) and MSG-3 (1993). Newer work and related work, such as that found in Gits (1984), Harris (1985) and Coetzee (1997/2) are also taken into account.

The proposed methodology is integrated with the more intuitive methods of Maintenance plan design such as Business Centred Maintenance [Kelly (1997)], equipment manufacturer's recommendations, statutory requirements, NOSA standards and HAZOP studies. It is also placed in context with the various maintenance task classifications such as preventive vs. corrective vs. design-out maintenance, scheduled vs. unscheduled work and planned vs. unplanned work.

In chapter 5 the proposed model is tested, using a high-risk chemical pump system as test bed. The system's failure history is analysed in full operational context, using the improved methodology. This leads to a proposed maintenance plan for the system.

This proposed maintenance plan is critically compared against a 'classical' RCM analysis done previously for the same system. The proposed methodology is found to be superior to the classical approach, leading to a more focussed, proactive and concise maintenance plan.

Finally, chapter 6 is devoted to the critical assessment of the result of the thesis as embodied in chapters 4 and 5. This comparison is made against the following five baseline references:

1. 'Classical' RCM as embodied in the SAE Standard JA1011 [1999]
2. 'Classical' RCM as embodied in the various RCM texts[1].
3. MSG-3 (1993), the latest version of the airlines' methodology.
4. The method of the Technical University of Eindhoven {Gits [1984, 1988 and 1992] and Le Clercq & Van den Broek [1999]}.
5. The method of Anthony Kelly {Kelly [1997]}.

It also recommends that certain follow-up research/work needs to be done, which would lead to further enhancing and improving the RCM methodology.

[1] Nowlan & Heap [1978], Moubray [1991], Smith [1993], Coetzee [1997/2].

Chapter 2: Problem Definition

2.1. RCM – A Definition

Before analysing the problems with the present versions of Reliability Centred Maintenance in some detail, it is expedient to give a short definition of the technique. In the next paragraphs and chapters, the question will often repeat itself in the mind of the reader: what version of RCM are we talking about, and: what is included in this version?

Because there is quite some difference of opinion regarding the structure and detailed techniques of RCM amongst different authors writing on the subject, this thesis will in general refer to the original definition as penned by Nowlan and Heap [Nowlan and Heap (1978)] as being Reliability Centred Maintenance. Any discussion of the various add-ons will be specifically referenced, quoting the source.

The original version of RCM consisted of the following steps, which are deemed to be part of this definition:

- System breakdown
- Identification of Maintenance Significant Items (MSI's)
- Identification of Functions of MSI's
- Identification of Functional Failures per Function
- Identification of Failure Modes per Functional Failure
- Evaluation of Failure Consequence per Failure Mode
- Task Evaluation and Selection

This definition certainly has many inadequacies, as is clear by studying the work of the various authors active in this area. But, it is good to develop the further discussion around this (simplest) definition as a base-line.

2.2. Historic Review

The roots of the maintenance discipline lie in the inability of mankind to design, build and operate production equipment without failure taking place. Because the production process causes wear and stress to production equipment, failure is an unavoidable consequential effect that makes maintenance such an inseparable part of the organisation.

Over the decades following the industrial revolution, a basic approach to the management of the failure problem was slowly evolving. Apart from efforts to improve the design of components, with the objective of improving the reliability of equipment, a philosophy was developing which had as its underlying principle that failure will not occur as long as the equipment was being kept as good as new. This was to be achieved through regular, mostly time based, replacement and overhaul of critical components and sub-systems. At the root of this thinking was the bathtub curve concept, which stated that the force of mortality (f.o.m.) curve remains constant over most of the life of a system / sub-system / component and then starts to increase in the so-called 'wear-out' zone. This was based on research done on the failure patterns of electronic components [Smith (1993), p. 44] during the 1940's and 1950's. If one could thus overhaul the equipment or parts of the equipment to the as-good-as-new state before entering this zone, the inherent reliability of the equipment could be restored and failure would thus be curtailed.

This thinking also prevailed in the commercial aviation industry. When the McDonnell Douglas DC-3, as maybe one of the best example of a highly successful pre-RCM commercial passenger aircraft, was being licensed for commercial use in the 1930's, very little information was available regarding the failure patterns of the plane's components [Jones (1995), p. 2]. Because public safety was a major concern, a very conservative maintenance approach was followed based on the regular (three-yearly) disassembly and detailed inspection of each aircraft.

The same approach was followed in general industry. Because of the dangers inherent to the use of equipment (boilers, pressure-vessels, rotating machinery, reciprocating machinery, conveyor belts, high voltage switchgear and the like), maintenance was to a large extent regulated through statutory requirements prescribing regular instances of equipment being dismantled for inspections and tests. This reinforced the idea in maintenance people's minds that regular reconditioning of equipment is beneficial to the condition of the equipment and thus to the production process.

This necessarily resulted in the maintenance of production equipment being very expensive. Because of the simplicity and relatively high inherent reliability of many of the designs involved, this strategy produced satisfactory results (apart from being expensive, but that was excepted as the norm). And while technology developed and designs improved, maintenance thinking remained stuck to the idea of the bath-tub curve and had no solution for the ever spiralling cost and unsatisfactory results from the largely time-based maintenance strategies that were being pursued.

Getting back to the commercial aviation industry, aircraft designs was getting more and more sophisticated in terms of speed, range and passenger capability. Building on the known base of maintenance wisdom, the expertise and specialised equipment needed to do the myriad of shutdowns / inspections / overhauls were getting more expensive and hard to come by. Moreover, the results were not commensurate with the effort put in. One advancement that was made during this period, was the introduction of continuous condition monitoring equipment to aircraft systems – this now allowed maintenance to be based on need, as well as on schedule [Jones (1995), p. 3].

By the late 1960's the commercial aviation industry was ready to enter a new era – that of the jumbo plane. The Boeing 747 was being built in Seattle. However, the sheer size of the aircraft and its complexity made it a safety nightmare, should it not be maintained in the correct way. The Federal Aviation Administration (FAA), who has to approve the aircraft before it can be sold, took the stand that preventive maintenance on the 747 will be very extensive [Matteson (1989)], putting a question-mark on the commercial profitability of the aircraft. This led to the commercial aviation industry, led by United Airlines[1], undertaking a complete re-evaluation of the principles involved in the typical maintenance strategies of the day.

The results of this investigation revolutionised the way in which the commercial aviation industry approached the maintenance of aircraft. Firstly, the result of the actuarial studies based on the accumulated operating history database of the operating experience of commercial carriers showed that the bathtub curve does (in 89% of the cases) not adequately represent the failure patterns of the components used in aircraft at that time. Secondly, a group named Maintenance Steering Group 1 (MSG-1), consisting of representatives from the airlines, the manufacturers and the FAA, was set up to devise a methodology for designing maintenance plans for commercial aircraft. The result of this group's work was embodied in a document named MSG-1: Maintenance Evaluation and Program Development, which was subsequently approved by the FAA. A Lockheed official commented: "These guidelines provided the first formalised breakthrough in establishing new criteria for maintenance programs. They replaced maintenance concepts that had been in use for almost 40 years." [Jones (1995), p. 4].

MSG-1 was so successful that a second steering group, Maintenance Steering Group 2 (MSG-2) was commissioned to improve and generalise the MSG-1 instrument to develop similar maintenance programs for other aircraft. The resulting methodology was used for the maintenance programs of the McDonnell Douglas DC-10 and the Lockheed L-1011. In 1980 MSG-2 was updated by a similar steering group and embodied in MSG-3: Airline/Manufacturer Maintenance Program Planning Document, which was used to develop the maintenance programs for aircraft such as the Boeing 757 and Boeing 767. Modified MSG-3 documents were used to develop the maintenance programs for the Concorde, the various Airbus planes and the Boeing 737-300/400/500. In all cases, the resultant maintenance programs are deemed extremely successful and cost-effective.

Because of the success achieved with the maintenance program implemented for the Boeing 747, the United States Department of Defence contracted

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[1] United Airlines has throughout the 1960's been at the forefront of an investigation into the reasons for doing maintenance and the best ways to accomplish it. People like Bill Menzer, Tom Matteson, Stan Nowlan and Harold Heap, all United Airlines employees at the time, took the lead in this effort [Smith (1993), p. 48].

United Airlines to develop similar maintenance programs for the Navy P-3 and S-3, as well as the Air Force F-4J aircraft. These were so successful that the U.S. Department of Defence directed in 1975 that the MSG concept should be applied to all major military systems and be named "Reliability-Centered Maintenance"[2] [Smith (1993), p. 48]. To facilitate this, United Airlines was contracted to write a manual for use in these pursuits [Nowlan and Heap (1978)].

RCM was subsequently used in the development of maintenance programs for all major military systems of the U.S. Department of Defence and has since the early 1980's been proclaimed as one of the primary developments in the maintenance world at maintenance conferences world-wide. This led to a plethora of consultants offering RCM services to the maintenance community, without much beneficial effects at the ground level. One of the notable exceptions must be Anthony M. Smith [Smith (1993)] and Thomas D. Matteson [Matteson (1989)] (the major innovator and force behind MSG-1), who were contracted by the Electric Power Research Institute (EPRI) to carry RCM into the American Power Industry. This has also had an impact in ESKOM.

Although many organisations will claim that they use RCM, such claim mostly means that they have spent substantial amounts in training and hiring consultants and that they have dabbled with RCM. It certainly, in nearly 100% of the cases, does not mean that the organisation has a RCM living program [Smith (1993), p. 188] in place. This is one of the areas that need to be addressed if RCM has to make a positive contribution to the well being of industry.

2.3. The scientific basis of RCM

There are two major problems with the application of RCM. The first of these is that some maintenance people are strong proponents of the technique, whilst others are strongly anti-RCM. It is often difficult to find out what problems people falling in the second category have with the technique, apart from the cursory claim that 'the technique is unscientific'. Moreover, ask them what the alternative is and they will murmur 'use general reliability principles', without any reference to the difficulties involved in practising such principles in the

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[2] The name 'Reliability Centered Maintenance', give to the technique by the United States Department of Defence does not imply the strict definition of the word 'reliability'. The term 'reliability' referred to here represents the idea that an equipment's failure conduct should be predictable, as opposed to the strict definition (probability of survival), which is a design outcome. Reliability can, as such, not be influenced by the maintenance program, apart from 'managing' the failure process as well as is possible.

Nevertheless, it is understandable that this choice of name was made, as for both the airline operators and the Department of Defence *mission reliability* is of utmost importance. That is, the probability that the mission will be completed successfully and safely is of paramount importance - thus the choice of name.

When Nowlan and Heap (1978) talk of Reliability, they are really referring to predictability of mission outcome. The average maintenance practitioner also calls such peace of mind 'reliability'.

average production concern without the structure afforded by RCM. The second problem is that there are a large number of unreliable 'consultants' who, while selling RCM programs, violate the very principles of the technique. This has given RCM a bad name in many parts of industry. In addition, many of the opponents of RCM have it specifically against the unscientific approaches and methods of these so-called RCM experts. It is thus very important to state whether you are referring to the Nowlan and Heap [Nowlan and Heap (1978)] definition or to which one of the alternative definitions when making statements regarding the scientific basis of RCM.

Many of the opponents of RCM come from the broad Operations Research community. They make a living through the development of mathematical models for maintenance strategy setting. For them, it is heresy to imply that you can formulate maintenance strategy without detailed mathematical analysis, using a mathematical model of some sort. Very often, this is due to a lack of understanding of the maintenance problem. Due to a lack of failure data, it is often not viable to apply mathematical modelling in maintenance strategy setting. Furthermore, the maintenance problem includes factors (such as the behaviour of people and the interfaces between systems/equipment/components) that cannot be adequately modelled using mathematics only and where responsible managerial discretion and synthesis plays a major role. Of course, one should analyse failure data, as far as is possible, to further proper understanding of the failure process. In the same sense, one should also investigate the physical evidence surrounding the failure and discuss the failure with maintenance and operational personnel to get a full understanding of the failure situation. Furthermore, it is also true that one has a problem in quantification if you do not have sufficient numerical data (it will, for instance, be virtually impossible to specify a use based maintenance task without quantification).

The problems mentioned in the previous paragraph are however not indicative of unscientific methods. Certainly the scientific basis of any method or technique depends on whether its different components are based upon premises, which were properly researched and tested, and were found to work. In both cases, RCM passes to the test of being scientific. Referring to the results achieved by the airline industry, one cannot but conclude that the methodology produces excellent results [Smith (1993), pp. 52, 53]. During the period from 1964 to 1987 the percentage of components allocated to time based maintenance have dropped from 58% to 9%. In the same period the percentage of components left to fail before maintenance action increased from 2% to 51%. In a study of comparing the first 10 years of RCM use (1970 to 1980) with the last years of pre-RCM operation, it was revealed that the maintenance cost per flight hour remained virtually constant. This is a miracle, taking into account the increase in sophistication and in the carrying capacity per flight hour (the fuel cost per flight hour has more than quadrupled in the same period). This is conclusive evidence that the maintenance strategies produced by RCM produces the required results (of course in combination with improvements in design which included many redundancy features, which results in lower levels of preventive maintenance).

The original treatise on RCM [Nowlan and Heap (1978)] can in a sense be regarded as being incomplete. In reading through the book, one gets the feeling of things being amiss, that the technique has not been fully developed. This may lead to the idea that the technique is unscientific. But this is certainly true of many new developments. Parts of the technique might even have been empirically derived, but the fact is that it reflects the realities of the maintenance problem in such a way that it's proper application leads to an optimal maintenance program. But, if you really work through Nowlan and Heap (1978) and get a grasp their own personal views of reliability modelling, and its effect on maintenance programs, one cannot but come to the conclusion that they were serious reliability practitioners. They certainly had a lack of understanding of some important issues that is understood today, for example the difference between wearout (IFOM[3]) and Reliability Degradation (increasing ROCOF[4]). But then, most reliability practitioners do not even understand it today [Ascher and Feingold (1984)]. It is also true that there are gaps in RCM, which should be filled in. The objective of this thesis is to make a meaningful contribution in this regard.

Nevertheless, many of the applications of RCM are certainly unscientific. Because the basic premises of RCM are not properly understood, fundamental changes are often made to the technique to make it simpler and more palatable. These changes undermine the scientific basis of RCM. Examples are both Moubray's and Smith's insistence on not applying failure data analysis when making choices regarding maintenance tasks [Moubray (1991), pp. 218-223], [Smith (1993), pp. 102, 103]. In both cases they side-step the issue. Even MSG-3 (1993) suffers from this. Another example is that of 'Streamlined RCM', which degrades the methodology to a mere decision tree approach [Moubray (2000)].

2.4. Problems in the application of RCM

Problems in the industrial application of RCM stem from misapplication rather than being due to some inherent scientific weakness in the method. The problem areas include the following:

- The application of the RCM technique to design a maintenance plan for the organisation too often leads to either a design task which becomes so large that it is abandoned; or the end result presents the organisation with such a high preventive work load that the RCM technique is discredited [Coetzee (1997)].
- Training: to be able to apply the RCM methodology with success, the analyst should be fully conversant with failure analysis methods, including both physical and statistical failure analysis techniques. The objec-

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[3] Increasing Force of Mortality (increasing Hazard Rate)

[4] Rate of Occurrence of Failures (or Failure Rate)

tive is that he/she should be able, through analysis, to understand the failure mechanisms through which failure takes place. In most cases, this is not true of the typical person(s) doing the analyses.

- A living RCM program: when an organisation decides to use RCM as the methodology for designing its maintenance plan, it should commit itself to a process of continuous improvement regarding its maintenance program. The first application of RCM provides the baseline definition of the preventive maintenance program, which should be continually improved [Smith (1993), p. 188]. Most organisations currently implementing RCM either sees it as a once off effort (one of the fads that should be tried) or loses the will to persevere when the going gets tough (to implement RCM successfully needs stamina).

- The will to change: the fact that an organisation's management initiated a RCM-analysis does not imply that they are fully committed to the change in ways that will be required to make a success of the process. They may see it as a cure-all that will solve all their maintenance problems without too much effort from their side. It is a fact that they, together with their employees, must achieve a high level of change in thought and practise, to be successful in using the technique. These changes include [Smith (1993), p. 173]:

  - A change of mind set from one where preservation of equipment is at the centre of the maintenance drive to one where the preservation of system function is at the centre. This is a critical shift in thinking which produces a maintenance plan that serves the goals of the organisation instead of an approach that maintains machinery regardless of their worth to the production process.

  - Achieving the buy-in of the total operations and maintenance staff of the organisation. The plan must be seen as the right way to go and people must believe that, when maintenance is done that way, similar results to that in commercial aviation will be forthcoming.

  - Setting up new task procedures for the proposed RCM tasks and the training of personnel in the successful execution of these tasks. The thought processes of the RCM analysts regarding the why of the tasks as well as the how should be embodied in these procedures.

  - Accepting that the new RCM program will in all probability have a significant short-term money impact on the organisation. One of the effects of the introduction of RCM is that Condition Based Maintenance will play a major role in the organisation in future - the majority of preventive tasks will be Condition Based. This may have capital implications regarding the purchase of measurement instruments, personnel implications, training implications and so forth. Furthermore, existing use based maintenance tasks will be affected through scrapping, modification or the extension of intervals. This will have an effect on labour requirements (mainly in the form of skill adjustments) and material requirements (in the form of new equipment/tool requirements and the reduction of stock levels).

- Existing preventive tasks that are regarded as sacred cows may have to be scrapped. This includes negotiations with government agencies (regarding statutory effects), OEM's (regarding guarantee/warrantee effects) and insurance companies where necessary. The high esteem with which employees regard these tasks should not be underestimated, as this endangers achieving their support for the RCM-derived maintenance program.

It is clear that one cannot approach RCM implementation in a haphazard way. There is much at stake, both on the cost and the income sides. The results of proper application are high gain (as can be seen in the airlines' example), but that is only to be achieved at a price. In most of the current industrial applications, this commitment is sadly lacking.

2.5. Problems in the definition of RCM

Most authors on the RCM methodology agree that RCM broadly consists of failure mode selection, maintenance task selection, task frequency selection and task packaging. But then authors, such as Smith [Smith (1993), p. 58], specifically exclude some of these steps from the definition. In Smith's case, the last two steps are regarded as not being part of RCM, although he includes these in his simple example of swimming pool maintenance [Smith (1993), chapter 6], which seems to contradict his argument that RCM only consists of the first two steps. Coetzee [Coetzee (1997/2)] includes the first three steps, but omits the last one (task packaging).

One can of course argue that it is not part of the mandate of RCM to involve itself in the organisation of the maintenance task load. However, the methodology must lend itself to relative ease of application in industry. Doing an RCM analysis without having the output in a format that it can be readily applied does not promote the application of the technique.

One of the major problem areas in the industrial application of RCM is that the technique is too cumbersome to apply to all equipment in a production concern. This is where many of the modifications of the original RCM-concept go wrong. To address this problem, the analysis process is simplified to spend less time on analysis. This is self-defeating, because the primary object of RCM is analysis with the view to achieve an optimal maintenance program. The correct way is to decrease the number of components for which the analysis is done. Some suggestions in this regard were made by Coetzee [Coetzee (1997/2), pp. 84 and 87] and Smith [Smith (1993), p. 58]. These will be further discussed in chapter 4.

Lastly, there are many diagrams and sub-processes of RCM that can be improved substantially. This includes many of the analysis formats that have evolved over time – often there are even alternative choices available. Nevertheless, these do not present a unified methodology that the average user of RCM can use with ease and confidence.

2.6. Related techniques

There exist a number of alternative techniques for the design of maintenance plans. Only the last of these was developed specifically for maintenance plan design.

2.6.1. Failure Modes and Effects Analysis (FMEA)

Failure Modes and Effects analysis was developed as a design tool. The purpose of this reliability-engineering tool is to systematically evaluate system and design weaknesses that could lead to unreliability, with the objective of design improvement to eliminate these weaknesses or reduce their negative effects. RCM was developed around FMEA as a basis. FMEA thus forms an integral part of RCM. On the other hand, the FMEA technique can be used on its own as an alternative method for the development of a maintenance plan, but such plan will be severely limited regarding the quality of the result due to the limitations of FMEA (having been developed as a design tool). The added functionality in the RCM methodology was specifically developed to address these limitations.

2.6.2. Failure Modes, Effects and Criticality Analysis (FMECA)

The FMECA technique comprises the FMEA technique with the addition of the Criticality Analysis part. The failure modes are evaluated regarding their relative criticality, assigning a criticality value to each. These criticality values are then used to prioritise the various Failure Modes, consequently focusing the design improvement process.

Some RCM users prefer to use FMECA, instead of FMEA, as the heart of RCM. The RCM process of failure mode evaluation is a type of prioritisation process to ensure that the analysis emphasis is placed on the right failure modes during the task selection process. FMECA thus provides a focussing input, namely the criticality of the failure mode, which can be utilised to give more prominence to and spend more time on critical failure modes in the task selection process. This focussing input is additional to the two suggested by Coetzee [Coetzee (1997/2), pp. 84 and 87].

Jones [Jones (1996), p. 204] suggests that a calculated risk value be used to replace this criticality value to focus the analysis input.

2.6.3. Maintenance Concept Design

The Technical University of Eindhoven (TUE) developed their own approach towards the design of a maintenance plan [Gits (1984)], [Gits (1992)]. TUE classifies the approach as being a 'satisficing' approach as compared to the qualitative approach of RCM. Due to the higher complexities of equipment, there is an ever-growing need to improve the control over the maintenance function. This presents one with the need for better maintenance "concepts" (plans), according to Gits (1992).

Where RCM selects tasks based on "applicability" and "effectiveness", the Maintenance Concept (MC) approach uses five criteria for the selection of tasks [Gits (1992)]:

- Effectiveness (equivalent to RCM applicability)
- Efficiency (equivalent to RCM effectiveness)
- Safety Impact
- Continuity Impact (impact on the continuity of production)
- Controllability (of maintenance)

TUE uses a two step method to develop a maintenance plan [Gits (1992)]:

- Setting up maintenance rules (they call maintenance tasks 'rules') – this is a procedure, which addresses the elementary maintenance needs. It consists of six steps:
  - The choice of maintenance rules
  - Detailing of maintenance rules
  - Limiting the maintenance frequency
  - Aggregation of maintenance rules
  - Harmonisation of maintenance intervals
  - Grouping of maintenance rules in blocks
- Evaluation of maintenance rules
  - Cost effectiveness of maintenance concept
  - Performance of maintenance concept
  - Regularity of maintenance demand (balancing the load)

The TUE method seems to be weaker than RCM in general[5] (this may in part be due to the lack of detailed descriptions of the method). Nevertheless, it has a very strong methodology for packaging the maintenance plan, consisting of various steps to achieve maximal task synchronisation and grouping (the first main step of the methodology). It also has features for ensuring that the resultant total plan will be performance effective, as well as cost effective and will result in a load-balanced program (the second main step of the methodology).

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[5] The TUE method, when compared to RCM, has the following shortcomings [Gits (1984)], [Gits (1992)], [Le Clercq & Van den Broek (1999):

a) It has no provision for the identification of the equivalent of Maintenance Significant Items.
b) It has no proper replacement for the FMEA process.
c) It's maintenance task selection process is not well thought through and can result in wrong /non-optimum tasks being selected.
d) The shape of the Force of Mortality (FOM) curve is guessed.

The first step in the maintenance plan design process, preceding the choice of maintenance rules [Gits (1984)] consists of the analysis of the technical system. This has three components:

- Failure behaviour analysis – a functional decomposition of the production function, identifying PFC's (Process Failure Combinations).
- Failure consequence analysis – identification of the consequences of each PFC.
- Hardware Structure Analysis – identification of plant/business asset/hardware interdependencies to assist in task synchronisation and evaluation of maintainability (replaceability and accessibility).

It is not clear how they manage the scope of the task of building a maintenance concept – no execution detail is given. Even their task selection process is not clear at all from the published work – no detail is given, only the process is delineated. Most of the description given above regarding the steps of the method comes from Gits (1992), which differs significantly from his earlier work [Gits (1984)] – clearly, they have developed the technique further during the eight years between the two publications. The earlier work consists of Gits' Ph.D. Thesis, and reports the technique in much more detail than the 1992 paper, but likewise only includes process detail, without any technical detail. This makes it very difficult to assess the quality of the method.

It is apparent, however, that this method has a very definite contribution to make towards improving the RCM methodology. Its task packaging section (the latter part of its first main step) and its investigation/checking of task performance / cost effectiveness / regularity of demand (its second main step) will have to be investigated further with the view of possibly improving the RCM methodology through the incorporation of some of these features.

A closing clarifying remark on the 'satisficing' approach [Gits (1984)] is necessary. The (1984) methodology can be applied in its standard (extended) format, which leads to a high design workload, similar to the problem with RCM described in paragraph 2.5 above. To solve this problem, Gits (1984) proposes the use of a 'satisficing' approach, which is really a simplification of the technical analysis process described above. The following simplifications are made:

- It is not necessary to identify all the PFC's (Process Failure Combinations) of the technical system.
- The functional decomposition of the production system is replaced by technical (part) decomposition, with the functional decomposition then done at part level.
- The parts are categorised as critical or non-critical.
- The further analysis is then only done for the critical parts.
- Gits comments that this process is very similar to an FMEA analysis.

2.6.4. Business Centred Maintenance

The Business Centred Maintenance (BCM) approach of Kelly [Kelly (1997)] is an attempt to develop a maintenance plan based on 'business' principles only, without doing an analysis of the underlying failure modes. This seems to be a viable approach on the surface, if one only considers the 'practicality' of the approach. However, the method leave huge gaps, which could lead to ineffective/wrong maintenance strategies being chosen.

Most authors on the RCM-process agree that RCM consists of failure mode selection, maintenance task selection, task frequency selection and task packaging. Analogous to this, BCM has three main steps, the plant/business asset structure and characteristics study step, the unit life plan (task selection and assembly) step, and the establishment of a maintenance schedule (task packaging) step [Kelly (1997), pp. 144-158].

Comparing the methodology to RCM, its weaknesses lie in three areas. The *first* of these comprises understanding the failures for which a maintenance plan is to be designed. Without doing a form of FMEA, one can never really achieve a total understanding of the failure process. Moreover, without a full understanding of the failure process, you cannot attempt to design an appropriate maintenance plan. One of the main problem areas here would be that one would not be able to judge the full *technical viability* of a maintenance task. The *second* weakness is that the relative conservatism of the order in which tasks are considered in RCM (Condition Based -> Recondition -> Replace) is not taken into account [Kelly (1997), p.127, example 2]. This can lead to task choices, which are sub-optimal (a less optimal task is chosen due to the non-conservative order of task selection). *Thirdly*, Kelly has a very simplistic view of the failure history of an item in a statistical sense [Kelly (1997), pp. 110-112]. The book [Kelly (1997)] has two chapters on Reliability Analysis and Reliability Modelling, which are contributed by Harris (prof John Harris, University of Manchester, with whom dr Kelly has also collaborated in a previous book). Nevertheless, one gets the feeling that Kelly, like most authors on RCM, does not understand and appreciate the importance of statistical failure data analysis in setting up a maintenance plan.

On the other hand, BCM has a definite contribution to make towards the improvement of the weaker areas in RCM. *Firstly*, the way in which an industrial system is studied parallels the method of Smith [Smith (1993)], although in less detail [Kelly (1997), pp. 144-147]. *Secondly*, Kelly follows a very good 'engineering' (or physical) approach to the decision regarding the technical viability of tasks. *Thirdly*, his approach to task packaging [Kelly (1997), pp. 149-158] is reasonably well thought trough and should be considered in suggesting improvements for RCM.

2.6.5. Risk-Centered Maintenance

Jones (1995) incorporates the concept of risk into RCM, which gives a criticality measure, but also gives an extra dimension, which can be used to reduce risk over the medium to long term. He gives a new name to the technique, although his method is standard RCM (although it seems to be a watered down version), with the exception of the addition of risk.

2.7. Closing remarks

When reading the literature on RCM and related techniques, one cannot but get under the impression that the related techniques are mostly not original, but are based on the foundation created by RCM. Many of the techniques and 'novel' ideas presented are nothing new, but do add to the base of RCM knowledge. The problem, however, is that many of these alternatives are being presented as if it represents valid alternatives. This tends to confuse users of RCM and adds to the resistance against the technique.