An optimised instrument for designing a maintenance plan

A sequel to Reliability Centred Maintenance

by

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> Christian, meditate much on heaven, it will help thee to press on, and to forget the toil of the way. This vale of tears is but the pathway to the better country: this world of woe is but the stepping-stone to a world of bliss.
>
> C.H. Spurgeon: Morning and Evening,
> Morning, 7 February

Synopsis

Reliability Centred Maintenance (RCM) started a new chapter in the history of preventive maintenance strategy setting. It was now possible to develop a scientifically based, highly successful maintenance program for complex systems. It 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, followed by the improved MSG-2. When MSG-2 was used contractually for the United States Department of Defence, it led to the present definition of RCM.

In academic circles there developed a growing dissatisfaction with the technique [Pintelon et al (1999)], of which part stems from watering down its scientific basis to make RCM more marketable [Moubray (2000)], while at least part is based on perceived inherent scientific weaknesses in the methodology itself.

This thesis, in setting out to solve these limitations, makes several important contributions to the RCM methodology. The *first* of these is a method of concentrating the RCM analysis effort on the most important failure modes encountered by the organisation. *Secondly*, it introduces a Quality Improvement task in the RCM task selection tree, based on a limitation identified by Harris (1985). The *third* contribution is the addition of a formal task packaging methodology, following Gits (1984). The thesis *also* combines the use of RCM for the most important failure modes with conventional maintenance tasks for the remaining failure modes, to form a total methodology for the typical industrial concern. It *furthermore* introduces the application of sound management principles in the implementation of RCM and *lastly*, blends concepts from different RCM authors, together with the innovations listed above, into one logical whole. In summary, the proposed revised methodology can play a very important part to achieve the goal of World Class manufacturing standards, including ensuring that the organisation's maintenance effort is as proactive as possible.

Keywords:

RCM, Reliability Centred Maintenance, maintenance, preventive maintenance, scheduled maintenance, planned maintenance, proactive maintenance, reliability, industry, World Class Manufacturing.

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Chapter 5: Model Testing

Chapter 6: Conclusion

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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.

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[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 reliabil-

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ity 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].

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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'.

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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)

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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).

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- 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.

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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.

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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.

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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,

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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.

Chapter 3: Literature Survey

3.1. Introduction

There is a scarcity of publications on the development and use of RCM. The only textbooks worth noting are those of Anderson and Neri (1990), Moubray (1991) and Smith (1993). The only other textbook giving proper coverage to RCM is Coëtzee (1997), while Jones (1995) and Campbell (1995) has overview chapters on the subject. No academic research of importance is being done on RCM as a technique. Academics that do write in the area of the design of maintenance plans do so from a mathematical modelling approach (there are a plethora of them) or has created own techniques - examples are Gits (1992) and Kelly (1997). Even non-academics are active in the creation of own methodologies for maintenance plan design - an example is Jones (1995). The only research of any consequence done to develop the RCM technique, is done by practitioners of the technique - examples are Smith (1993) and Moubray (1991).

At least two of the major textbooks on the RCM methodology Moubray (1991) and Smith (1993) have followed the broad RCM structure proposed by Nowlan and Heap (1978). This same structure will be used for both this and the next chapters to facilitate comparison with the RCM standard works. The main headings that will be used for this purpose are:

- The principle behind RCM: preserve function or preserve equipment?
- The selection of application areas for RCM
- Information Assembly
- Identification of Failure Modes
- Prioritisation of Failure Modes
- Classification of Failure Modes
- Task Selection
- Task Frequencies
- Task Packaging
- Critical assessment of resulting program

3.2. A survey of publications and trends in the development of the RCM technique and related techniques

Most of the groundwork for the following discussions will be laid by first exploring and discussing the original RCM work [Nowlan and Heap (1978)]. The work of later authors of works on RCM and related techniques will then be evaluated against these original principles, with a view to identifying any real improvements to the original methodology.

Because RCM is sometimes thought to be complex, a simple overall structure is introduced, which serves to communicate to the reader of this chapter the position of the specific topic in the overall RCM structure. This framework is introduced in figure 3-1.

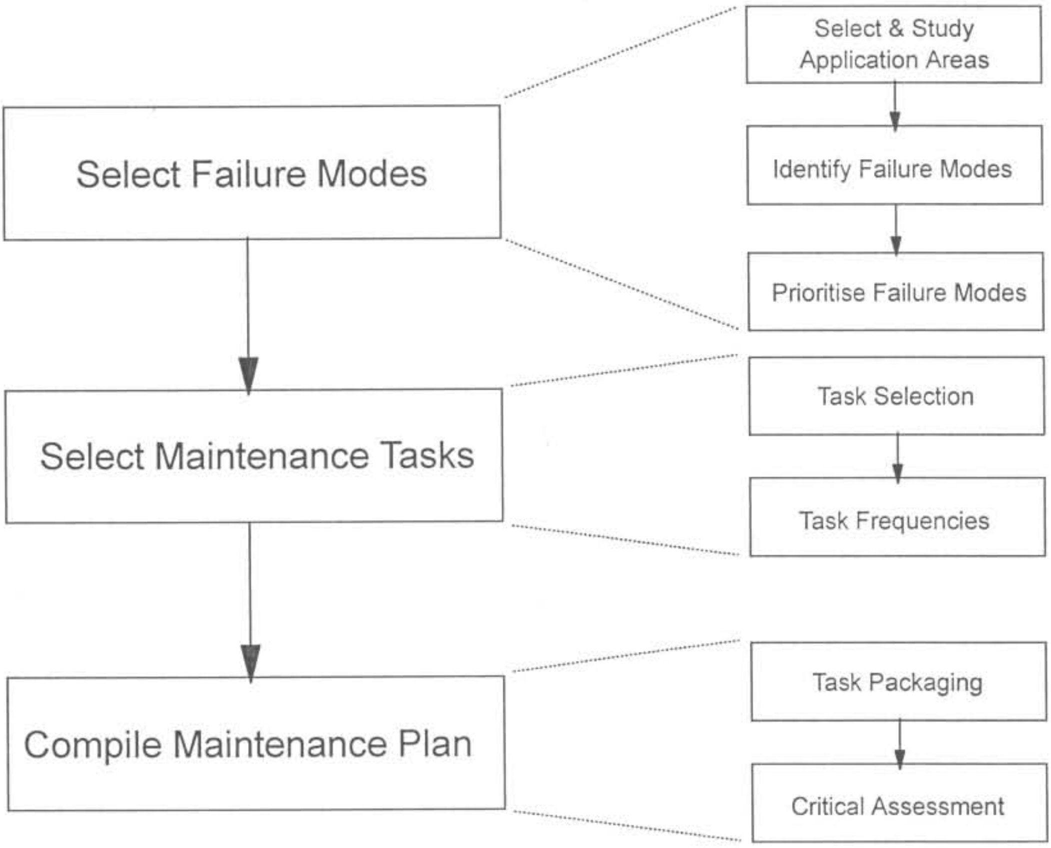

Figure 3-1: Outline of RCM process

This framework shows that the total RCM process consists of three sub-processes:

- Select failure modes, which has as objective to identify the failure modes, which are most detrimental to achieving the objectives of the organisation.
- Select maintenance tasks, consisting of finding the best maintenance tasks and task frequencies to deal effectively with the failure modes selected in the first step.
- Compile maintenance plan, where the maintenance tasks found in the previous step are packaged into a practical maintenance programme and the resultant programme critically evaluated for correctness and practicality.

The figure above will be used in the form of the tracking diagram shown in figure 3-2 to assist the reader in following which part of the RCM methodology is being addressed in any particular paragraph. The smaller blocks on the

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right of the main RCM process blocks in figure 3-2 represents the sub-processes depicted in figure 3-1, and will be filled to indicate that a particular sub-process is being addressed in a particular paragraph.

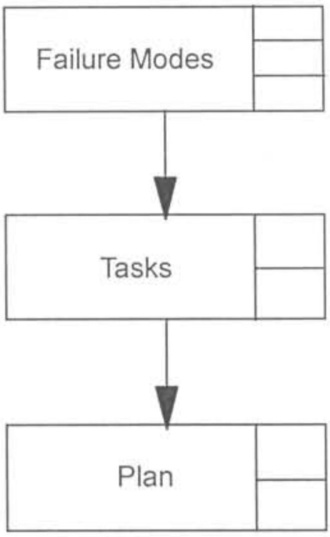

Figure 3-2: Tracking Diagram

3.2.1. The principle behind RCM: preserve function or preserve equipment?

Although the designation 'Reliability Centred Maintenance' was coined by the U.S. Department of Defence in 1975 [Matteson (1989), p. 6], the task of writing the first textbook (really a book-length report) [Nowlan and Heap (1978)] on RCM was given to United Airlines under contract. The content of this textbook was based on and refined the principles by now already firmly established in MSG-2, as successor to the successful Boeing 747 maintenance program design methodology, MSG-1.

One of the principal drives behind the development and use of MSG-1 was to move away from the principle of preserving equipment, to a principle of preserving function (especially functions essential to operating safety, but also those affecting economy of operation). Under the pre-RCM principle of preserving equipment, all equipment and all functions of such equipment had to be maintained (preserved), regardless of whether the preservation mattered or not. Under the RCM principle of preserving function, functions for which preservation does not matter are disregarded and the total force of maintenance actions is focussed on preserving essential equipment functions. Nowlan and Heap (1978), p.7 state this as follows: "*In short, the driving element in all maintenance decisions is not the failure of a given item, but the consequences of that failure for the equipment as a whole.*" If a specific failure does not have significant consequences at the equipment level, it is totally disregarded in the design of the maintenance plan for the equipment. That is not to say that maintenance resources will not be spent on it – but it will be handled in a corrective way and not preventively.

This change in attitude is one of the major contributions of RCM to improving the quality of maintenance plans. Any text on the subject should thus emphasise both the fact of the change and its importance. The user of the methodology should realise that RCM does not merely assist him in designing a universal 'good' maintenance plan. It rather creates a maintenance plan that will, because it preserves function, result in the organisation reaching its goals.

The principle of preserving function is neglected in the RCM literature. Because of this, the majority of the users of the technique do not appreciate the enormity of the move from preserving equipment to that of preserving function. The responsibility for this can certainly be laid at the door of the various authors, who fail to make RCM analysts and users aware of the subtle, but critical difference. Moubray (1991), when defining RCM, states (p.7) that 'a fuller definition of RCM could be "a process used to determine *what must be done to ensure that any physical asset continues to fulfil its intended functions* in its present operating context".' He then refers to this in a later chapter (p.37) regarding asset maintenance as being "the state we wish to preserve is one in which it continues to fulfil its intended *functions*." Nevertheless, not once is the difference between the two concepts accentuated. This is not only true of Moubray, so that this critique is not aimed only against him, but against all the other authors that fail to get this concept across.

Smith (1993) is the only author that gets this concept across properly. When listing the principal features of RCM, he states that '*Traditional methods for determining PM tasks start with the issue of preserving equipment operability, and such methods tend to focus the entire task selection process on what can be done to the equipment. As a rule, why it should be done is never clearly addressed (or documented, if such consideration was, in fact, ever investigated). RCM is a major departure from this traditional practice! Its basic premise is "**preserve function**" - not "**preserve equipment**." This approach forces the analyst to systematically understand (and document) the system functions that must be preserved without any specific regard initially as to the equipment that may be involved. It then requires the analyst to think carefully about how functions are lost - in functional failure terms, not equipment failure terms. The purpose of this approach is to develop a credible rationale for why one might eventually desire to perform an appropriate PM task rather than just arbitrarily deciding to do something because "it sounds right."* (italics and accentuation added)

Jones (1995) mentions in his introduction to RCM that "The shift of emphasis, however, is from maintenance of *equipment operation* to the RCM theme of maintenance of *system function*." This states the point exactly, but like Moubray, the difference between the two concepts is not explained in the remainder of his text, nor is it accentuated.

Business Centred Maintenance (BCM) [Kelly (1997)] is an extremely practical approach to the design of a maintenance plan, as is evident from the short description in chapter 2 (paragraph 2.6.4). It is typical of the way in which maintenance plans were developed in the pre-RCM era. The two opposing principles of preserving *equipment function* versus that of preserving

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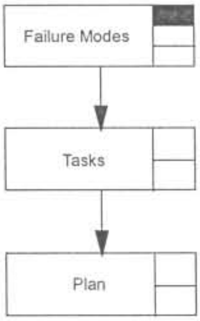
equipment operation are not mentioned and the method uses the outdated principle of preservation of *equipment operation*.

MSG-3 (1993), Anderson and Neri (1990), Coetzee (1997/2) and Campbell (1995) do not even mention the principle of *preserving function* at all.

3.2.2. The selection of application areas for RCM

When one anticipates the maintenance of a complex system, you are confronted by the decision regarding which of the myriad of components and their failure modes should be taken into account to base the (successful) maintenance plan on. In the case of a single system, such as an aircraft, the answer to this question is less complex than in a typical industrial system (plant, mine, or the like). In the case of an aircraft, although the system is very complex, it does not have the complexity of as many different and uncoordinated manufacturers of different parts of the system.



Nowlan and Heap addressed this problem through the introduction of the concept of a *Maintenance Significant Item (MSI)*, which they defined as follows:

> *A (maintenance) significant item is one whose failure could affect operating safety or have major economic consequences* [Nowlan and Heap (1978), p.80].

They also suggested that a 'partitioning' process be used to break the equipment down, first into major divisions (systems, powerplant and structure in their case), then further into systems, subsystems, assemblies and lastly parts (see figure 3-3).

The resultant tree in figure 3-3 must then be 'pruned' upwards to remove the obviously non-significant items. These are those items for which it can be demonstrated that they are non-significant because:

- their functions are unrelated to operating capability *or*
- the functions are replicated (this will be the case where redundancy has been designed into the system, either by parallel sub-systems or through standby sub-systems) *or*
- the item can be restored quickly following failure *or*
- the item cannot benefit from scheduled maintenance

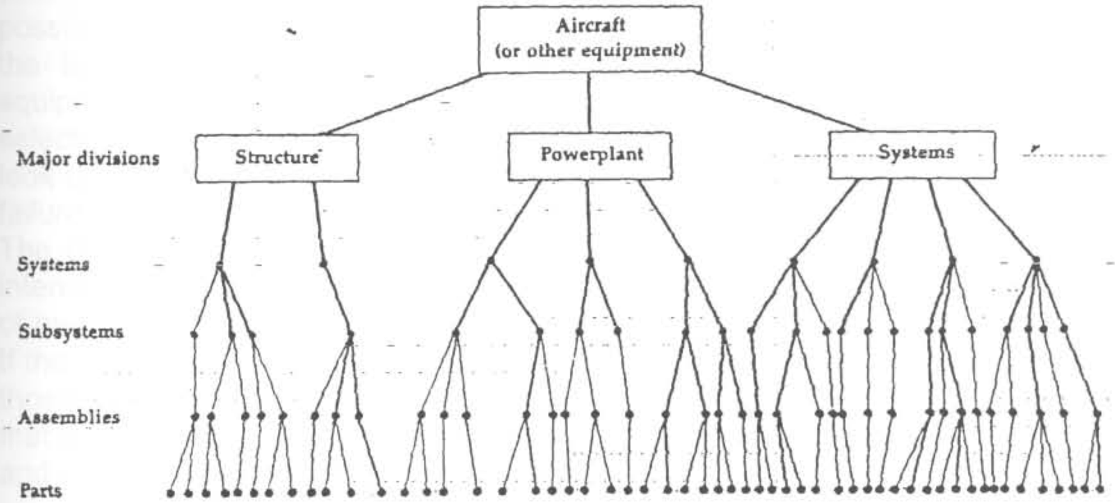


Figure 3-3: Tree breakdown structure (partitioning process)

The only exception in this process of classifying items non-significant is in the case of items with hidden functions. Such items might be classified as non-significant using the reasoning process described above, but will still be listed as items having to receive scheduled maintenance to reduce the occurrence of hidden failures to an acceptable level (so to reduce the probability the resultant multiple failure[1] to an acceptable level). The tree of significant items is shown in figure 3-4.

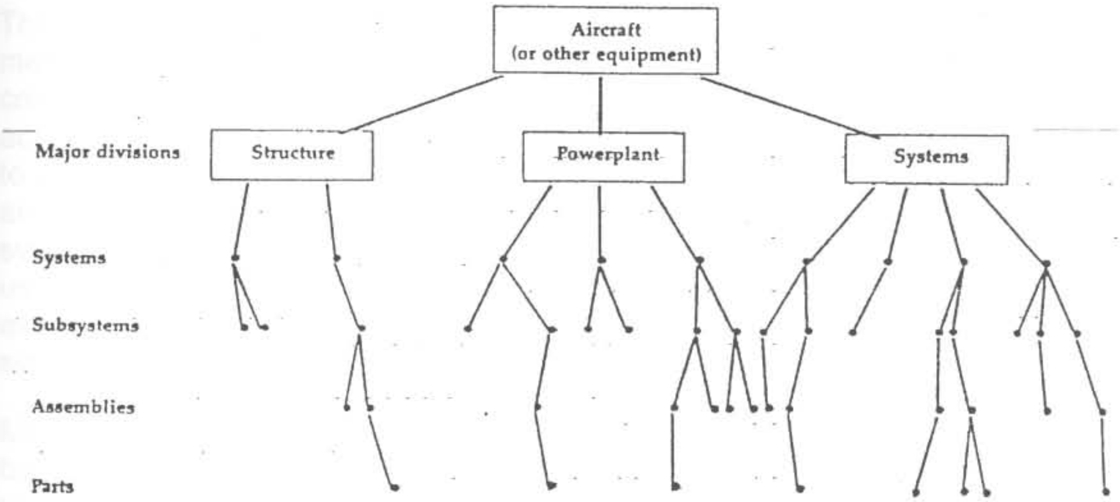


Figure 3-4: Tree of Maintenance Significant Items

The objective of this process, according to Nowlan and Heap (1978), is to find the most convenient level of each system or assembly to classify as significant. This resultant level must be low enough to ensure that no failure possibilities are overlooked, but high enough for the loss of function to have

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[1] A typical example of a hidden failure consequence item comprises a non-failsafe safety device. If the device has failed there are no direct adverse consequences, but when the safety function of the device is needed and it is not available a catastrophic failure of the protected system mostly occurs. This failure plus the original (hidden) failure of the safety device are called a 'multiple failure'.

an impact on the equipment itself. The higher the level chosen, the more unwieldy the number of failure possibilities becomes, and the higher the possibility of missing important failure modes. On the other hand, the lower the level chosen, the higher the probability of losing contact with the equipment itself. Nowlan and Heap states (p.83) that "the level of item selected as significant is important only as a frame of reference. Whether we look up at a multiple failure or down at a failure mode, an analysis of all the failure possibilities will ultimately lead to exactly the same preventive task. The chief advantage of the partitioning process is that it allows us to focus intensive study on just a few hundred items *comprising a sub-system* instead of many thousands *in a major division*." (italicised portions added for clarity). If the process is followed correctly, the parts selected as significant are usually those in which a critical failure mode originates. The authors caution (p.354) that there is a tendency amongst analysts to identify items based on their cost and complexity instead of based on their failure consequences.

As can be anticipated, the original Nowlan and Heap technique works best for the situation for which it was developed. It is perfect for a situation where many of a specific design of equipment are sold to a large market. In such a situation, one can afford the expense of a meticulous dissection of the equipment with the objective of creating the best possible maintenance plan. To that, one can add the high profile of operating safety in the airline business as an additional reason why this approach works perfectly well for the airline situation. On the other hand, in the general industrial application of RCM, the method tends to be overly demanding and users then seek for shortcuts.

The RCM method that has been popularised in South Africa is the adapted method as suggested by Moubray (1991). Moubray has a reasonably comprehensive chapter on the plant register, which seems to suggest that he advocates the use of the plant register as a means to decide which machines to include in the RCM analysis. He then proceeds to the analysis of functions and failures without explaining how he selected certain systems/sub-systems/components for analysis. Appendix 2 of his book also proposes the use of the equipment hierarchy to guide the analysis process without explaining how the decision regarding the specific systems/sub-systems/components to be analysed should be taken.

Moubray warns (p.302) that "an analysis carried out at too high a level can become too superficial, while one done at too low a level can become unintelligible." He then follows up by giving guidelines regarding the dangers of analysing at too low or too high a level. The dangers of doing the analysis at too low a level includes:

- ➢ that it becomes difficult to conceptualise and define performance standards
- ➢ it becomes difficult to visualise failure consequences
- ➢ control and protective loops can become difficult to deal with
- ➢ the process generates vast amounts of paperwork, which can become quite intimidating.

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On the other hand, the disadvantage of doing the analysis at too high a level is that one could overlook several failure modes. He then suggests that the correct level of analysis is that one which supports the function(s) of the asset being analysed best. One cannot find fault with this approach, which really expands and supports the approach of Nowlan and Heap, apart from the fact that it is not specific at all regarding the use of the plant register as guideline.

Smith (1993) suggests that, based on experience, the system level is the most appropriate choice for the design of a maintenance plan. In evaluating his approach, it must be taken into account that he and Tom Matteson [Matteson (1989)] was involved with the Electric Power Research Institute (EPRI) to transfer the knowledge gained in the airline industry to the power industry. Most of his experience was therefore gained in a process type industry. He, like Moubray, suggests that to carry the analysis out at too low a level causes many problems, such as:

- that it becomes difficult to define the significance of functions and functional failures
- it is difficult to perform priority rankings between failure modes that are competing for limited PM resources

At the other end of the spectrum, he suggests that even combining two systems in one analysis proved to be extremely cumbersome and difficult. He thus suggests that the analysis process start with a list of all the systems in the plant/business asset/major system to be analysed. This is very specific and it seems to be a very practical guideline, at least for use in process industries.

Neither Nowlan and Heap, nor Moubray suggested any way of concentrating the analysis effort on systems that are more important. Smith is the first author to suggest a choice of only certain systems for analysis. The choice is based on selection by using one of the following 'schemes':

i. systems with a present high preventive task and/or cost content
ii. systems with a history of a high number of corrective maintenance tasks being done
iii. a combination of the previous two schemes
iv. systems with high corrective maintenance cost
v. systems which contributes significantly towards partial and total plant/business asset shutdowns
vi. systems which cause concern regarding safety and the environment

He states that from experience it seems as if all of the above-mentioned schemes, apart from scheme (vi), have the same result. Scheme (vi) has, according to Smith, proven not to be a good indicator of where the maintenance improvement effort should be concentrated as it often tends to create a bias towards systems that, maintenance-wise, are low-cost/low-problem systems. This solution, excluding scheme (vi), looks like a good, solid practical approach.

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The RCM descriptions given by Jones (1995) and Campbell (1995) roughly agree with that of the previous authors, although not one of them has sufficient detail to guide a user in using the RCM methodology. Their description of the method is meant more as an introduction to RCM than to expounding its detailed use. Jones' description of 'functional decomposition' follows a combination of the ideas of Nowlan and Heap and Smith. Campbell, on the other hand, follows the notions of Moubray regarding the use of the plant register as basis. Jones does not suggest any way of selection of only certain parts of the plant/business asset for analysis. Campbell suggests the use of the following parameters for this purpose: availability, process capability, quality, cost as well as safety and environmental risk. He does not give detail, though.

Gits (1984) first describes an elaborate approach of functional decomposition, leading to the identification of PFC's (Process Failure Combinations), but then settles for what he calls 'technical decomposition' in his 'satisficing approach'. This is none other than Nowlan and Heap's partitioning process. In fact, Gits defines technical decomposition as being the 'hierarchical partitioning of the TS (*TS ≡ Technical System*) into its parts.' He then goes on to explain that the level of analysis should be determined through 'pragmatic considerations'. These include:

- organisational aspects, such as:
  - spare part policy
  - outsourcing policy
  - the availability of maintenance resources
  - statutory requirements
- hardware structural aspects, such as:
  - replaceability of parts
  - accessibility of parts
- information that are available regarding failure behaviour

Through these 'pragmatic considerations' he leaves the field open for interpretation but gives good guidelines on how to do such an analysis. Le Clercq and Van den Broek (1999) is a case in point. Figure 3-5 shows an example of a resultant decomposition using the Gits method.

Kelly (1997) also uses a hierarchical breakdown of the plant/business asset in the order: plant -> units -> assemblies -> sub-assemblies -> components. The purpose of this decomposition is to identify the 'maintenance causing items'. These are very similar to the MSI's of Nowlan and Heap (1978). His analysis approach looks at the maintenance requirements of each maintenance-causing item on an item by item basis. He does not specifically address the level of analysis, but ranks units in order of criticality according to the impact of their failure on production and safety.

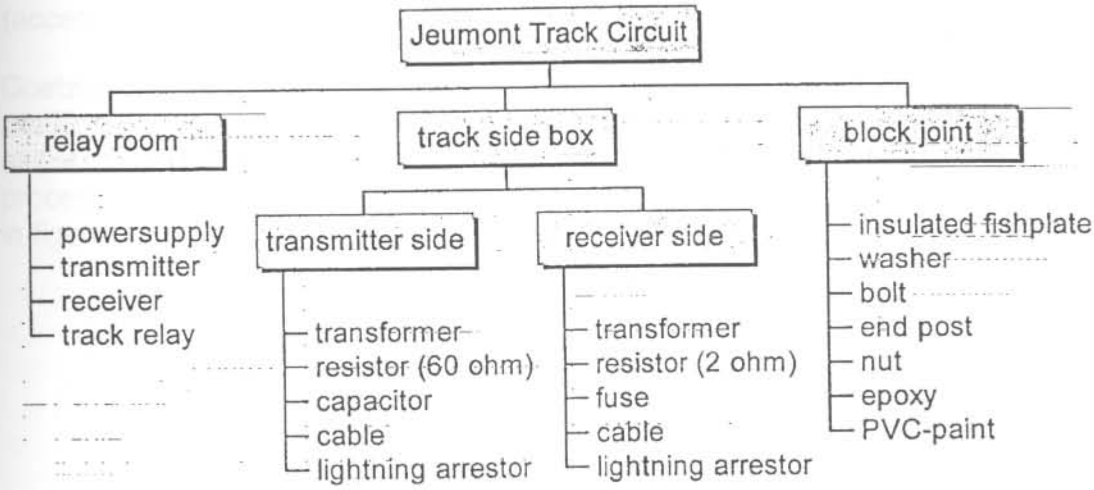

Figure 3-5: Technical Decomposition a la Gits

MSG-3 (1993) uses a top-down approach similar to that of Nowlan and Heap (1978) to identify the significant items on an aircraft. *Firstly* the aircraft is partitioned into major functional areas (or ATA Systems and Sub-Systems) and *then* further until sub-components, which are not replaced on-aircraft are identified. A candidate MSI is *then* usually a system or sub-system that is, in most cases, one level above the lowest (on-aircraft) level identified in the previous step. This level is considered the highest manageable level, i.e., one which is high enough to avoid unnecessary analysis, but low enough to be properly analysed to ensure that all functions, failures, and causes are adequately covered. They describe the process of identifying Maintenance Significant Items (MSI's) as a conservative process (using engineering judgement) based on the anticipated consequences of failure. The resultant MSI's are those items identified by the manufacturer whose failure could have any one or more of the following effects:

i. It affects safety (on ground or in flight).

ii. It could be undetectable or are not likely to be detected during operations.

iii. It could have significant operational impact.

iv. It could have significant economic impact.

The RCM handbook of the Naval Sea Systems Command (1983) prescribes the identification of all the ship's systems and then partitioning them in a logical way. It cautions that this partitioning process should rarely go below sub-system level. It states that "The need for analysis below the subsystem level depends on the complexity of the system and your knowledge and expertise. ... Nevertheless, understanding all of the functions of a complex system ... may require that you go, selectively, to the equipment level or below." It cautions that the tendency to want to analyse at too low a level is the direct result of misunderstanding the intention of an RCM analysis: "RCM is a methodology intended for use in developing ... the **preventive maintenance program for a ship**. If you are involved ... in the application of RCM, you should understand that intention. Otherwise, you may focus on

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some lesser level of assembly and its function rather than **on how it, in concert with other hardware, provides all the functions of the ship**." (accentuation added)

Coetzee (1997/2) makes use of the Nowlan and Heap method of partitioning/decomposition. He adds a simple decision diagram (p.86) that assists the user of the technique to decide when to stop the decomposition process down a specific leg of the decomposition tree. This diagram is shown in figure 3-6.

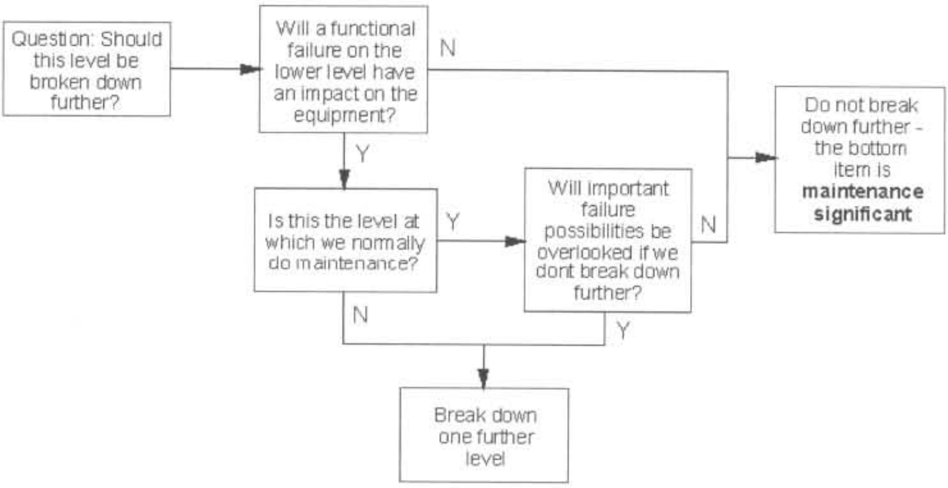

Figure 3-6: Item breakdown decision diagram

This diagram is based on the principle stated by Nowlan and Heap that the resultant level (of MSI's) must be low enough to ensure that no failure possibilities are overlooked, but high enough for the loss of function to have an impact on the equipment itself. This surely results in a more detailed RCM analysis than is the case with many of the later authors. The principle as stated above by the Naval Sea Command (1983) should be added to this diagram to make sure that the analysis remains function driven.

Coetzee also adds two prioritisation steps to ensure that the RCM analysis is concentrating on the high priority plant items or business assets. Before doing the partitioning as described above, he suggests that the plant/business asset be divided into logical groups of plant items/major systems/equipment. A Pareto analysis based on the profit contribution per group is then used to select those groups that should be analysed further using the RCM methodology. Following the partitioning process for these selected groups, he then suggests a further Pareto analysis of the resultant MSI's, based on each MSI's contribution to the downtime of the particular system/equipment to identify the MSI's that contribute most to the downtime of these, the highest profit contributing items. These two prioritisation processes constitute an effective 'funnelling' action to reduce the size of the total RCM analysis effort and to focus the effort on the most important items. The problem with the first prioritisation process is that it only focuses on profit and leaves out safety and quality as specific instances of results. Coetzee does however add in a footnote, that "Care should be taken not to disregard those plant

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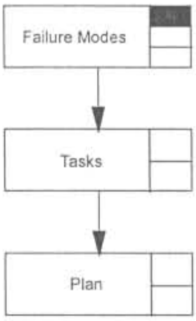
items/business assets that do not contribute directly to profit, but which are of cardinal importance in ensuring long term profit." Care should be taken at all times while selecting the items for analysis that all important MSI's, based on the overall business objectives, be selected for further analysis.

3.2.3. Information Assembly



Probably because of the very specific business area for which it was written, the book of Nowlan and Heap (1978) does not specifically address the issue of the study of application areas. They do mention the necessity of providing analysts with schematics, full descriptions of the hardware and its relationship to other aspects of the aeroplane, though, in the appendix on auditing the RCM process (p.354). They apparently assume that the relevant information is normally available at the fingertips of the analysts performing RCM analyses for airlines and military aircraft. They even assume a close relationship with the designer of the system, which in their case might be a reasonable assumption. Moreover, they put a very large emphasis on the management of the process through auditors (see paragraph 3.2.10 for a discussion of the auditing process). However, in the industrial application of RCM this (information assembly - collecting all the relevant information that are necessary for the RCM analysis) is a very important aspect of the analysis process, and as such gets attention from most of the authors writing application texts.

Although Moubray (1991) stresses the importance of information, he depends on the knowledge of people (mostly operating and maintenance staff) to provide the information inputs to the process. The knowledge and experience of the people involved in the operation and maintenance of equipment are often one of the best sources of information regarding, especially, the short term history and behaviour of the plant/business system. In his chapter on implementing RCM (p.229) Moubray asks the question 'Who knows?' and then resolves the question with the comment 'More often than not, "somewhere" actually turns out to be "someone" – someone who has intimate knowledge and experience of the asset under consideration.' He then leaves it at that. His approach is centred on the knowledge of people operating and maintaining the plant/business system. He does make provision for technical experts to sit in on the RCM sessions, but even then he relies on the expertise of a person instead of verifying it with information from reputable sources, plant maintenance and operational manuals, plant maintenance and operational history and design documentation.

Smith (1993) has a high regard for the inputs from people, in line with that of Moubray. However, he does not see that as being sufficient and adds the use of plant-specific and generic data files (p.56). Under the heading 'Information collection' he presents the following list of documents and information that are required for the RCM analysis process:

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- system piping and instrumentation diagram
- system schematic and/or block diagram
- individual vendor manuals for the various pieces of equipment in the system
- equipment history files
- system operation manuals
- system design specification and descriptive data

It is again apparent, that most of his later experience was gained in the process industries. The above-mentioned list of information items will not apply exactly as is to all industries, but the principle is sound. One should get as much help as is possible from documented sources. Smith adds that one will often have to create the system piping and instrumentation diagram via a 'system walkdown' and visual reconstruction of the as-built configuration. He mentions that the one obvious omission from the above list is the present (non-RCM) maintenance plan. He recommends that this should only be made available near the point of completion of the RCM plan. This principle is sound, taking into account the nature of mankind and is very specifically borne out by Nowlan and Heap in their appendix on RCM plan auditing (p. 361). They state that some analysts have the tendency to work backwards through the decision logic from either the present task or their own favourite task, in order to justify it and to save some analysis effort.

Gits (1984, 1992) does not specifically mention the aggregation of information as a specific step in his process. Nevertheless, the project of Le Clercq and Van den Broek (1999) had a very definite information gathering phase, which included the experience of maintenance and operations staff, manuals, schematics as well as material (such as annual reports and promotional brochures) to understand the business of Metrorail.

Kelly (1997) makes use of process flow diagrams (separate ones at system and sub-system levels) and a plant/business asset inventory, which are drawn up as part of the first step of his BCM process. The flow diagrams have to specify plant logistical information, such as plant production rates and buffer storage capacities, as well as item-redundancies. He specifies that the analyst should develop a proper understanding of the plant operating characteristics and the production management policies followed. The user requirements regarding maintenance results (i.e. availability) should be obtained as well and translated down to unit level as input to the plan design process. Additionally to this, the scheduling characteristics of the plant should be studied and documented regarding *firstly* maintenance opportunity windows arising from production schedules and operational characteristics (e.g. batch operation). *Secondly*, plant item/major system interdependencies should be determined (this can involve flexible downtime opportunities flowing from the buffer capacity created through in-process storage, as well as limitations concerning series system availabilities). He moreover makes use of manufacturer's manuals, drawings and schematics in the process of plan design.

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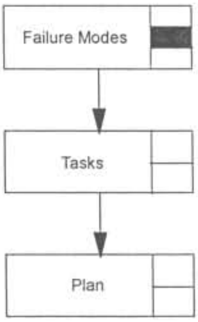
MSG-3 (1993) suggests that one or more working groups, consisting of specialist representatives from the participating operators (airlines), the prime manufacturer, and the regulatory authority, be constituted. Their task is to ensure that the highest amount of operating and maintenance experience, data and other source material are available for the ensuing maintenance plan analyses. The steering committee, which steers the maintenance plan analysis, may alternatively arrange some other means for obtaining the detailed technical information necessary to develop recommendations for maintenance programs in each area. The point is that, irrespective of the organisation of the working activity, written technical data, which is not specified in detail in the MSG methodology, must be provided to support the recommendation to the steering committee. After approval by this committee, these analyses and recommendations are consolidated into a final report for presentation to the regulatory authority.

Naval Sea Systems Command (1983) has very specific requirements regarding the information requirements. They classify the information under the headings 'descriptive information' and 'operating information':

- Descriptive Information
    - Narrative descriptions
    - Design specifications
    - System schematics
    - Assembly drawings
    - Field and engineering changes
- Operating Information
    - Operating and maintenance instructions
    - Condition and performance standards
    - Failure data
    - Existing maintenance specification

They state explicitly that the last item should only be used for reference purposes after the RCM analysis has been completed.

3.2.4. Identification of Failure Modes



The identification of failure modes was not addressed in the case of Nowlan and Heap (1978). Their book has very few references to the process of identifying failure modes, as they use a Failure Modes and Effects Analysis (FMEA) which is supplied by the manufacturer (p. 80). In addition to this, they accentuate that airlines have knowledge and operating experience with similar items, as well as knowledge of the failure consequences in the particular operating context in which the equipment is used. The important implication is that RCM was developed around the technique of FMEA as a basis to provide

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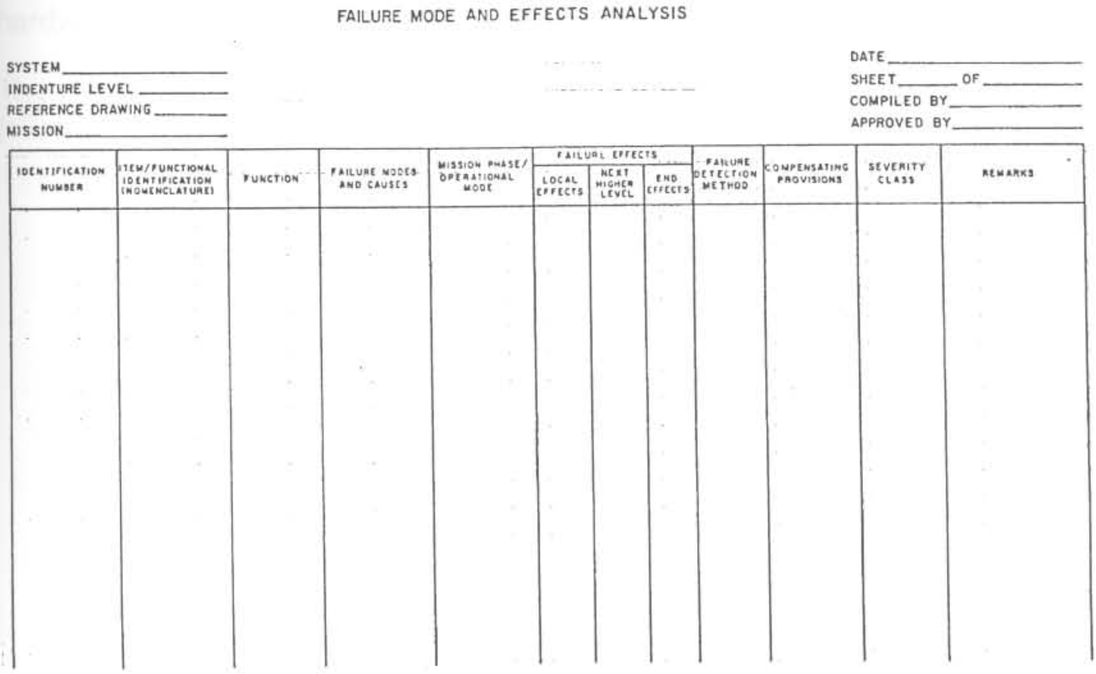
the majority of the knowledge regarding failure modes for the RCM analysis process. Different to the typical industrial situation, the FMEA knowledge that is available up front gave them an edge in the choice of MSI's (paragraph 3.2.2).

In industrial applications the FMEA analysis is not a given and needs to be done as part of the analysis process. As the industrial version of the technique developed, it was in most cases enhanced by practical experience. In many cases, the FMEA was extended to a form of FMECA (Failure Mode, Effects and Criticality Analysis) to provide a way of classifying the failures as being more or less critical. The criticality aspect is addressed in paragraph 3.2.5. The format of an FMEA worksheet as given in MIL-STD-1629A will be regarded as the standard format and is shown in figure 3-7.



FAILURE MODE AND EFFECTS ANALYSIS

SYSTEM ____________
INDENTURE LEVEL ____________
REFERENCE DRAWING ____________
MISSION ____________

DATE ____________
SHEET ______ OF ______
COMPILED BY ____________
APPROVED BY ____________

IDENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION (NOMENCLATURE)	FUNCTION	FAILURE MODES AND CAUSES	MISSION PHASE/ OPERATIONAL MODE	FAILURE EFFECTS			FAILURE DETECTION METHOD	COMPENSATING PROVISIONS	SEVERITY CLASS	REMARKS
					LOCAL EFFECTS	NEXT HIGHER LEVEL	END EFFECTS				

Figure 3-7: Standard FMEA worksheet

The standard content format for the different columns of the FMEA worksheet (figure 3-7), as found in MIL-STD-1629A is given in Table 3.1. The FMEA is really a design document, which is used to analyse a technical system during the systems design process with the objective of designing out critical failure modes, to improve the inherent design reliability of the system. MIL-STD-1629A defines the purpose of the FMEA as follows:

> *The purpose of the FMEA is to study the results or effects of item failure on system operation and to classify each potential failure according to its severity.*

The idea is to eliminate at least Category I (catastrophic) and Category II (critical) failures (see Table 3.1 for the definition of severity classes) during the design and system development phases. The same technique can (and should) of course be used by production organisations in the process of purchasing systems 'off the shelf'. This could ensure that design flaws are

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corrected prior to the purchase, which will lead to less downtime, less maintenance cost and less logistical headaches. Unfortunately, this is done in very few cases.

There are two approaches that can be followed in the analysis process, a *hardware approach* and a *functional approach*. The *hardware approach* is usually followed in less complex situations where the hardware items can be uniquely identified from schematics and drawings and is typically performed in a bottom-up way (from the parts level upward). It will thus develop the FMEA analysis, progressing from the parts level upward until the systems level is reached and the analysis being complete. On the other hand, the *functional approach* is used in complex situations and where the hardware cannot be uniquely identified. Such analysis is typically conducted from the systems level downward. For complex systems, a combination of the functional and hardware approaches may also be considered.

The procedure for conducting an FMEA, according to MIL-STD-1629A, is as follows:

i. The first step is to define the system to be analysed. This includes the overall system function(s) in its intended operating situation. As part of this definition, the intended use of the system is analysed to reveal multiple functional use profiles and multiple modes of operation per functional use profile.

ii. Use is made of functional and reliability block diagrams to support the analysis process. The functional block diagram is required to show the functional flow sequence, while the reliability block diagram is used to show the series dependence/independence of functions and operations. More than one block diagram will be needed in the case of alternative operational modes. Both types of block diagrams is needed if the FMEA is conducted using the functional approach, while only the functional block diagram is used for the hardware approach, as the reliability interrelationships are already implied in the hardware method.

iii. The FMEA analysis is performed using Table 3.1 as guideline. Each single item failure, as its effects are analysed, is considered to be the only failure in the system (i.e. the remainder of the system's functions and components are in a non-failed state). There are two exceptions to this rule. The *first* of these is where the single item failure, that is being analysed, is hidden – in such a case the analysis will investigate whether the failure of a second component or more components, given the hidden failure, will lead to a catastrophic or critical multiple failure condition. The *second* exception occurs in the analysis of safety, redundant or back-up systems. In such a case, the analysis is widened to include the failure condition(s) that led to the incorporation of the safety, redundant or back-up items.

Table 3.1: Standard FMEA process

Column Heading (figure 3-7)	Column Content
Identification number	A serial number or other reference number – used for traceability purposes – typically the block numbers in a Reliability Block Diagram – can also be used to refer to MSI numbers
Item/Functional identification	The name or number which identifies the item or system function being analysed
Function	A concise statement of the function performed by the item. This includes both the inherent function of the item and its relationship to interfacing items
Failure modes and causes	All predictable failure modes for each level analysed are identified and described. Failure modes are identified by studying the item outputs and functional outputs identified in applicable block diagrams and schematics Each failure mode typically has more than one probable cause – all of these are listed for each failure mode identified. It is often helpful to also identify failure causes as seen from one level above and one level below the present level as well To ensure that a complete analysis results, each failure mode and output should be examined in relation to the following failure possibilities: ▪ Premature operation ▪ Failure to operate at the prescribed time ▪ Intermittent operation ▪ Failure to cease operation at the prescribed time ▪ Loss of output or failure during operation ▪ Degraded output/operational capability

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Table 3.1: Standard FMEA process (continued)

Column Heading (figure 3-7)	Column Content
Mission phase/operational mode	A concise statement of the mission phase and operational mode during which the failure occurs
Failure Effect	Evaluate and record the consequences of the failure on item operation, function or status. In this process, also consider mission objectives, maintenance requirements and personnel/system safety. Because the failure may impact levels other than the present one, the effect is also evaluated under the following three sub-headings: *Local effects*: impact of the failure at the present level of investigation. This forms a basis for evaluating compensating provisions (column 10). It is possible for the local 'effect' to be the failure mode itself. *Next higher level effect*: the impact of the failure at the level of which the present one forms part. *End effects*: the impact of the failure on the operation, function or status of the system itself. This end effect may be the consequence of more than one failure.
Failure detection means	The failure detection means, through which the operator detects the occurrence of the failure mode, is identified. These include: ▪ Identified warning devices and instruments ▪ Other indications The most direct method to isolate the failure should also be investigated and reported

Table 3.1: Standard FMEA process (continued)

Column Heading (figure 3-7)	Column Content
Compensating provisions	This includes design provisions or operator actions, which circumvent or mitigate the effect of the failure. Design provisions: include redundancy, safety/relief devices and alternative modes of operation. Operator actions: The action that could best be taken by the operator should be identified and listed. Any incorrect action(s) by the operator should also be listed with the anticipated effect(s).
Severity classification	Each failure mode and each item is assigned a severity classification, according to the failure effect, from the following list: ▪ Category I – Catastrophic – a failure that may cause death or system loss. ▪ Category II – Critical – a failure that may cause severe injury, major property damage, major system damage, which will result in mission loss. ▪ Category III – Marginal – a failure that may cause minor injury, minor property damage, minor system damage, which will result in delay, mission degradation. ▪ Category IV – Minor – a failure that will not cause injury, property damage, system damage, bur which will result in unscheduled maintenance or repair.
Remarks	Any remarks which could clarify why certain conclusions were made in the preceding columns on this row. Notes regarding recommendations for design improvements.

A simpler approach to an FMEA analysis is proposed by McDermott et al (1996), which will be attractive to many maintenance users. They define (p.3) FMEA as "*a systematic method of identifying and preventing product and process problems before they occur*". They suggest a less rigorous approach, using teams of people to develop FMEA analyses, instead of the analyst in the corner approach of MIL-STD-1629A.

Their approach to FMEA's is a more generalised one, advocating the use of the FMEA process to solve any problem at hand – examples listed include safety hazards, financial strategies, software quality, marketing strategy and purchasing of major (capital) equipment.

The teams in this approach are formed whenever needed and disbanded when their task is complete. Each area of expertise involved should have at least one representative on the team, with a team size of four to six people working best, according to McDermott et al (1996). They also suggest that using some people on the team, who are relative outsiders regarding the problem at hand, may be helpful in achieving a balanced result. Such person(s), while not having the required expertise, often have valuable insights which may be missed by people working near to the problem from day to day. They also do not have an emotional investment in the specific situation and thus tend to be objective.

Team members must know the basics of working in a team. Training, if necessary, should include knowledge of consensus building techniques, team project documentation and idea-generating techniques such as brainstorming. They should also be comfortable in the use of flowcharting, data analysis and graphing techniques. The team leader is the only person that must have a good knowledge of the use of the FMEA process.

The leader of the team should be appointed by management or selected by the team members immediately following the formation of the team. Such an individual, who takes part in the process as facilitator and not decision-maker, is responsible for co-ordinating the FMEA process. Such co-ordination includes (1) setting up meetings, (2) facilitating meetings, (3) securing the necessary team resources, and (4) ensuring progress in the right direction. Other roles in the FMEA process includes that of scribe (a role which is typically rotated amongst the team members, excluding the leader) and the process expert. The process expert is someone who has extensive knowledge/experience of the process being investigated and typically has quite an investment in it. The purpose of the FMEA is to find fault with the process expert's work, which makes it difficult for the person. Whereas such a person can help speed up the process, the emotional aspects involved can also slow it down, if not handled correctly by the leader.

Figure 3-8 shows a form suggested by the authors [McDermott et al (1996)] to clarify the boundaries of freedom, within which the team performs its duties, as well as the scope of the FMEA. The former relieves the team of any unnecessary pressures and thus allows them to progress purposefully, while the latter ensures focus on the correct problem.

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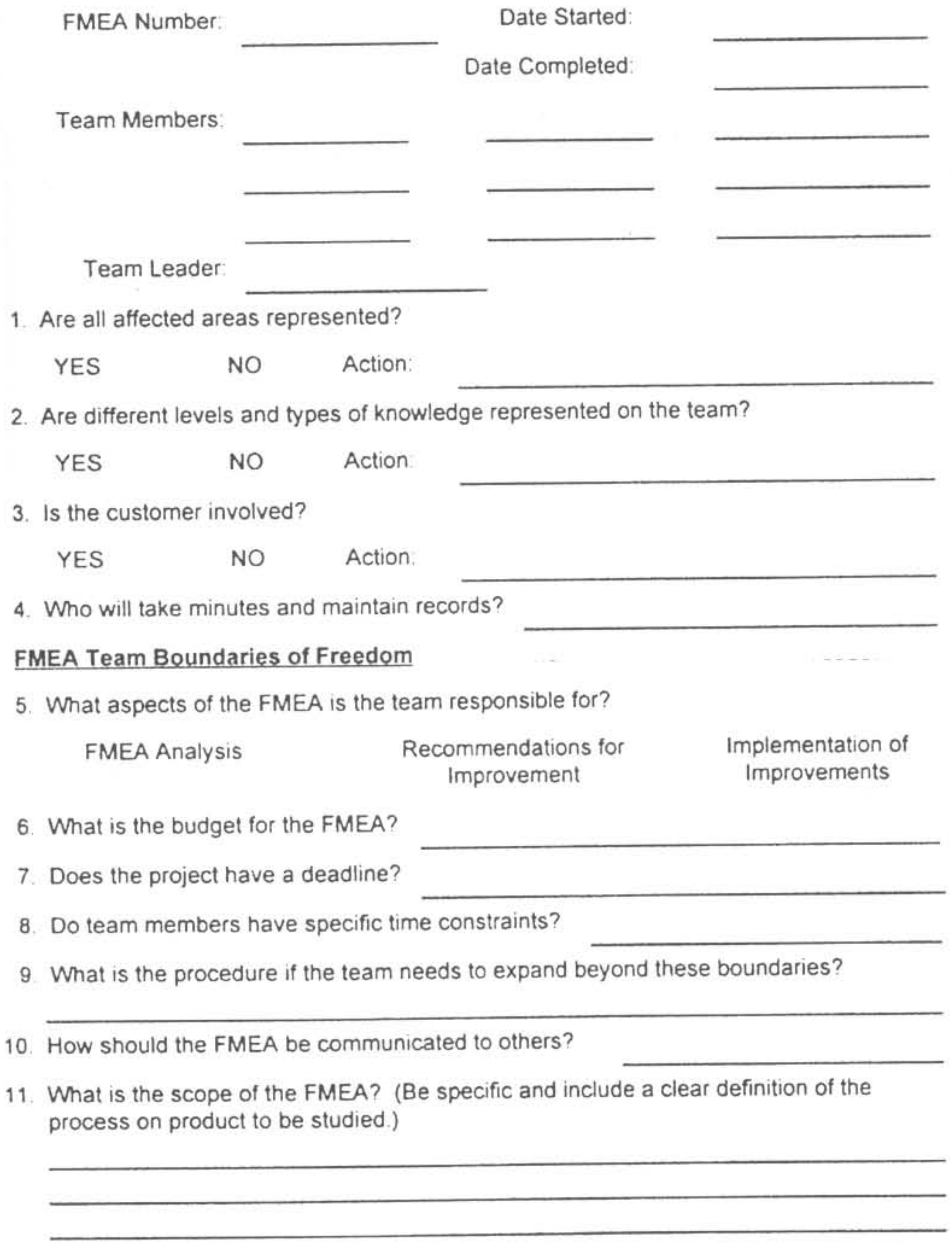


FMEA Number: ______________ Date Started: ______________

Date Completed: ______________

Team Members: ______________ ______________ ______________

______________ ______________ ______________

______________ ______________ ______________

Team Leader: ______________

1. Are all affected areas represented?
   YES NO Action: ______________
2. Are different levels and types of knowledge represented on the team?
   YES NO Action: ______________
3. Is the customer involved?
   YES NO Action: ______________
4. Who will take minutes and maintain records? ______________

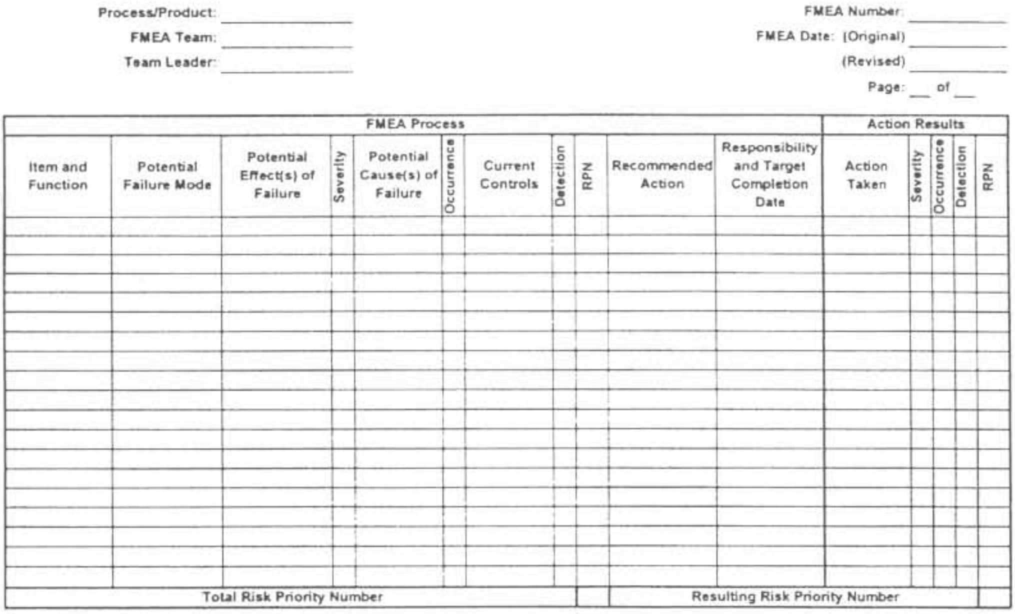
FMEA Team Boundaries of Freedom

5. What aspects of the FMEA is the team responsible for?
   FMEA Analysis Recommendations for Improvement Implementation of Improvements
6. What is the budget for the FMEA? ______________
7. Does the project have a deadline? ______________
8. Do team members have specific time constraints? ______________
9. What is the procedure if the team needs to expand beyond these boundaries?
   ____
10. How should the FMEA be communicated to others? ______________
11. What is the scope of the FMEA? (Be specific and include a clear definition of the process on product to be studied.)
    ____
    ____
    ____

Figure 3-8: FMEA Team Start-up Worksheet [McDermott et al (1996)]

Figure 3-9 shows the FMEA worksheet used by the authors, utilising a 10-step process explained in Table 3.2. Only the first 8 steps are shown, as the last two are not relevant to the discussion.

The main deficiency of this method, when compared with the more rigorous standard FMEA analysis in MIL-STD-1629A, is that it does not lean as heavily on documentary proof of actual experience, but tend to be more subjective due to the team approach. On the other hand, it is much simpler to implement and will certainly lead to an FMEA, which can be used for the generation of a maintenance plan. Some failure modes may be missed, however, and non-existent failure modes may be listed due to the 'group talk' (subjective) effect.



Process/Product: ______
FMEA Team: ______
Team Leader: ______

FMEA Number: ______
FMEA Date: (Original) ______
(Revised) ______
Page: __ of __

FMEA Process											Action Results				
Item and Function	Potential Failure Mode	Potential Effect(s) of Failure	Severity	Potential Cause(s) of Failure	Occurrence	Current Controls	Detection	RPN	Recommended Action	Responsibility and Target Completion Date	Action Taken	Severity	Occurrence	Detection	RPN
Total Risk Priority Number									Resulting Risk Priority Number						

Figure 3-9: FMEA analysis worksheet [McDermott et al (1996)]

Rating	Description	Definition
10	Dangerously high	Failure could injure the customer or an employee.
9	Extremely high	Failure would create noncompliance with federal regulations.
8	Very high	Failure renders the unit inoperable or unfit for use.
7	High	Failure causes a high degree of customer dissatisfaction.
6	Moderate	Failure results in a subsystem or partial malfunction of the product.
5	Low	Failure creates enough of a performance loss to cause the customer to complain.
4	Very Low	Failure can be overcome with modifications to the customer's process or product, but there is minor performance loss.
3	Minor	Failure would create a minor nuisance to the customer, but the customer can overcome it in the process or product without performance loss.
2	Very Minor	Failure may not be readily apparent to the customer, but would have minor effects on the customer's process or product.
1	None	Failure would not be noticeable to the customer and would not affect the customer's process or product.

*Should be modified to fit the specific product or process.

Figure 3-10: Generic Severity rating scale [McDermott et al (1996)]

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Table 3.2: Simplified FMEA process [McDermott et al (1996)]

Column Heading (figure 3-9)	Column Content
Step 1: Review the process	Before starting the process the team should review the available documentation (see paragraph **Error! Reference source not found.**). If a detailed flowchart is not available, the team should create one (appendix 1 of the booklet). An expert is helpful here to answer any questions that the team may have.
Step 2: Brainstorm potential failure modes	To facilitate a thorough list of failure modes, the authors suggest that a series of brainstorming sessions be used, each focussed on a different element (e.g. people, methods, equipment, materials and the environment). Once the brainstorming is complete, the team can organise the various ideas into like categories to facilitate the elimination of non-viable ideas and the combination of similar ideas.
Step 3: List potential failure effects of each failure mode	There may be several effects for each failure mode – each must be listed separately. This step should be performed very thoroughly, as its result will form the basis of the work performed in the next steps. The analysis is performed by repeatedly asking the question: *if* the failure occurs; *then* what are the consequences?
Step 4: Assign Severity Rating	Severity ≡ Consequence of failure Rating done on a scale of 1 (not severe at all) to 10 (extremely severe). Each effect should be given its own severity rating, even if there are several effects for a particular failure mode. Authors give a generic rating scale – see figure 3-10.

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Table 3.2: Simplified FMEA process [McDermott et al (1996)] (continued)

Column Heading (figure 3-9)	Column Content
Step 5: Assign Occurrence Rating	Occurrence ≡ Probability of failure occurring (or the frequency at which it occurs) Rating done on a scale of 1 (probability virtually nil) to 10 (probability extremely high). Authors give a generic rating scale – see figure 3-11.
Step 6: Assign Detection Rating	Detection ≡ Probability of failure being detected Rating done on a scale of 1 (probability extremely high) to 10 (probability virtually nil). Authors give a generic rating scale – see figure 3-12.
Step 7: Calculate the Risk Priority Number (RPN) for each failure mode	RPN = Severity x Occurrence x Detection Those failure modes with highest RPN's are the ones with most potential for savings through preventive action.
Step 8: Prioritise the failure modes	The team must decide which of the failure modes deserve further attention (preventive action). A cut-off RPN may be set by the organisation for this purpose. Pareto-analysis may be used.

On the micro level, the analysis worksheet (figure 3-9) has certain deficiencies when compared to the standard worksheet (figure 3-7). These include a lack of codification/cross referencing facilities and a lack of differentiation between different modes of operation. It also does not analyse the difference between failure effects between the own (local) level, the next higher level and the systems level. This is probably because the authors do not use any systems segmentation. This lack of sophistication may lead to an inferior analysis, with a resultant sub-optimal maintenance plan.

On the other hand, the RPN risk assessment is a simple, but effective, method to limit maintenance actions to the more risky failure modes.

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Rating	Description	Potential Failure Rate
10	Very High: Failure is almost inevitable	More than one occurrence per day or a probability of more than three occurrences in 10 events ($C_{pk} < 0.33$).
9		One occurrence every three to four days or a probability of three occurrences in 10 events ($C_{pk} \approx 0.33$).
8	High: Repeated failures	One occurrence per week or a probability of 5 occurrences in 100 events ($C_{pk} \approx 0.67$).
7		One occurrence every month or one occurrence in 100 events ($C_{pk} \approx 0.83$)
6	Moderate: Occasional failures	One occurrence every three months or three occurrences in 1,000 events ($C_{pk} \approx 1.00$)
5		One occurrence every six months to one year or one occurrence in 10,000 events ($C_{pk} \approx 1.17$)
4		One occurrence per year or six occurrences in 100,000 events ($C_{pk} \approx 1.33$).
3	Low: Relatively few failures	One occurrence every one to three years or six occurrences in ten million events ($C_{pk} \approx 1.67$).
2		One occurrence every three to five years or 2 occurrences in one billion events ($C_{pk} \approx 2.00$).
1	Remote: Failure is unlikely.	One occurrence in greater than five years or less than two occurrences in one billion events ($C_{pk} > 2.00$)

*Should be modified to fit the specific product or process.

Figure 3-11: Generic Occurrence rating scale [McDermott et al (1996)]

Rating	Description	Definition
10	Absolute Uncertainty	The product is not inspected or the defect caused by failure is not detectable.
9	Very Remote	Product is sampled, inspected, and released based on Acceptable Quality Level (AQL) sampling plans.
8	Remote	Product is accepted based on no defectives in a sample.
7	Very Low	Product is 100% manually inspected in the process.
6	Low	Product is 100% manually inspected using go/no-go or other mistake-proofing gauges.
5	Moderate	Some Statistical Process Control (SPC) is used in process and product is final inspected off-line.
4	Moderately High	SPC is used and there is immediate reaction to out-of-control conditions.
3	High	An effective SPC program is in place with process capabilities (C_{pk}) greater than 1.33.
2	Very High	All product is 100% automatically inspected.
1	Almost Certain	The defect is obvious or there is 100% automatic inspection with regular calibration and preventive maintenance of the inspection equipment.

*Should be modified to fit the specific product or process.

Figure 3-12: Generic Detection rating scale [McDermott et al (1996)]

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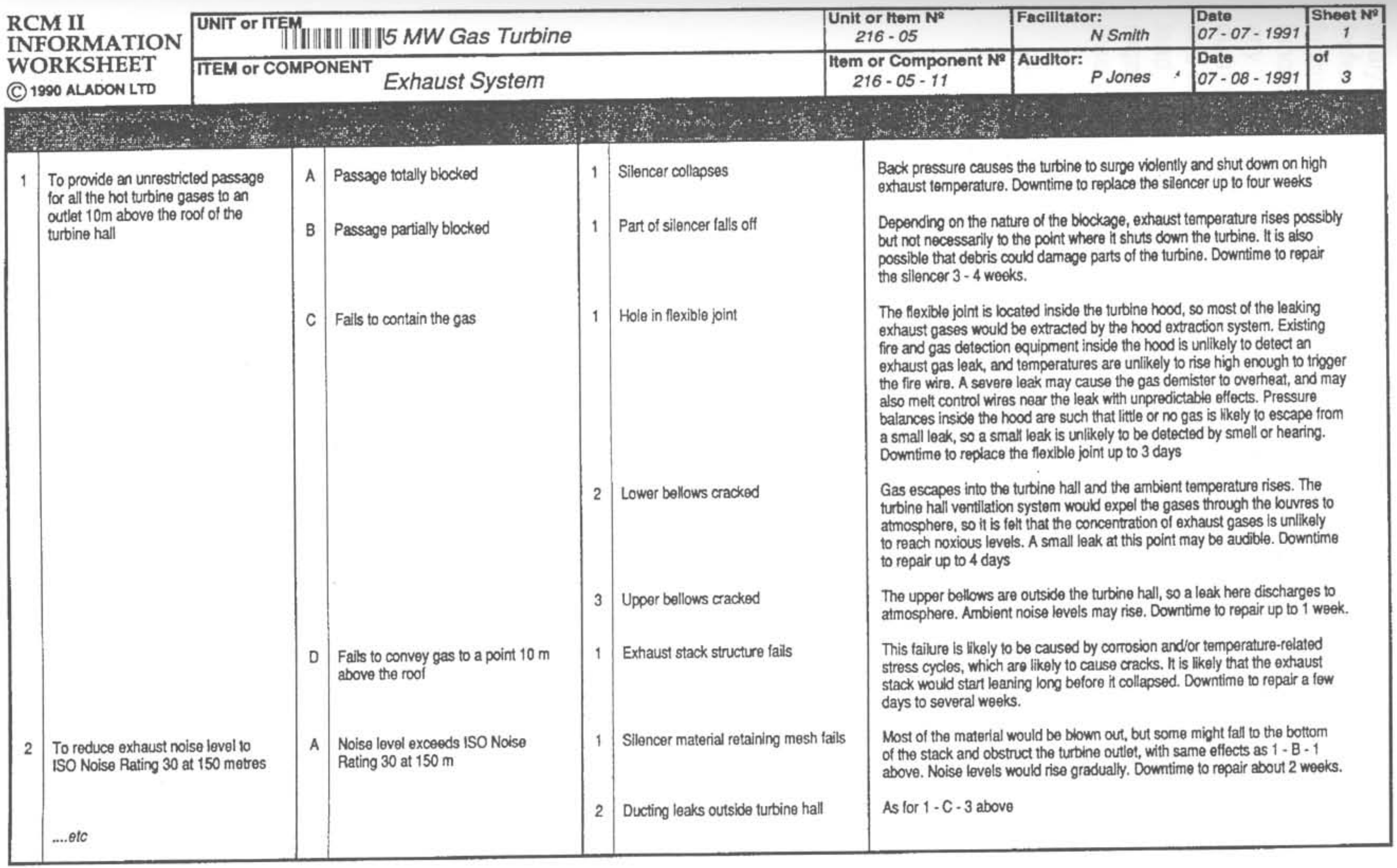
Moubray (1991) uses a worksheet that is a simplified version of that of MIL-STD-1629A, but with certain added features. The worksheet is shown in figure 3-13. The worksheet has a comprehensive identification part in the heading, which corresponds to and improves upon that of MIL-STD-1629A (especially when taking into account that it has an industrial, non-military function). Moubray uses one (or more) sheet per item, so that the first two columns in MIL-STD-1629A become redundant, at the expense of more paperwork. He then adds a column for Functional Failures after Nowlan and Heap (1978), who, although they did not include the FMEA in their text, implied this structure in their further analysis of failure consequences (p.87). This column, which is also used by practically all of the application texts (including Coetzee (1988), Smith (1993), Jones (1995) and Coetzee (1997/2)), assists the analyst in identifying all the relevant failure modes through a process more logical to the human mind. The process followed here is item | function | functional failure | failure mode, which corresponds with MIL-STD-1629A's item | function | failure mode | cause (in other words, it is only a matter of definition as to whether a failure mode is the functional failure or the root cause of failure – see Moubray p.57). The latter definition, as used by Moubray and other RCM texts, is the preferred one in the RCM world.

Moubray (1991) inadvertently addressed at least part of the problem identified by Harris (1985) (see paragraph 3.2.6) by including functional standards in the function descriptions. This makes it less probable that functional failures of the 'process degradation' class will not be identified - these are often overlooked in standard RCM, according to Harris.

Another feature, that Moubray (1991) adds (see figure 3-13), is a codification that is used as cross reference back to the FMEA analysis sheet from his later 'RCM II Decision Worksheet'. He uses numeric characters to codify the Functions and Failure Modes, while he uses alphabetic characters to codify functional failures. Then, lastly, he prefers to write down the failure effect(s) in words instead of analysing them with the purpose to determine the size of the risk involved (MIL-STD-1629A's severity class and McDermott's RPN [McDermott (1996)]). The verbatim description of the failure effect is a large benefit during the further analysis and for archiving purposes, but is not sufficient to assist the user to limit the application of his preventive maintenance resources to critical/important failure modes only.

Smith (1993) divides the FMEA into three separate worksheets within two of his RCM steps. He first uses the worksheet depicted in figure 3-14 within his step 4: System Functions and Functional Failures. This worksheet is used *firstly* to list all the system functions – in this case, 'black box' functions provided by the present sub-system to other systems/sub-systems as well as passive functions required for system success (such as fluid boundary integrity). *Secondly*, the functional failures are listed per function, as is the case in the discussion above on Moubray's approach.



RCM II INFORMATION WORKSHEET
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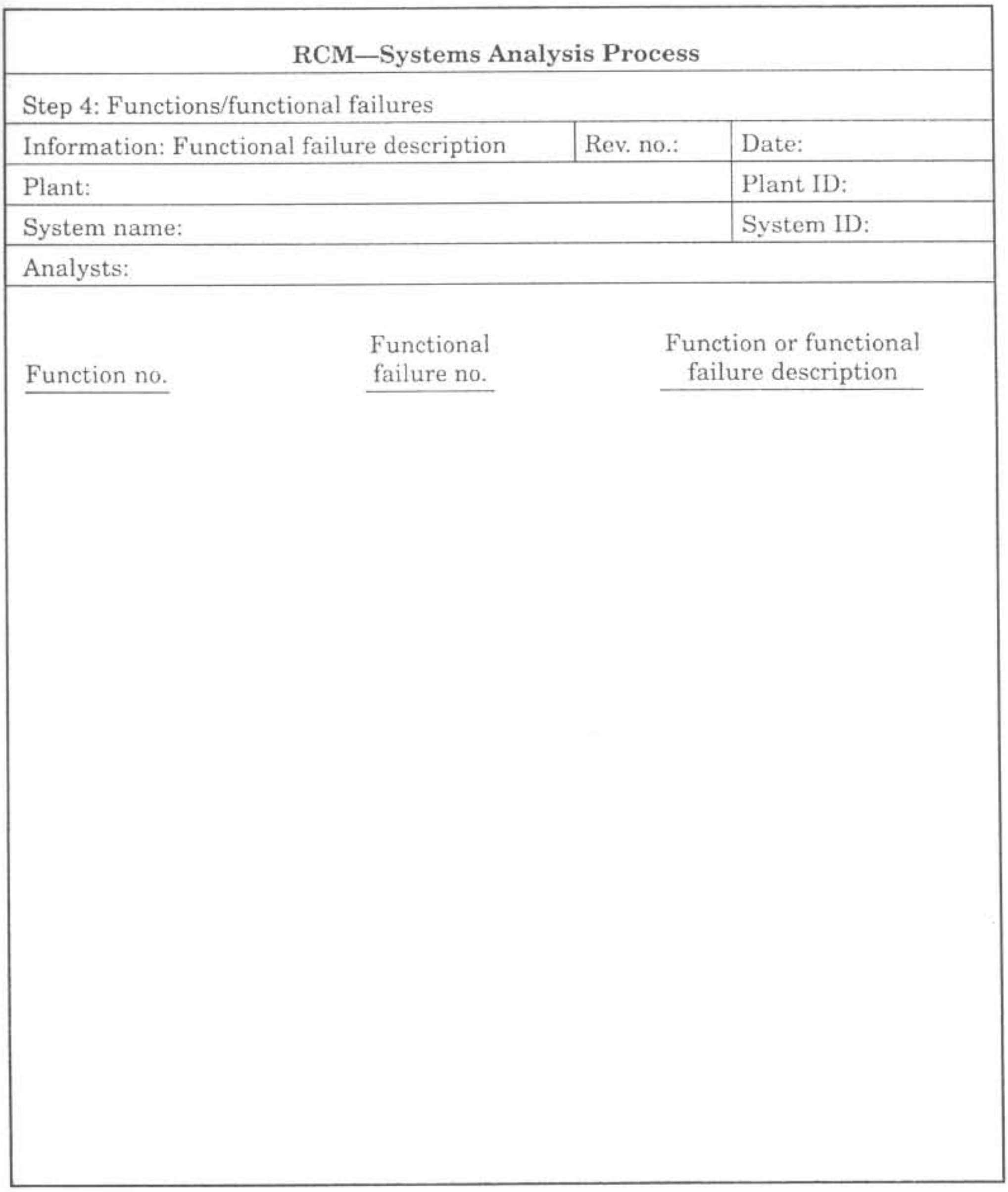
UNIT or ITEM 5 MW Gas Turbine	**Unit or Item Nº** 216 - 05	**Facilitator:** N Smith	**Date** 07 - 07 - 1991	**Sheet Nº** 1
ITEM or COMPONENT Exhaust System	**Item or Component Nº** 216 - 05 - 11	**Auditor:** P Jones	**Date** 07 - 08 - 1991	**of** 3

1	To provide an unrestricted passage for all the hot turbine gases to an outlet 10m above the roof of the turbine hall	A	Passage totally blocked	1	Silencer collapses	Back pressure causes the turbine to surge violently and shut down on high exhaust temperature. Downtime to replace the silencer up to four weeks
		B	Passage partially blocked	1	Part of silencer falls off	Depending on the nature of the blockage, exhaust temperature rises possibly but not necessarily to the point where it shuts down the turbine. It is also possible that debris could damage parts of the turbine. Downtime to repair the silencer 3 - 4 weeks.
		C	Fails to contain the gas	1	Hole in flexible joint	The flexible joint is located inside the turbine hood, so most of the leaking exhaust gases would be extracted by the hood extraction system. Existing fire and gas detection equipment inside the hood is unlikely to detect an exhaust gas leak, and temperatures are unlikely to rise high enough to trigger the fire wire. A severe leak may cause the gas demister to overheat, and may also melt control wires near the leak with unpredictable effects. Pressure balances inside the hood are such that little or no gas is likely to escape from a small leak, so a small leak is unlikely to be detected by smell or hearing. Downtime to replace the flexible joint up to 3 days
				2	Lower bellows cracked	Gas escapes into the turbine hall and the ambient temperature rises. The turbine hall ventilation system would expel the gases through the louvres to atmosphere, so it is felt that the concentration of exhaust gases is unlikely to reach noxious levels. A small leak at this point may be audible. Downtime to repair up to 4 days
				3	Upper bellows cracked	The upper bellows are outside the turbine hall, so a leak here discharges to atmosphere. Ambient noise levels may rise. Downtime to repair up to 1 week.
		D	Fails to convey gas to a point 10 m above the roof	1	Exhaust stack structure fails	This failure is likely to be caused by corrosion and/or temperature-related stress cycles, which are likely to cause cracks. It is likely that the exhaust stack would start leaning long before it collapsed. Downtime to repair a few days to several weeks.
2	To reduce exhaust noise level to ISO Noise Rating 30 at 150 metres	A	Noise level exceeds ISO Noise Rating 30 at 150 m	1	Silencer material retaining mesh fails	Most of the material would be blown out, but some might fall to the bottom of the stack and obstruct the turbine outlet, with same effects as 1 - B - 1 above. Noise levels would rise gradually. Downtime to repair about 2 weeks.
				2	Ducting leaks outside turbine hall	As for 1 - C - 3 above
	....etc					

Figure 3-13: FMEA worksheet in RCM II

He then uses the two worksheets depicted in figures 3-15 and figure 3-17 in his step 5: Failure Mode and Effects Analysis, for the remainder of the FMEA analysis. He now uses the segmentation of the system that he did previously (refer to paragraph 3.2.3) to show the relationship between the various functional failures and the equipment/components using the Equipment-functional failure matrix (figure 3-15). He specifically refrains from creating any connection between sub-assemblies/components and functions earlier during the process and only now identifies the connection between hardware and functional failures. This very important distinction should, in most cases, lead to a better RCM analysis - this follows from the previous discussion regarding the difference between *preserve function* and *preserve equipment* (see page 3-4).



RCM—Systems Analysis Process		
Step 4: Functions/functional failures		
Information: Functional failure description	Rev. no.:	Date:
Plant:		Plant ID:
System name:		System ID:
Analysts:		
Function no.	Functional failure no.	Function or functional failure description

Figure 3-14: Functions/Functional Failure Worksheet [Smith (1993)]

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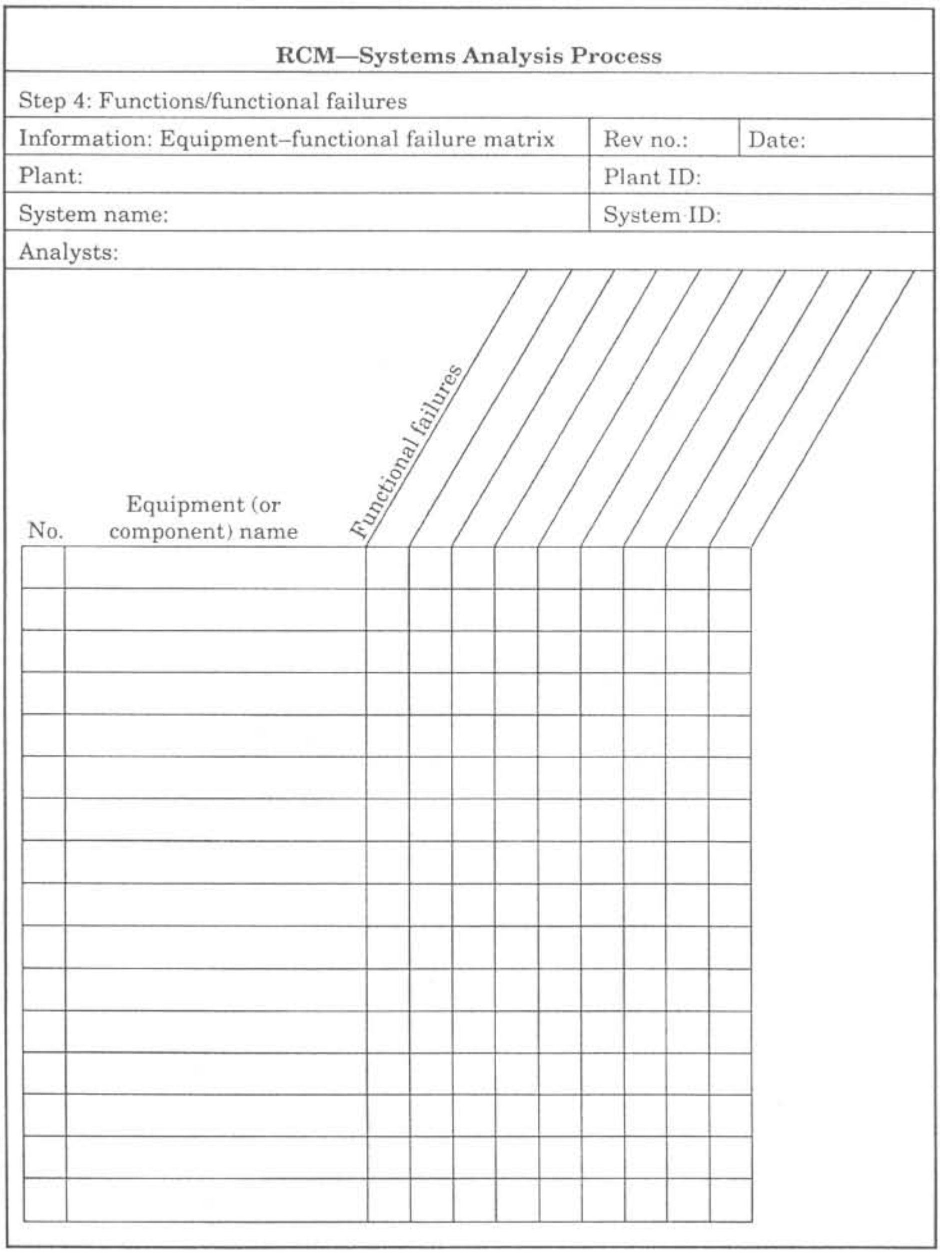
The FMEA Worksheet used by Smith (figure 3-17) is to a large extent compatible with the standard FMEA Worksheet as depicted in figure 3-7. The *first* difference is that he uses one sheet per functional failure, on which he then lists the various Component | Failure Mode | Cause combinations. The *second* difference is that he now extends the <item | function | functional failure | failure mode> or <item | function | failure mode | cause> (page 3-26) to <item | function | functional failure | failure mode | cause>. However, the reason for this is fairly clear – he uses the term 'functional failure' for a collection of smaller functional failures and then uses 'failure mode' for the real functional failure and 'cause' for the failure mode. The way in which the various authors confuse these terms and their use must of necessity be very confusing to the average user of RCM. A part of this problem of course lies with the difference in use of these terms between MIL-STD-1629A and that of



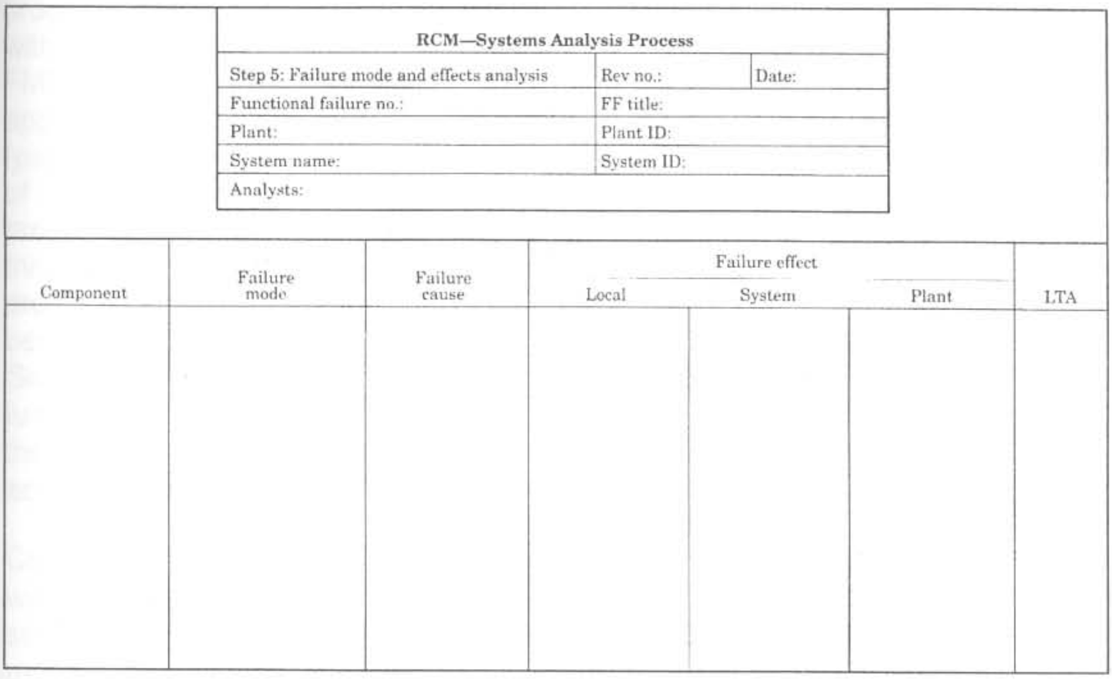
RCM—Systems Analysis Process

Step 4: Functions/functional failures

Information: Equipment–functional failure matrix	Rev no.:	Date:
Plant:	Plant ID:	
System name:	System ID:	
Analysts:		

No.	Equipment (or component) name	Functional failures								

Figure 3-15: Equipment-functional failure matrix [Smith (1993)]

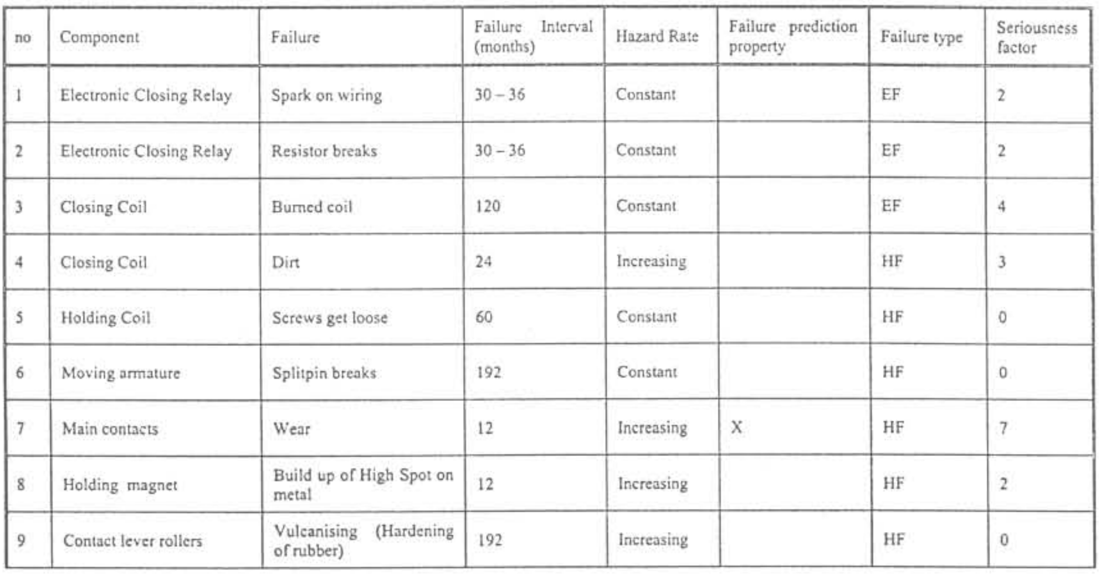


RCM—Systems Analysis Process		
Step 5: Failure mode and effects analysis	Rev no.:	Date:
Functional failure no.:	FF title:	
Plant:	Plant ID:	
System name:	System ID:	
Analysts:		

Component	Failure mode	Failure cause	Failure effect			LTA
			Local	System	Plant	

Figure 3-17: FMEA Worksheet [Smith (1993)]

standard RCM, so that the various authors are not fully to be blamed. The problem really lies in the definition (or lack thereof) of the different concepts. *Thirdly*, the FMEA Worksheet (figure 3-17) does not have columns for identifying different operational modes, failure detection methods and the severity class. The first of these (lack of columns) can be a severe restriction in military applications, while the others are more specific to the way in which Smith structures his version of RCM.



no	Component	Failure	Failure Interval (months)	Hazard Rate	Failure prediction property	Failure type	Seriousness factor
1	Electronic Closing Relay	Spark on wiring	30 – 36	Constant		EF	2
2	Electronic Closing Relay	Resistor breaks	30 – 36	Constant		EF	2
3	Closing Coil	Burned coil	120	Constant		EF	4
4	Closing Coil	Dirt	24	Increasing		HF	3
5	Holding Coil	Screws get loose	60	Constant		HF	0
6	Moving armature	Splitpin breaks	192	Constant		HF	0
7	Main contacts	Wear	12	Increasing	X	HF	7
8	Holding magnet	Build up of High Spot on metal	12	Increasing		HF	2
9	Contact lever rollers	Vulcanising (Hardening of rubber)	192	Increasing		HF	0

Figure 3-16: FMEA Worksheet [Le Clercq and Van den Broek (1999)]

Gits (1984) (p.99), when discussing his 'satisficing approach', comments that his way of 'part classification' has 'far reaching analogies' with FMEA. He never, in any of his referenced work, explains this part of his methodology properly, but in Gits (1988) he shows an example, which can be combined with the work of Le Clercq and Van den Broek (1999) to get an idea of the FMEA analysis used. These two examples are practically identical in approach and a small part of table 4.2 of Le Clercq and Van den Broek (1999) (page 35) is shown here (figure 3-16). This is very much a simplified version of the standard FMEA – when compared with the RCM standardised procedure of analysis of <item | function | functional failure | failure mode>, this only has two of the analysis steps, i.e. <item | failure mode>. The problem with this is, *firstly*, that the idea of *preserve function* (page 3-4) is lost because the analysis works only with hardware items and no functions. *Secondly*, this leads to a mixture of functional failures and failure modes in the functional failure column and *thirdly*, because of the extreme simplification, there is no certainty regarding whether all failure possibilities have been accounted for.

Columns 4, 5, 6 and 7 in the worksheet above are only used in later steps and will be referred to then. The seriousness column (column 8) is used in a way similar to the severity class in the standard FMEA worksheet (figure 3-7), but using a purpose-made classification system. One of the seriousness factor tables used by Le Clercq and Van den Broek (1999) (table 4.1, p. 35) is shown in figure 3-18. This table is used to allocate a seriousness factor (weight) to each failure based on its combination of failure effects on input/output variables, such as functionality, costs, manpower needed, quality impact, safety impact and secondary damage. This is a good, yet somewhat simplistic method of assessing risk factors that can be used with good effect to enhance the RCM methodology. However, this should be combined with the full functional analysis and failure effects estimation of the full FMEA methodology.

Failure consequence	Weight factor			
	0	1	2	3
1. Functional	None	Tripping	HSCB won't close	N/a
2. Material costs	Low	Medium	High	N/a
3. Workload needed	≤1 hour	1 ≤ 2 hours	≥ 2 hours	N/a
4. Safety	No	N/a	N/a	Yes
5. Secondary Damage	No	N/a	Yes	N/a

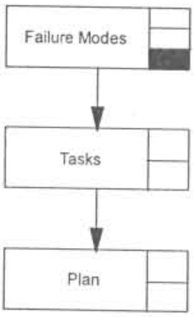
Figure 3-18: Seriousness Factor Table

The Business Centred Maintenance (BCM) approach of Kelly (1997) does not perform its analysis through a formal study of item functionality, and the failure modes that cause functional failures. It rather relies on either the manufacturer's unit life plan or, if that is not available, an engineering study of the item and its known failures.

The MSG-3 document of the Air Transport Association of America (ATA) [MSG-3 (1993)], differs from Nowlan and Heap (1978) in that it does not specify the use of the FMEA at all. What it does is to specify an 'FMEA like' approach where the following must be identified for each MSI: *firstly* functions (defined as the normal characteristic actions of the item), *secondly* functional failures (how the item fails to perform its function), *thirdly* failure effects (the result of the functional failure) and *fourthly* failure causes (why the functional failure occurs). This is similar to the item | function | functional failure | failure mode approach of Moubray (1991) and other authors, where *failure causes* ≡ *failure modes*. The problem with the MSG approach is that it does not provide any specific guidelines regarding the process of identifying failure modes. It probably means to suggest that a technique such as the FMEA or FMECA or equivalent be used. The premise presumably is not to prescribe the specific technique, but to allow freedom of choice. In the airline industry, this is possibly a valid approach, but in general industry, with its dearth of failure analysis expertise, one has to provide a much more detailed 'recipe'.

The version of RCM used for the maintenance programs of USA army aircraft is based on the original (1979) version of MSG-3 [Anderson and Neri (1990), p.19]. Nevertheless, it does specify the use of an FMECA as a basis of understanding the failure process [p.16 op. cit.].

3.2.5. Prioritisation of Failure Modes



The original implementation of RCM [Nowlan and Heap (1978)] did not address the problem of the relative criticality of failure modes at all. That is, apart from the classification of failure modes (paragraph 3.2.6), which differentiates between different failure modes on the basis of their relative criticality, but never attempts to assign an absolute criticality value to individual failure modes. Such value is indispensable in applying limited preventive resources to a system (especially when combined with the prioritisation suggested by Coetzee (1997/2), described in paragraph 3.2.2, page 3-11). Both versions of the FMEA technique described above (paragraph 3.2.4) includes a form of criticality allocation:

- MIL-STD-1629A (1980) allocates a severity class to each failure mode, based on the severity scale (repeated from paragraph 3.2.4):
    - Category I – Catastrophic – a failure that may cause death or system loss.
    - Category II – Critical – a failure that may cause severe injury, major property damage, major system damage, which will result in mission loss.
    - Category III – Marginal – a failure that may cause minor injury, minor property damage, minor system damage, which will result in delay, mission degradation.
    - Category IV – Minor – a failure that will not cause injury, property damage, system damage, bur which will result in unscheduled maintenance or repair.

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- McDermott et al (1996) uses a Risk Priority Number (RPN), which is the product (through multiplication) of three factors (repeated from paragraph 3.2.4):
  - Severity ≡ Consequence of failure. Rating is done on a scale of 1 (not severe at all) to 10 (extremely severe). Each effect of the failure mode is given an own severity rating, even if there are several effects for a particular failure mode. The authors suggest a generic rating scale – see figure 3-10
  - Occurrence ≡ Probability of failure occurring (or the frequency at which it occurs). Rating is done on a scale of 1 (probability virtually nil) to 10 (probability extremely high). The authors suggest a generic rating scale – see figure 3-11.
  - Detection ≡ Probability of failure being detected. Rating is done on a scale of 1 (probability extremely high) to 10 (probability virtually nil). The authors suggest a generic rating scale – see figure 3-12.

As discussed in paragraph 3.2.4 above, Gits (1988) uses a column (column 8) in his FMEA-type worksheet (figure 3-16) in a way similar to the severity class in the standard FMEA worksheet (figure 3-7), but using a purpose-made classification system. One of the seriousness factor tables used by Le Clercq and Van den Broek (1999) (table 4.1, p. 35) is shown in figure 3-18. This table is used to allocate a seriousness factor (weight) to each failure based on its combination of failure effects on input/output variables, such as functionality, costs, manpower needed, quality impact, safety impact and secondary damage.

Additional to the above-mentioned criticality measures, many practitioners of RCM uses a prioritisation of failure modes through the criticality analysis afforded by the extension of the FMEA to a full FMECA (Failure Mode, Effects and Criticality Analysis). One of the more important standard works on FMECA is again MIL-STD-1629A (1980), that describes the purpose of a criticality analysis as follows:

> "*The purpose of the criticality analysis (CA) is to rank each potential failure mode identified in the FMEA Task 101, according to the combined influence of severity classification and its probability of occurrence based upon the best available data.*"

The FMECA supports two ways of establishing the criticality of a failure mode. When no data regarding the failure rate of the item is available, it suggests a qualitative approach based on a standard probability of occurrence scale as follows:

- Level A – Frequent. A single failure mode probability larger than 20% of the total probability of failure of the item during the operating time interval.
- Level B – Reasonably probable. A single failure mode probability larger than 10% but less than 20% of the total probability of failure of the item during the operating time interval.

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- Level C – Occasional. A single failure mode probability larger than 1% but less than 10% of the total probability of failure of the item during the operating time interval.
- Level D – Remote. A single failure mode probability larger than 0,1% but less than 1% of the total probability of failure of the item during the operating time interval.
- Level E – Extremely Unlikely. A single failure mode probability less than 0,1% of the total probability of failure of the item during the operating time interval.

On the other hand, if sufficient data regarding the failure rate of the item is available, it suggests a quantitative approach based the combination of several parameters, as follows:

- Failure effect probability β - referring back to the FMEA, the β value is the conditional probability that the failure effect will result in the allocated severity classification, given that the failure mode occurs. The β value thus represents the judgement of the analyst regarding the conditional probability that the loss will actually occur. This judgement is based on the scale:
  - Actual loss: $\beta=1,00$
  - Probable loss: $0,1<\beta<1,00$
  - Possible loss: $0<\beta<0,1$
  - No effect: $\beta=0$
- Failure mode ratio α - the fraction of the item failure rate attributable to the particular failure mode (i.e. the probability that the item will fail in the specific failure mode, expressed as a decimal fraction).
- The item failure rate λ_p (1/MTTF).
- Operating time t (in hours) or the number of operating cycles of the item per mission.

The failure mode criticality number C_m is then calculated as the specific failure mode's contribution to the total criticality of the item, after which the total item criticality C_r is calculated by adding the C_m values for all the n failure modes of the item:

$$C_m = \beta\alpha\lambda_p t$$

$$C_r = \sum_{i=1}^{n} (C_m)_i$$

The standard format for the criticality analysis is presented in figure 3-19, which is self-explanatory, as it is based on a logical extension of the FMEA worksheet presented in figure 3-7.

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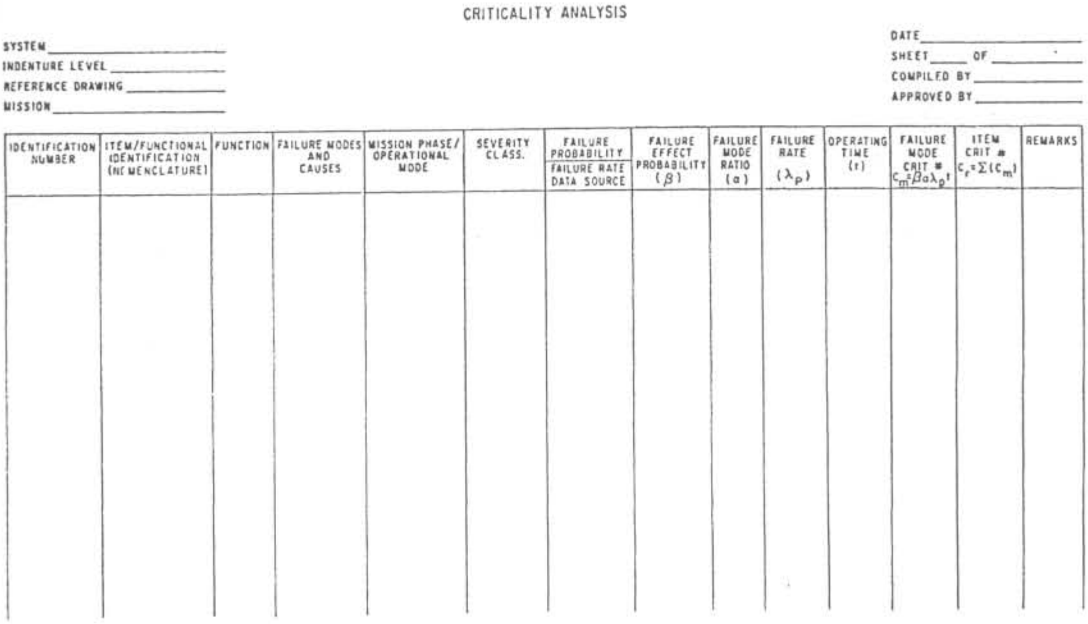

CRITICALITY ANALYSIS

SYSTEM ________________
INDENTURE LEVEL ________________
REFERENCE DRAWING ________________
MISSION ________________

DATE ________________
SHEET _____ OF ________
COMPILED BY ________________
APPROVED BY ________________

IDENTIFICATION NUMBER	ITEM/FUNCTIONAL IDENTIFICATION (NOMENCLATURE)	FUNCTION	FAILURE MODES AND CAUSES	MISSION PHASE/ OPERATIONAL MODE	SEVERITY CLASS.	FAILURE PROBABILITY FAILURE RATE DATA SOURCE	FAILURE EFFECT PROBABILITY (β)	FAILURE MODE RATIO (α)	FAILURE RATE (λ_p)	OPERATING TIME (t)	FAILURE MODE CRIT # $C_m=\beta\alpha\lambda_p t$	ITEM CRIT # $C_r=\Sigma(C_m)$	REMARKS

Figure 3-19: Criticality Analysis Worksheet

The criticality numbers (C_m and C_r) as calculated above (or the probability of occurrence levels in the case of the qualitative approach) can be used directly to prioritise items/failure modes. However, the *criticality matrix* presented in figure 3-20 gives a better way of prioritisation. It provides the analyst with a template that can be used to prioritise by using both the criticality numbers (or probability of occurrence) and the *severity classification* allocated in the FMEA in a single prioritisation action. The matrix is constructed by inserting item or failure mode numbers in matrix locations representing the severity classification and either the probability of occurrence or the criticality number (whichever applies). The completed matrix then gives a visual representation of the relative priorities of the various items/failure modes.

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 defines risk as:

$$R_i = P_i \times C_i$$

R_i = Risk of the i^{th} risk consequence factor

P_i = Probability of occurrence of the i^{th} risk factor

C_i = Consequence of occurrence of the i^{th} risk factor

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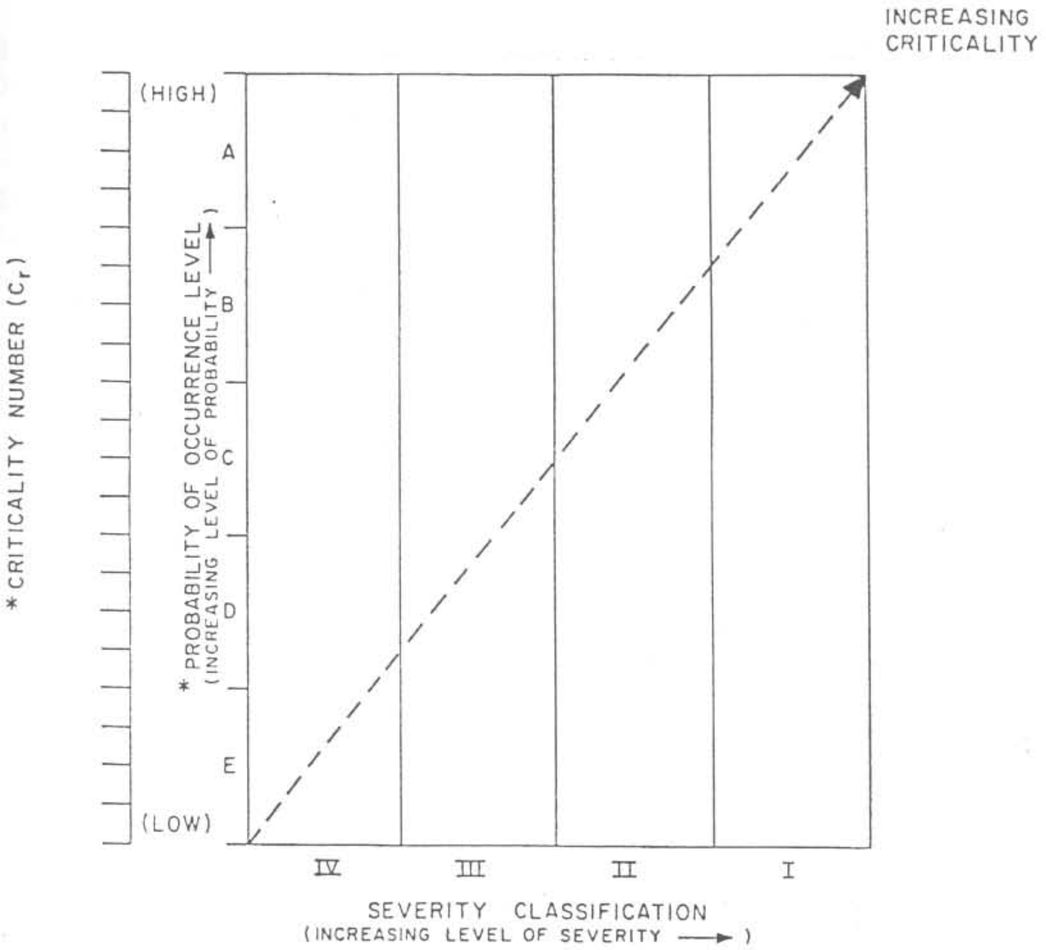


* NOTE: BOTH CRITICALITY NUMBER (C_r) AND PROBABILITY OF OCCURRENCE LEVEL ARE SHOWN FOR CONVENIENCE.

Figure 3-20: Criticality Matrix Template

The typical consequence factors considered are:

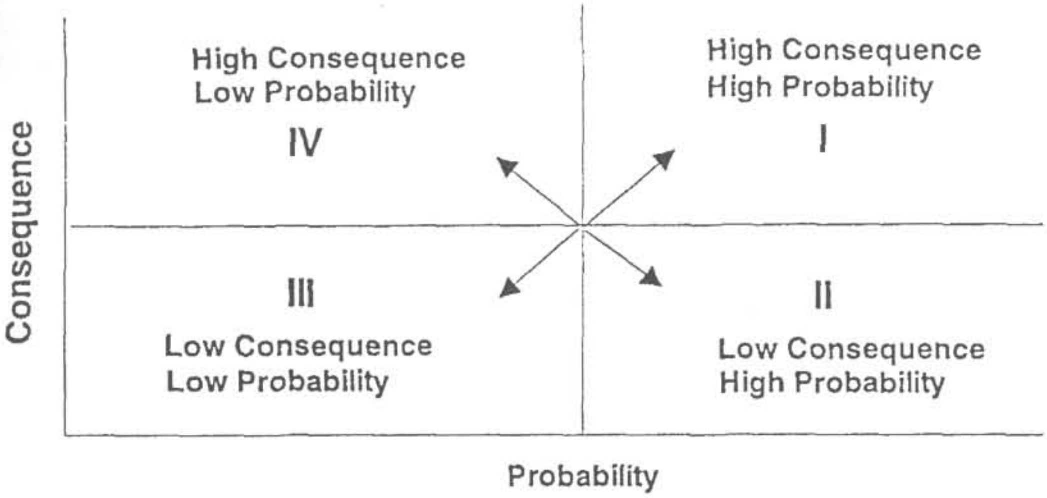
Risk consequence factor 1: **Safety**
Risk consequence factor 2: **Lost Production**
Risk consequence factor 3: **Lost Quality**
Risk consequence factor 4: **Environmental Effects**
Risk Consequence factor 5: **Maintenance**

The total risk for the combined consequence factors is given by:

$$R_t = \sum_{i=1}^{5} R_i = \sum_{i=1}^{5} \left(P_i \times C_i\right)$$

As is the case with the other criticality measures presented above, the total risk can be calculated per failure mode and totalled per item. This gives a quantitative measure which is based on the same premise as the McDermott et al (1996) Risk Priority Number (RPN)[2] and similar to that of FMECA [MIL-STD-1629A (1980)], but from a different perspective. In the case of FMECA, the probability of occurrence of a single failure effect ($\beta\alpha\lambda_p$) is multiplied with the consequence in terms of duration of mission or mission phase and then totalled over all the failure effects to give the total criticality (or risk) per item. In the present case the probability of occurrence of multiple failure effects are used to calculate a total risk per failure mode and per item in common consequence terms, which could be mission time in military applications and which will certainly be monetary terms in industrial applications.

Another benefit of the risk approach, which should be shared by FMECA, is that the risk can be plotted on a Consequence-Probability matrix. This affords the possibility of managing the risk over the medium to long term by either reducing the consequence severity or the probability of occurrence or both. The possibilities are shown in figure 3-21, which shows the different risk change options – the preference for risk change should be in the order direction III | direction II, direction IV, direction I (direction I is one of negative growth). Figure 3-22 shows iso-risk lines on the same set of axes, while figure 3-23 depicts a typical two-year failure mode risk reduction result.



igure 1 Risk change possibilities

Kelly (1997) does not analyse at the level of failure modes (paragraph 3.2.4) and thus failure mode criticality is not relevant in the case of his Business Centred Maintenance.

This facet is not addressed at all by MSG-3 (1993). On the other hand Anderson and Neri (1990), p. 16, prescribes the use of FMECA, although their RCM approach for US army aircraft is based on MSG-3.

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[2] In the case of McDermott et al (1996) the Risk Priority Number (RPN) also includes a third factor, the possibility of detection. On the other hand, it does not take into account the five consequence areas suggested by Jones (1995).995).I I

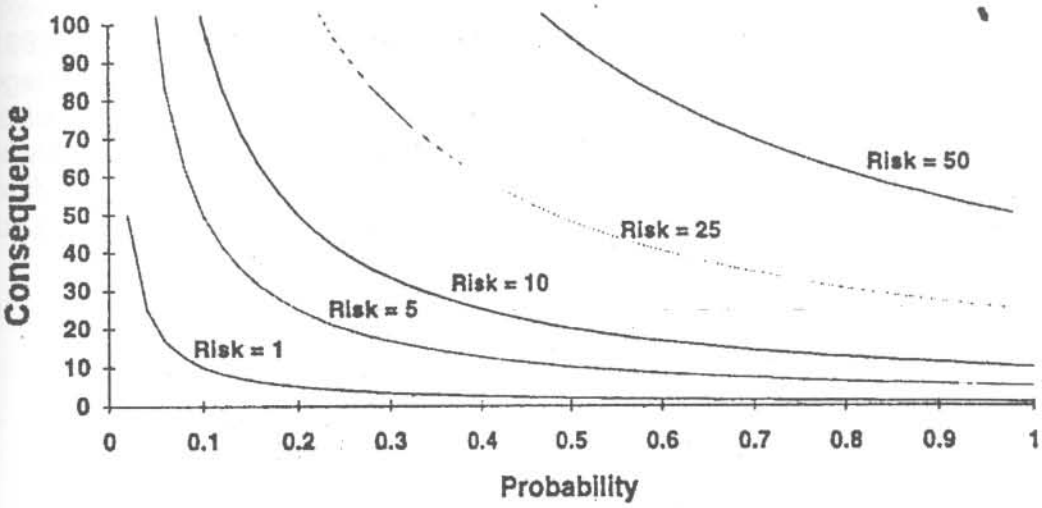


Figure 3-22: Constant risk contours

Although the methods presented by Gits (1988) and McDermott et al (1996) has a contribution to make and will be preferred by many users and practitioners of RCM, they are really too simplistic in nature and one will have to base any improved methods on FMECA [MIL-STD-1629A] and the risk calculations of Jones (1995).

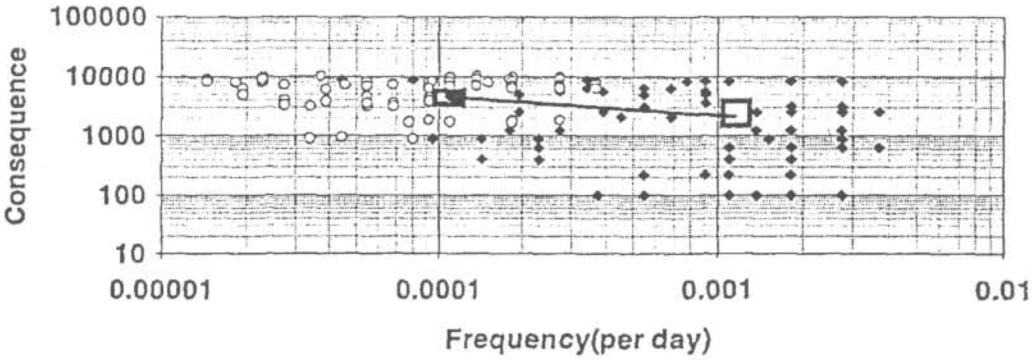
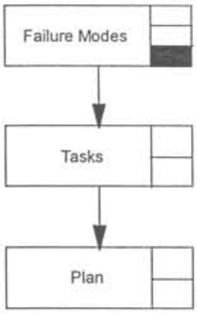


Figure 3-23: Two-year risk reduction result

3.2.6. Classification of Failure Modes



The 'new approach' to scheduled maintenance that was developed during the late 60's of the previous century had its foundation at United Airlines: "In 1966, an internal memorandum at United suggested that a decision tree approach, ... might provide a more orderly and more objective means for designing preventive maintenance programs." [Matteson (1989)]. This basic decision tree was further developed to the one that, together with the segmentation process (paragraph 3.2.2) and task selection decision tree (paragraph 0) formed the basis of the original RCM approach of Nowlan and Heap (1978). This decision tree [Nowlan and Heap (1978) exhibit 4.2, p.88], which is shown in figure 3-24, forms the basis of the classification of failure modes in RCM.

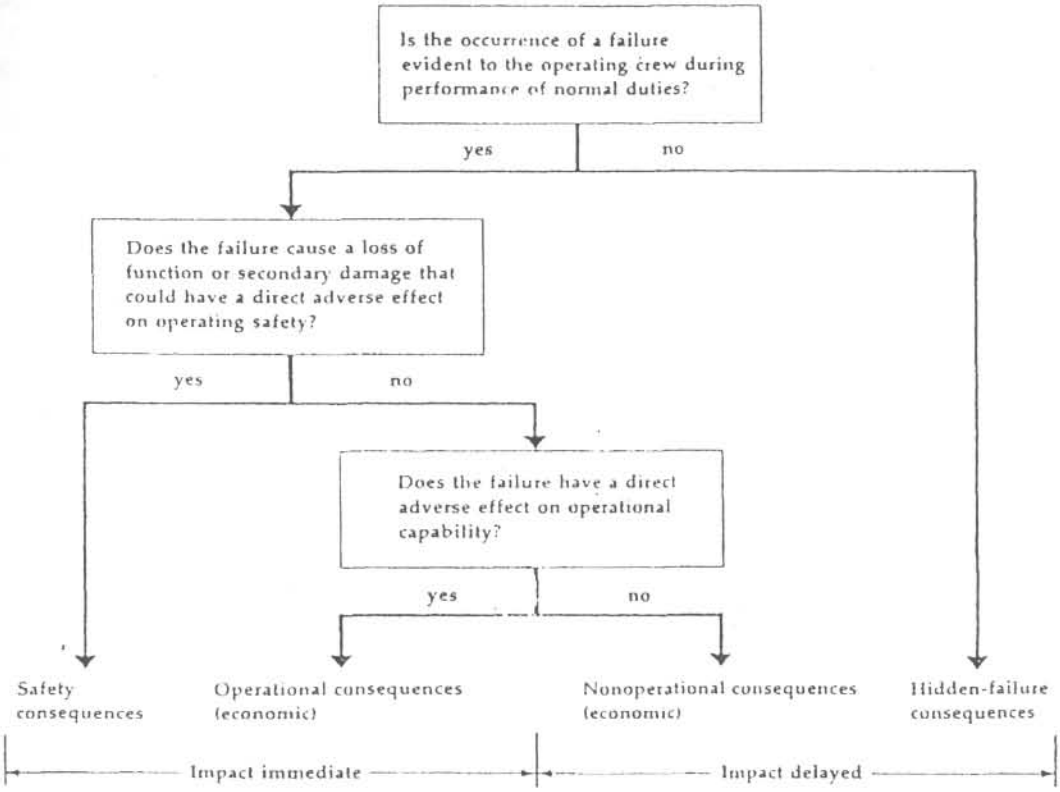


Figure 3-24: Failure Consequence Decision Tree [Nowlan and Heap (1978)]

The original version of RCM classified failure modes into four failure consequence classes:

- Hidden failures – these are failures that will not have an effect on the system performance at all, but which, if it remains undetected, can lead to a multiple failure. A typical example of a hidden failure is the failure of a non-failsafe safety device – if such a device fails, the failure will typically not be detected. When the function which is protected by the device misbehaves and the device is in the failed state, the protected function will fail, mostly catastrophically (a so-called multiple failure).
- Failures with safety and/or environmental consequences – this includes all failures that will cause danger to people, the environment and property.
- Failures with operational consequences – failures that will result in partial or total loss of operational capability, resulting in loss of revenue.

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- Failures with non-operational consequences – failures that do not affect operational capability, but are costly due to the impact of repair cost.

The importance of this top structure classification of failure modes is that the task selection process differs depending on the failure consequences. The structure of the decision tree discussed above is also based on the relative criticality of the four classes of failure consequences. The most critical of the consequence categories is that of hidden failures. The relative criticality then progresses downward from hidden -> safety and environmental -> operational -> non-operational. The following short descriptions highlights this difference between the four failure consequence classes:

- Hidden failures, as previously defined, have a safety impact, mostly with a risk of multiple failure (often of catastrophic nature). For a preventive task to be the acceptable strategy in this category, it must reduce the risk of a multiple failure to an acceptably low level. If a preventive task is not found that reduces the risk to a low enough level, the default strategy is to specify a failure finding task or, if that is not effective, to redesign if a multiple failure can negatively affect safety or the environment. This (and the next) categories are those for which economics play a lesser role due to the possible loss of life, property and permanent environmental damage.
- Safety and Environmental Consequences includes all failures that will cause danger to people, the environment and property. For a preventive task to be the acceptable strategy in this category, it must reduce the risk of failure totally or to a very (acceptably) low level. If a preventive task is not found that reduces the risk to a low enough level, the default strategy is to redesign, as a compromise in this category is not acceptable. As was stated above this is the second category where economics play a lesser role due to the possible loss of life, property and permanent environmental damage.
- Operational Consequences - this and the next category (non-operational consequences) are the two categories for which the consequences are primarily of an economic nature. For a failure mode to have operational consequences, it must affect the production output of the business negatively. It thus causes a production loss, with an accompanying loss in sales and thus profit. Each time that a failure thus occurs, money is lost due to production being lost, as well as due to the cost of repairing the failure. For a preventive task to be an acceptable strategy, it must firstly be technically feasible in preventing a failure mode with operational consequences. That is, it must reduce the risk of failure to a low enough level so that the benefits of the preventive action (less production lost and lower breakdown costs) are worth the cost of implementing it. Secondly, it must also be economically feasible. The added cost due to the implementation of the task must be lower than the benefit in terms of reduction of lost production and cost of failure. If a preventive task is not found that is both technically and economically feasible, the default strategy is to repair the failure mode only after failure (corrective maintenance), with redesign as an option.

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- Non-operational consequences - This category is very similar to the previous one (operational consequence) in that its consequences are also primarily of an economic nature. Its difference lies in the fact that it does not affect the production output of the business negatively. Its negative economic effect is thus limited to the cost incurred in repairing the failure each time that such failure occurs. As is the case for operational consequences, a preventive task will be an acceptable strategy if it is both technically feasible in preventing the failure mode and economically feasible (the added cost due to the implementation of the task lower than the benefit in terms of reduction of the cost of failure). If a preventive task is not found that is both technically and economically feasible, the default strategy is to repair the failure mode only after failure (corrective maintenance) with redesign as an option.

The original Nowlan and Heap approach suggested that the *first* question (whether failure is evident) in the tree be asked for each function of an item and the *second* (operational safety) for each functional failure and for each failure mode (pp.87/88). The reason for this differentiation is not clear and practically all of the later practitioners use each of the three questions in the decision tree per failure mode. Examples are Moubray (1991), pp.71and87, Smith (1993), p. 89 and Coetzee (1997/2), p.98 (also refer to table 3.3 below). This is a more conservative approach that will ensure that each failure mode (being one of the many failure possibilities of a typical item) is classified correctly according to its specific failure consequences.

The decision diagram of figure 3-24 has weathered the further development of the methodology well. Most of the later authors use it with only a few adaptations in terminology and detail changes in the three questions to promote clarity (apart from cosmetic changes). One of the more fundamental changes was the addition of the environmental consequence sub-class to what then became known as the safety *and environmental* consequence class by Moubray (1991). The detailed questions used by the various authors are shown in table 3.3. It is clear that, although no fundamental changes were made to the principle, there was an attempt towards producing more clarity in the questions.

MSG-3 (1993), on the other hand, has made a more fundamental change in introducing a fourth question to differentiate between hidden failures with a safety impact (the traditional stand) and those with an economic impact (bottom line in table 3.3). This is shown in figure 3-25, which is presented in a slightly different format than that of MSG-3, but with the same logic and wording as MSG-3. This change, which is a severity sub-classification of hidden failures, has, apart from Smith (1993), not been taken up in the commercial applications of RCM. MSG-3 also substituted the term 'consequence' by 'effect', such that the result of failure is called its 'failure effect' instead of the usual 'failure consequence'. This change could have been well accepted by the RCM user population, apart from the fact that it is in conflict with the terminology of FMEA and FMECA, where the 'E' represents a 'failure effect' with a different meaning. The old terminology should thus preferably be retained.

Table 3.3: Comparison of Failure Consequence questions

Consequence class	Author	Question
Hidden	Nowlan and Heap (1978)	Is the occurrence of a failure evident to the operating crew during performance of normal duties?
	Moubray (1991)	Will the loss of function caused by this failure mode on its own become evident to the operating crew under normal circumstances?
	Smith (1993)	Under normal conditions, do the operators know that something has occurred?
	Coetzee (1997/2)	Is the loss of function due to the occurrence of this failure mode evident to the operations personnel?
	MSG-3 (1993)	Is the occurrence of a functional failure evident to the operating crew during the performance of normal duties?
Classification of hidden failures (safety/ economic)	MSG-3 (1993)	Does the combination of a hidden functional failure and one additional failure of a system related or back-up function have an adverse effect on operating safety?

Harris (1985) divides the Operational Consequence category into two sub-categories, namely a 'mechanical performance' category and a 'process performance' category. His motivation for this is *firstly* that he defines the concept of 'chemical plant integrity', which he considers to be the sum of plant mechanical performance, plant process performance and plant financial performance. *Secondly*, he points out that the "the literature tends to largely ignore the relationship between maintenance and process performance" [Harris (1985), p. 47]. *Thirdly*, he considers the inclusion of a process performance category necessary "because the RCM technique does not explicitly account for the effect of functional failures on process performance." [Harris (1985), p. 255]. Examples of maintenance tasks following on process

Table 3.3: Comparison of Failure Consequence questions (continued)

Consequence class	Author	Question
	Nowlan and Heap (1978)	Does the failure cause a loss of function or secondary damage that could have a direct adverse effect on operating safety?
	Moubray (1991)	Does the failure mode cause a loss of function or other damage, which could (i) hurt or kill someone or (ii) breach any known environmental standard or regulation?
Safety / Environment	Smith (1993)	Does this failure mode cause a safety problem?
	Coetzee (1997/2)	Does the failure mode cause a loss of function or secondary damage that could have a direct adverse effect on operating safety or the environment?
	MSG-3 (1993)	Does the functional failure or secondary damage resulting from the functional failure have a direct adverse effect on operating safety?

performance degradation that he lists are the cleaning of boiler surfaces, the replacement of catalyst, overhaul of process pumps, cleaning of process piping and cleaning of heat exchangers. He adds that these are the more well-defined and quantifiable situations: "An additional dimension is added to the problem of relating maintenance to process performance when the less quantifiable effect of maintenance actions such as lubrication, servicing and minor adjustment is considered." [Harris (1985), p. 49]. Whether one should go to the extreme of adding an additional failure consequence category to the already well established four category consequence classification is an open question. It could further add to the confusion that the RCM user experiences. However, the concerns aired by Harris should possibly be addressed in the detailed definition of the operational consequence category.

Table 3.3: Comparison of Failure Consequence questions (continued)

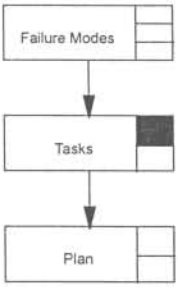
Consequence class	**Author**	**Question**
Operational	Nowlan and Heap (1978)	Does the failure have a direct adverse effect on operational capability?
	Moubray (1991)	Does the failure mode have a direct adverse effect on operational capability (output, quality, customer service or operating costs in addition to the direct cost of repair)?
	Smith (1993)	Does this failure mode result in a full or partial outage of the plant?
	Coetzee (1997/2)	Does the failure mode have a direct adverse effect on operational capability?
	MSG-3 (1993)	Does the functional failure have a direct adverse effect on operating capability?

As was mentioned in the previous paragraph (paragraph 3.2.4), Kelly (1997) does not analyse at the level of failure modes and thus failure mode classification is not relevant in the case of his Business Centred Maintenance.

3.2.7. Task Selection

3.2.7.1. Introduction

The task selection part of RCM is in a certain sense the heart of the methodology. Although all the previous are necessary to identify those failure modes that needs to be addressed, the task selection process is really where the constituent 'parts' of the maintenance plan are formulated. Again, the basis laid by Nowlan and Heap (1978) has withstood the test of time and is in most cases used in the same format to this day. MSG-3 (1993) has made certain changes in this area, but those are mostly in adding additional blocks of a minor nature (lubrication and pre-flight checks) to the front end of the original decision tree.



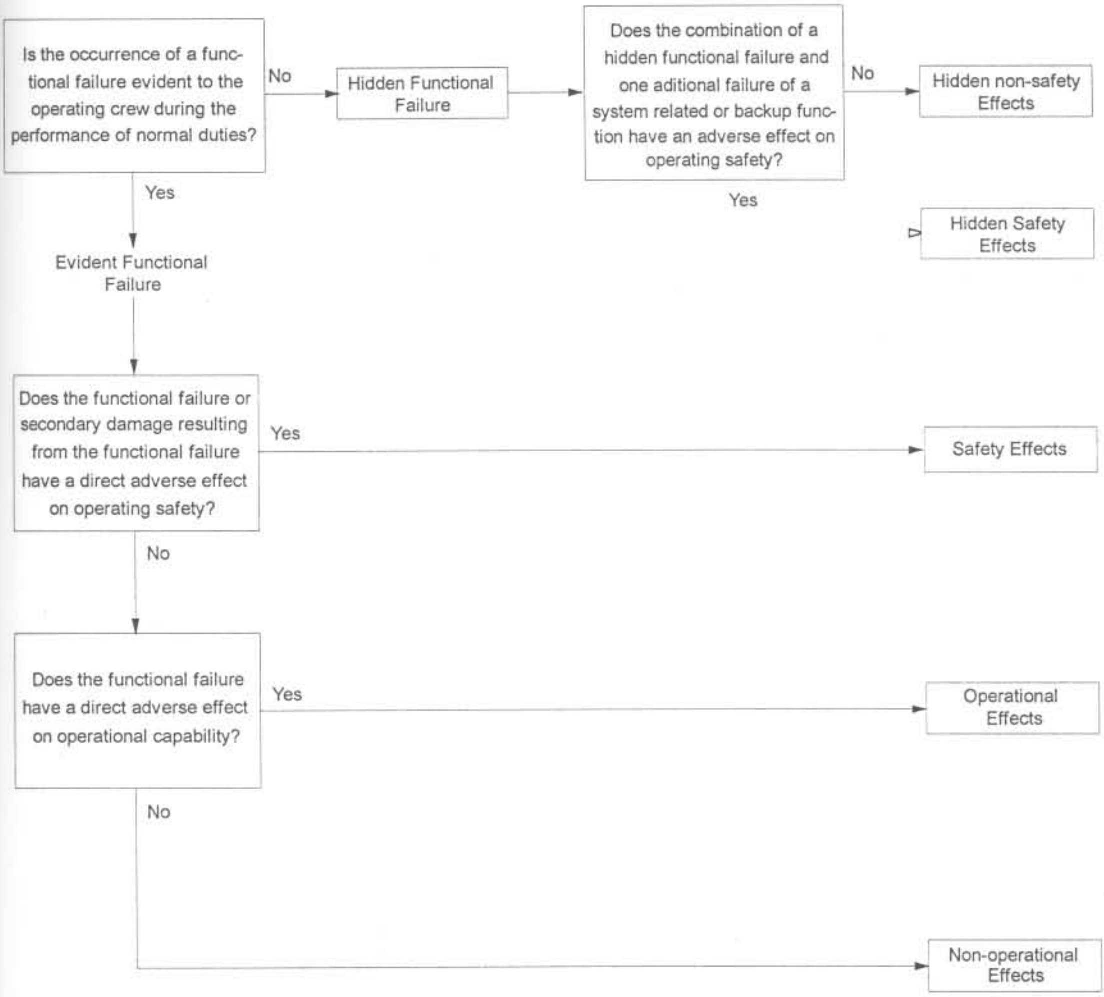


Figure 3-25: Failure Effects Decision Tree [MSG-3 (1993)]

3.2.7.2. Task types

If one widens one's definition of what constitutes a maintenance task type, the original RCM text [Nowlan and Heap (1978)] suggests seven task types:

- On-condition task
- Rework task
- Discard task
- Failure Finding task
- Servicing and Lubrication task
- Redesign task
- Corrective Maintenance task

Apart from naming changes, none of the other authors on the subject made significant changes to this task structure:

(i) An On-condition task (inspection) is also called a Condition Monitoring task in general industry or a Predictive task. Coetzee (1997/2) retains the name On-condition task, Moubray (1991)

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calls it a Scheduled On-condition task, Smith (1993) a Condition-directed task and Kelly (1997) and Gits (1984) a Condition-based task. MSG-3 (1993) differentiates between two types of on-condition tasks, i.e. Inspection and Functional Checks. A third type, Operating Crew Monitoring, was included in the original (1979) version of MSG-3, but was removed as from MSG revision 1 (1987).

(ii) The name Rework task has not withstood the test of time. Moubray (1991) calls it a Scheduled Restoration task, Smith (1993) a Time-directed task (name shared with next category), Gits (1984) a Use-based task (name shared with next category), Kelly (1997) Fixed-time maintenance (name shared with next category), MSG-3 (1993) a Restoration task and Coetzee (1997/2) a Reconditioning task.

(iii) The name Discard task, on the other hand, did remarkably well. MSG-3 (1993) has kept it as is, while Moubray (1991) calls it a Scheduled Discard task. Smith (1993) calls it a Time-directed task (name shared with previous category), Gits (1984) a Use-based task (name shared with previous category), Kelly (1997) Fixed-time maintenance (name shared with previous category) and Coetzee (1997/2) a Replacement task.

(iv) The Failure-Finding task category is also retained by two of the major authors, i.e. Moubray (1991) and Smith (1993) using the exact name as proposed by Nowlan and Heap (1978) - the only major 'RCM' - publication that uses different terminology is MSG-3 (1993), which calls it a 'Check to verify operation'. Kelly (1997) and Gits (1988) (both non-RCM) also call it by different names. Kelly calls it Proof Testing and Gits State Inspection, but the idea is the same: an inspection must be done to find whether the function is still operative - this inspection can be visual or using instruments or through physically testing the function.

(v) Servicing / Lubrication task – this task type, although mentioned in most texts on the subject (see paragraph 3.2.7.1), never got formal attention in the strategy decision making process. MSG-3 (1993) is an exception and puts this decision as an extra one preceding even the Condition Based Maintenance decision. It seems as if authors of RCM texts agree that one will have something as mundane as servicing and lubrication, but that it needs not be part of the strategy-setting exercise.

(vi) Redesign task – most authors will immediately tell you that this is not a part of maintenance at all. This is of course true and is not to be argued with. However, in the process of the design of a maintenance plan one sometimes comes to a point where the correct strategy is that the particular failure mode should be designed out. The initiative then typically lies with the maintenance department to initiate (and sometimes manage) the design-out process. Thus, the name 'redesign task'. Most authors have kept the terminology as is, the exceptions being Smith (1993) with Design Modification and Coetzee (1997/2) with Design-out task.

(vii) Corrective Maintenance task – the alternative name for Corrective Maintenance conceived by Nowlan and Heap (1978) and followed by most authors is No Scheduled Maintenance. Smith (1993) calls it Fly to Failure, Kelly (1997) calls it Operate to Failure, while Gits calls it Failure Based Maintenance (FBM), while it seems as if MSG-3 regards it as non-existent in its task selection logic (although it refers to non-scheduled tasks under its listing of task types).

The list given above from Nowlan and Heap (1978) is nearly exhaustive. The first five of these task types can broadly be classified as being Preventive Maintenance [Smith (1993), p. 51], leading to the principle of three main task types, Preventive, Corrective and Design-out [Coetzee (1997/2), p.48]. Nevertheless, valid maintenance task types other than the ones listed above are listed by various authors and should be taken note of in the RCM process. These include Opportunistic Maintenance [Kelly (1997) and Coetzee (1997/2)] and Adjustment [Kelly (1997)]. One of the fads of the early to middle 90's was the so-called Pro-active Maintenance[3] [Fitch (1992)] – this is not really a new class of maintenance task as Fitch would have it, but is a way of thought [Coetzee (1997/2), p.51]. Nevertheless, it is an important aspect, which should be dealt with in RCM. Another aspect of importance mentioned by Kelly (1997) regards the maintenance task category repair. Although repair can include restoration and discard, often repair is used in an exclusive way. In other words, repair is when one brings an item back into operation by means other than full restoration or replacement. Mostly repair by definition does not include prevention, but is rather one of the ways of effecting Corrective Maintenance, which can be through reconditioning, replacement or repair.

3.2.7.3. Task Selection

The standard task selection decision tree proposed by Nowlan and Heap (1978) is shown in figure 3-26. This decision tree is based on the fact that, in most instances, we do not know the full failure characteristics of a certain system or component. It consequently proposes a basic framework for the evaluation of maintenance tasks that is overly conservative in its order of maintenance task selection [Coetzee (1997/2), p.101]. The tasks are evaluated and selected in the order *on-condition* (condition based) task, *scheduled reconditioning* (restoration or overhaul) task, *scheduled replacement* (discard) task.

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[3] Pro-active Maintenance was the name that Fitch (1992) gave to a strategy of measurement (similar to Condition Based Maintenance) - where the objective of the measurements in the Condition Based case is to detect the failure in time for preventive action to be taken, its objective in the Pro-active case is to discover failure modes that should be designed out.

Hence, if any one of the three basic tasks is selected, the remainder of the selection process is truncated. If one of these are not selected, the answer to the task selection process is *corrective maintenance* (or *no scheduled maintenance* or *replace only on failure* (r.o.o.f.)) - if this is not acceptable *design-out maintenance* is the only alternative left. The basic premise of the RCM technique is therefore to propose a condition based task as the first strategy option. Only if this is not viable will the technique propose either a scheduled reconditioning or scheduled replacement task. It so ensures that the task with the least risk of doing unnecessary (costly) work is selected in each case.

Again, as is the case with the consequence classes, table 3.3, the various authors use different question formats in asking the task selection questions. These are compared in table 3.4. The differences are as follows:

- Differences in maintenance task terminology – see paragraph 3.2.7.2.
- Differences in task effectiveness measures – see paragraph 3.2.7.4.
- Differences in purpose for use based tasks – reduce failure rate / reduce hazard rate / avoid failures. These important differences will have to be resolved - see chapter 4.
- Language preference.

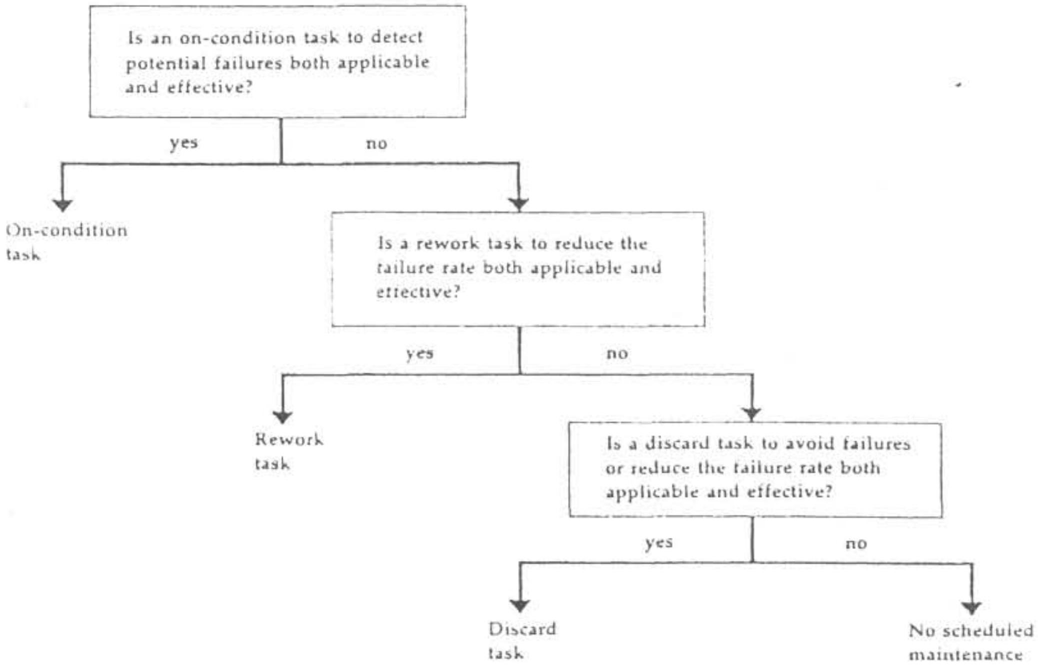

Figure 3-26: Task selection decision tree [Nowlan and Heap (1978), p.90]

Smith (1993) uses a similar but completely different looking concept in the choice of maintenance tasks, which will be considered in full when designing the new methodology in chapter 4. The method is shown in figure 3-27. The abbreviations used in the figure is as follows: CD ≡ Condition – directed; TD ≡

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Time-directed; FF ≡ Failure Finding; Category C failure mode ≡ Minor to insignificant economic problem; Category D failure mode ≡ Hidden failure; Category D/C failure mode ≡ Hidden failure which only has minor to insignificant economic consequences. The differences between this and the standard decision tree are as follows:

- There is no formal distinction regarding the analysis of the four consequence classes, apart from the differentiation built into the decision tree itself. The standard tree affords a difference in handling the decisions for the four consequence classes – see paragraph 3.2.7.4. This can be a crucial difference in using / not using this approach.
- The decision tree is not truncated following task specification, as is the case with the standard tree. This typically results in multiple preventive tasks specified per failure mode of which one or more must be chosen which will achieve the required result. This is similar to the method of Gits (1988) – see discussion below.
- The order of questions has been drastically altered – because of the development of multiple task choices per failure mode. This is not necessarily negative, as the objective is to find the task with the best fit in terms of a combination of prevention and economy.
- It does not handle the compulsory redesign of the hidden and safety/environment consequence classes and the optional choice of redesign in the case of economic consequences well.

Gits (1988) uses a method similar to that of Smith above to develop a list of possible tasks based on its effectiveness. An example of such analysis is shown in figure 3-28 [Le Clercq and Van den Broek (1999), p.39]. The result of this method (compare with their FMEA – figure 3-16) is a list of task initiation possibilities (with the possibilities of task initiation being failure, age and condition). The result of such analysis is lists of the failures (represented by their relevant reference numbers) in each category. The following descriptions serve to shortly describe each category:

- Column 1: Hidden failures – task initiation when failure takes place – typical task specified Failure Finding.
- Column 2: Unimportant non-hidden failures (low seriousness factor) - task initiation when failure takes place – typical task specified Corrective Maintenance.
- Column 3: Important non-hidden failures (high seriousness factor) with increasing hazard rate and an identified failure indicating quantity – task initiation can take place based on any one of failure, use or condition – task choice based on efficiency (mostly cost) between these three possibilities.
- Column 4: Important non-hidden failures (high seriousness factor) with increasing hazard rate and no failure indicating quantity – task initiation can take place based on any one of failure and use – task choice based on efficiency (mostly cost) between these two possibilities.

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Table 3.4: Comparison of task selection questions

Task selection step	Author	Question
Lubrication/ Servicing	MSG-3 (1993)	Is a lubrication or servicing task applicable and effective?
Operational/ Visual Check	MSG-3 (1993)	Is a check to verify operation applicable and effective?
On-condition	Nowlan and Heap (1978)	Is an on-condition task to detect potential failures both applicable and effective?
	Moubray (1991)	Is a task to detect whether the failure is occurring or about to occur technically feasible and worth doing?
	Coetzee (1997/2)	Is an on-condition task to detect potential failures both technically and economically feasible?
	MSG-3 (1993)	Is an inspection or functional check to detect degradation of function applicable and effective?
Rework	Nowlan and Heap (1978)	Is a rework task to reduce the failure rate both applicable and effective?
	Moubray (1991)	Is a scheduled restoration task to reduce the failure rate[4] technically feasible and worth doing?
	Coetzee (1997/2)	Is a reconditioning task to reduce the hazard rate both technically and economically feasible?
	MSG-3 (1993)	Is a restoration task to reduce failure rate applicable and effective?

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[4] In the case of safety and environmental consequences, "reduce the failure rate" is replaced with "avoid failures".

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Table 3.4: Comparison of task selection questions (continued)

Task selection step	Author	Question
Discard	Nowlan and Heap (1978)	Is a discard task to avoid failures or reduce the failure rate both applicable and effective?
	Moubray (1991)	Is a scheduled discard task to reduce the failure rate[5] technically feasible and worth doing?
	Coetzee (1997/2)	Is a replacement task to reduce the hazard rate both technically and economically feasible?
	MSG-3 (1993)	Is a discard task to avoid failures or to reduce the failure rate applicable and effective?

- Column 5: Important non-hidden failures (high seriousness factor) with constant or decreasing hazard rate and an identified failure indicating quantity – task initiation can take place based on any one of failure and condition – task choice based on efficiency (mostly cost) between these two possibilities.
- Column 6: Important non-hidden failures (high seriousness factor) with constant or decreasing hazard rate and no failure indicating quantity – task initiation when failure takes place – typical task choice corrective.

The method is simple and attractive if somewhat simplistic (for instance, a failure finding task is certainly not the only option in the case of a hidden failure - condition based and use based tasks should also be considered). The fact that this one diagram is used for all four failure consequence types (as in the case of Smith above) does not necessarily create a problem, but the loss of the reliability logic does. However, this type of diagram will have to be considered either on its own or possibly as an additional assist type of function in the task selection decision-making process. This diagram and the one of Smith highlight the fact that the standard decision tree, although theoretically sound, depends too much on the detailed knowledge of the analyst. It should be the objective to either replace or augment the standard tree by a diagram that builds all the relevant knowledge into the tree itself, as far as that is possible. It is a fact that most analysts in industry are not trained and capable to the level of expertise, which is necessary when using the standard decision tree. A 'decision diagram for dummies', if possible, will address this shortcoming.

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[5] See footnote on previous page

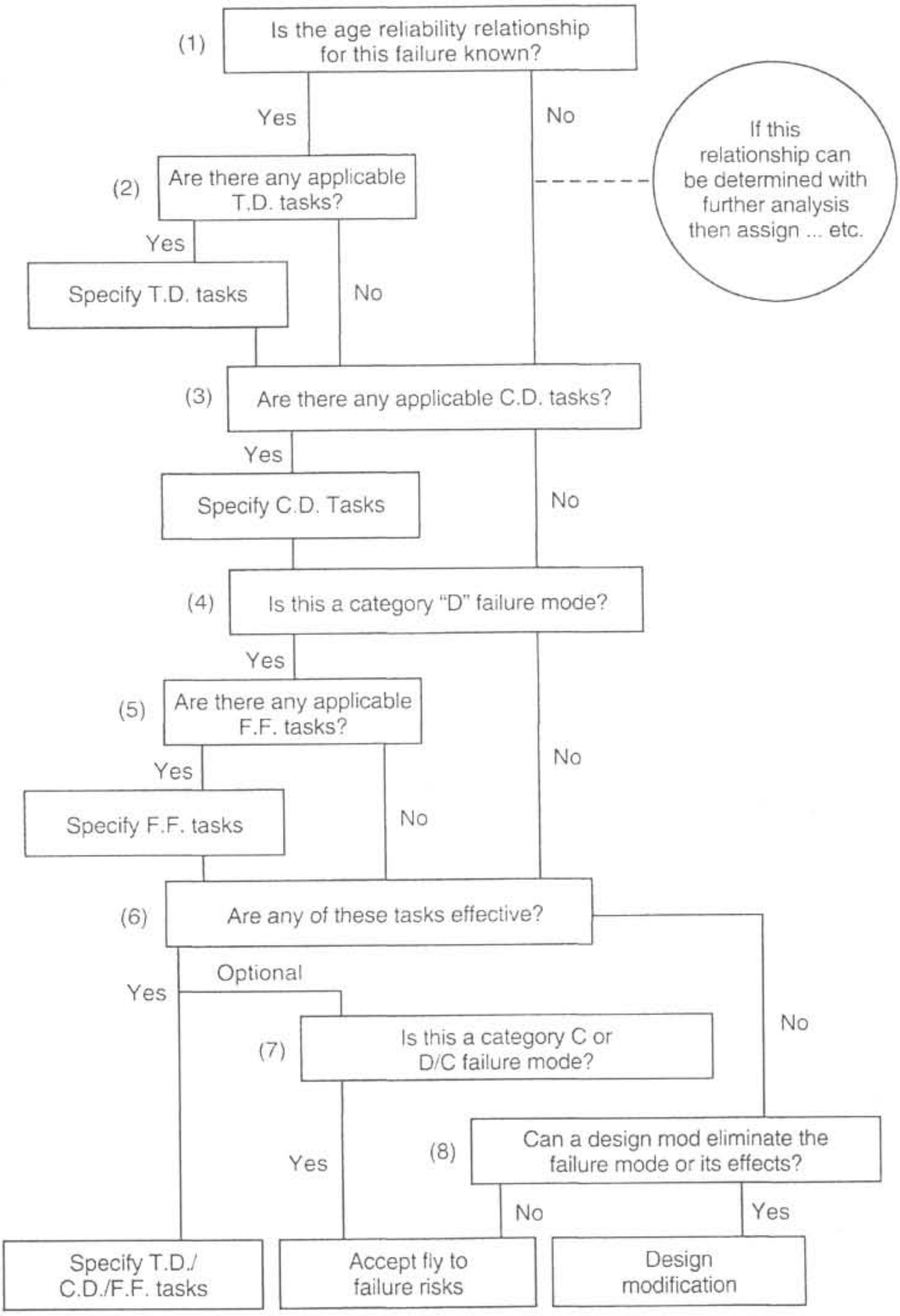
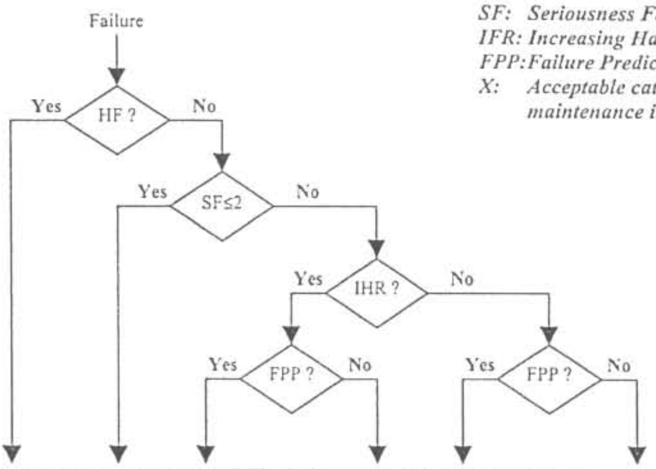


Figure 3-27: Task selection road map [Smith (1993)]

Task selection in the Business Centred Maintenance approach of Kelly [Kelly (1997)] is a very simplistic process of studying the design of the item and then using its known failures, as well as the analyst's prior knowledge regarding the operation to choose the best maintenance possibility.

MSG-3 (1993) modified the Nowlan and Heap task selection tree (figure 3-26) in a few ways. The standard MSG-3 tree (reproduced) is shown in figure 3-29, which is applicable for operational consequences and economic (non-operational) consequences. The *first* change is the introduction of the Lubrication/Servicing task at the top of the tree. This task is described as 'any act of lubrication or servicing for the purpose of maintaining inherent design capabilities'. As was stated earlier in this text, this was one of the important shortcomings of the original version of RCM. The *second* change is the fact that the decision-tree is not truncated if a lubrication/servicing task is specified.



HF: Hidden Failure
SF: Seriousness Factor
IFR: Increasing Hazard Rate
FPP: Failure Prediction Property
X: Acceptable category of maintenance initiation

FBM	×	×	×	×	×	×
UBM			×	×		
CBM			×		×	
Failure	4, 5, 6, 7, 8, 9,18, 20, 21, 24, 25, 36, 37	1, 2, 10, 11, 12, 13, 15, 16, 26, 27, 29, 30, 31, 33, 34, 35, 39, 40	14, 19, 22,	17	23, 28, 38	3, 32

FBM: Failure Based Maintenance
UBM: User Based Maintenance
CBM: Condition Based Maintenance

Figure 3-28: Qualification of maintenance initiation categories [Le Clercq and Van den Broek (1999)

For safety tasks (both of the evident and hidden varieties), this last change is carried further in that no truncation takes place at any level of the task selection process (see figures 3-30 and 3-31). The *third* change is the fact that after each task level is tested for safety tasks (both evident and hidden), the last step is to choose the best combination of tasks selected in the previous steps (if such combination will be applicable and effective) – otherwise redesign is mandatory. The *last* change is the introduction of the 'verify operation' task (failure finding) between the lubrication/servicing task and the inspection/functional check task in the case of hidden consequences (both for safety and for economic varieties) – see figures 3-31 and 3-32. This task is described as 'a task to determine that an item is fulfilling its intended purpose - the check does not require quantitative tolerances'. The task can be an operational check or a visual check.

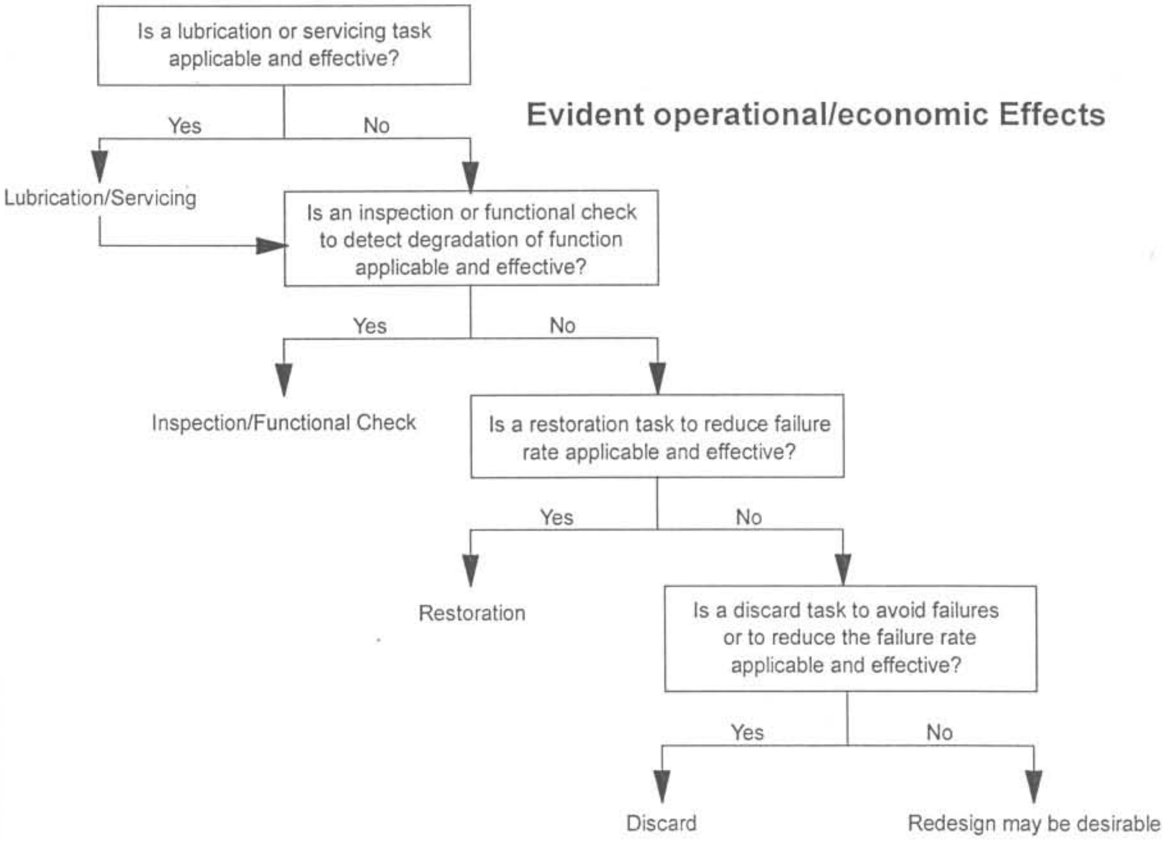


Figure 3-29: Basic task selection tree [MSG-3 (1993)]

Harris (1985) also adds an extra task at the top of the task selection ladder (before the on-condition task option). He calls this additional task category the "non-maintenance related improvement" (NMI) task category. He states that failure modes often occur, which cannot be eliminated by preventive maintenance, but which can be eliminated through different means. Examples of these are incorrect operational procedures, poor maintenance workmanship and faults in manufacture of equipment. The first of these can be solved through better operational procedures and training of operators, the second by improved maintenance procedures and the third through improved quality assurance. It is clear that all three examples relate to quality in some or other form. Thus a quality question may be the solution to this very important shortcoming in the present RCM methodology.

He also divides operational consequences into mechanical (technical) consequences and process consequences. This aspect was discussed on page 3-42. His proposed NMI task category will also address the problem of process consequences, without going to the extreme of introducing a new failure consequence category (page 3-43).

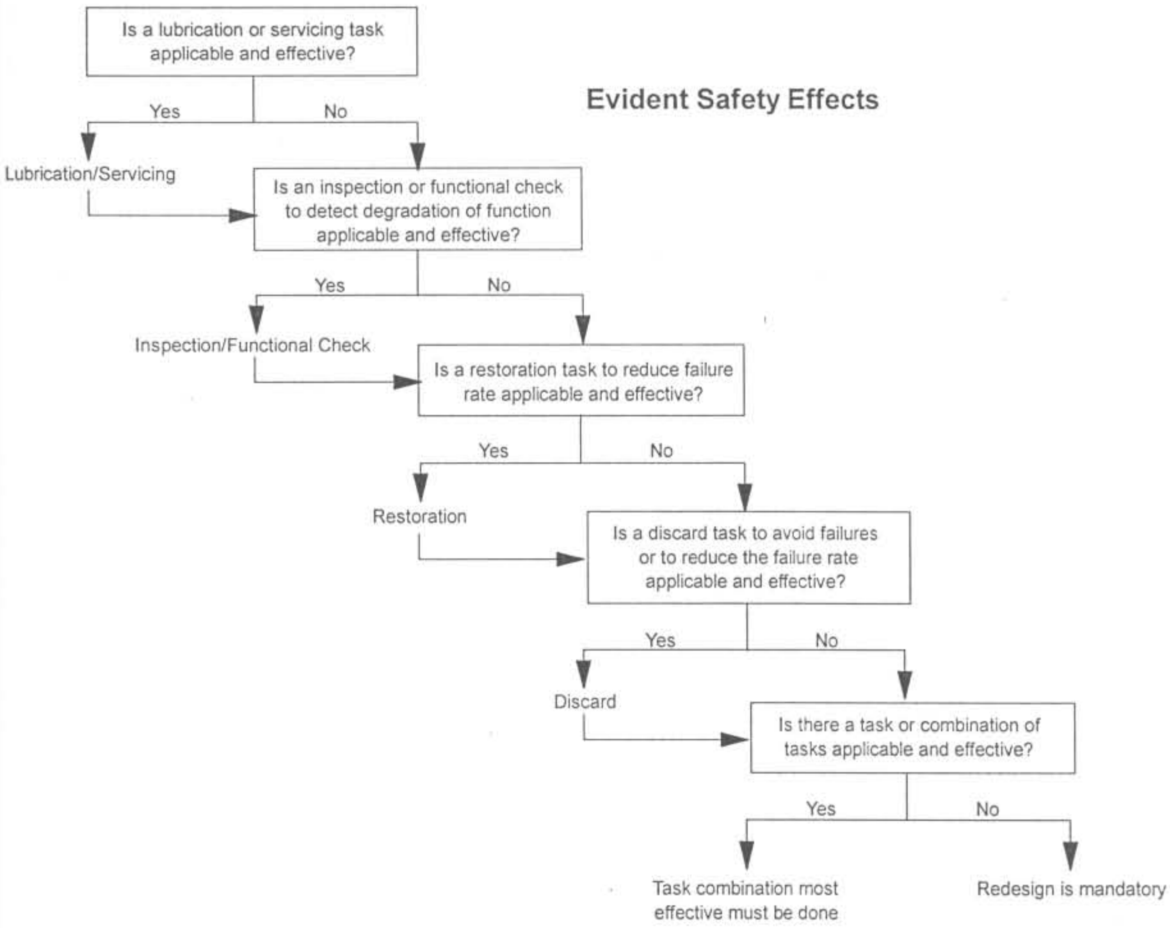


Figure 3-30: Evident safety task selection tree [MSG-3 (1993)]

3.2.7.4. Technical/Economic viability

In the original version of RCM, Nowlan and Heap (1978) defined the terms 'applicable' and 'effective' as being two prerequisites for task selection (see figure 3-26). Applicability is a measure that ascertains whether the specific task is 'right' as preventive measure regarding the occurrence of the specific failure mode. If it is applicable, the issue of its effectiveness must be resolved – it must do the job at the right level functionally and in terms of cost, depending on the objective of the task. The two terms are defined [Nowlan and Heap (1978), p.50] as follows:

> *Applicability depends on the failure characteristics of the item. Thus, an inspection for potential failures can be applicable only if the item has characteristics that make it possible to define a potential-failure condition. Similarly, an age-limit task will be applicable only if the failures at which the task is directed are related to age.*
>
> *Effectiveness is a measure of the results of the task; the task objective, however, depends on the failure consequences involved. A proposed task might appear useful if it promises to reduce the overall failure rate, but it could not be considered effective if the purpose in applying it was to avoid functional failures altogether.*

These terms (applicability and effectiveness) have been retained in MSG-3 (1993).

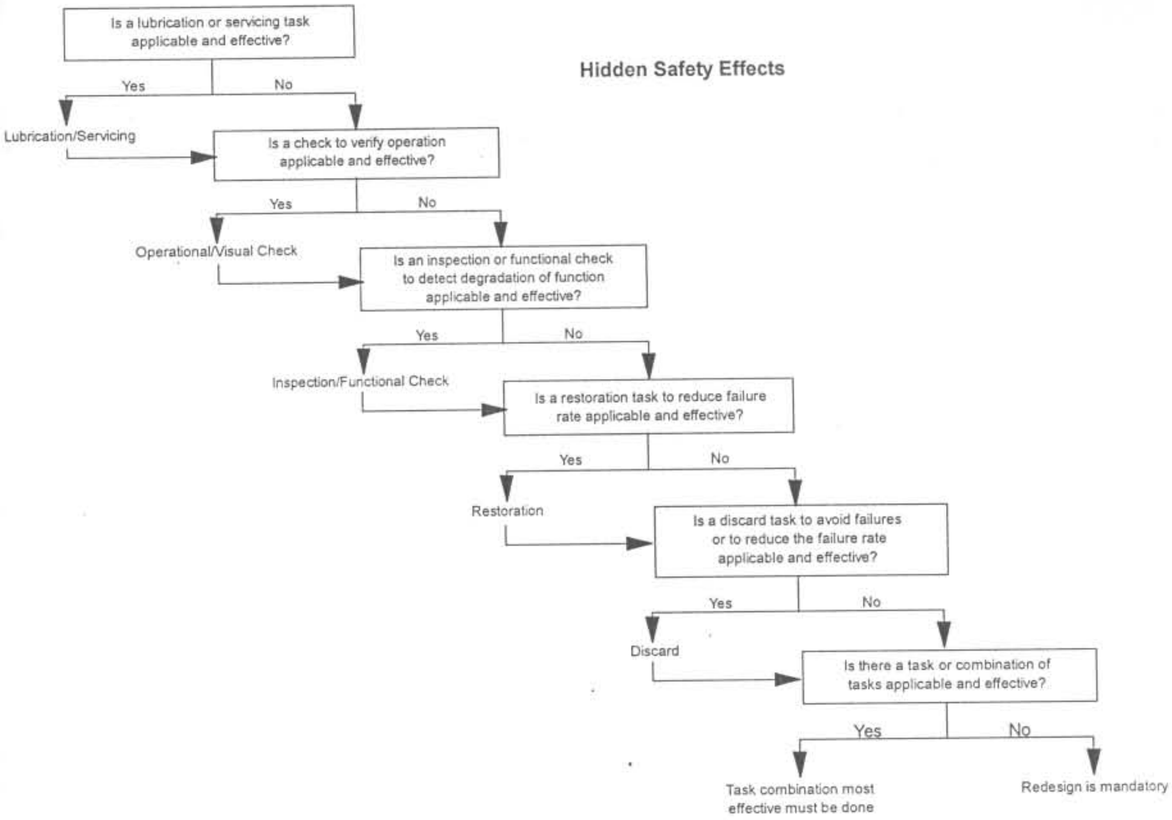


Figure 3-31: Hidden safety task selection tree [MSG-3 (1993)]

These terms are not completely satisfactory in that their definitions leave room for doubt and wrong interpretation. Additional problems regarding task 'effectiveness' in MSG-3 is that it freely talks of 'risk reduction' in the case of safety related tasks and 'cost effectiveness' in the case of economic related tasks. Nowhere does it however define what constitutes 'risk' or 'cost effectiveness'.

Moubray (1991) redefined and renamed the two measures for task selection as being *technical feasibility* and whether it is *worth doing*. He defined the two terms as (p.14):

> *Whether or not a task is technically feasible is governed by the technical characteristics of the task and of the failure, which it is meant to prevent.*
>
> *Whether it is worth doing is governed by how well it deals with the consequences of the failure*

These terms are more palatable and the definitions are given in much simpler and clearer terms. Notwithstanding, the basic idea are still the same. The applicability (technical feasibility) is dependent on the technical characteristics of the failure and that of the proposed task. Likewise, the effectiveness (worth doing) measures the success of the task, both in terms of *technical success* (hidden and safety/environmental consequences) and *economic success* (operational and non-operational consequences). It is especially this second category (which is a mixture of two different result types) that creates a problem in user's minds.

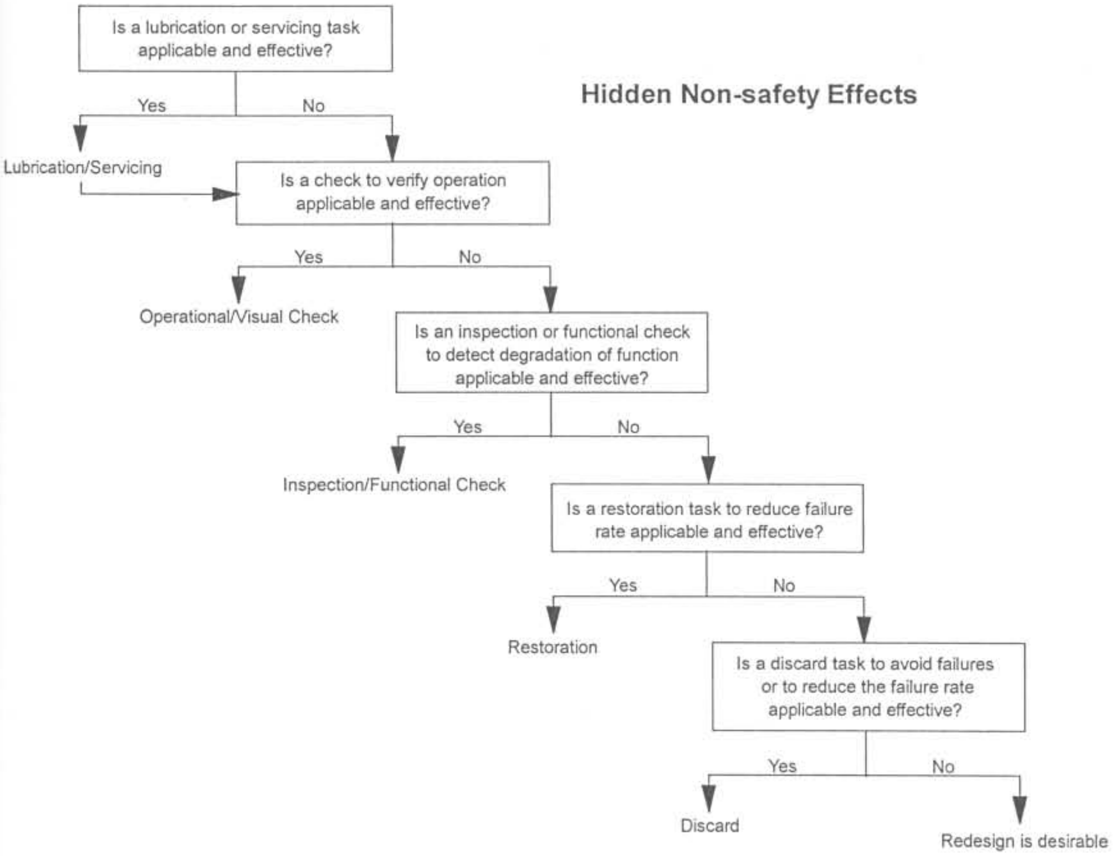


Figure 3-32: Hidden economic task selection tree [MSG-3 (1993)]

Coetzee (1997/2) contemplated these problems and used the terms *technically feasible* and *economically feasible*. The term *technical feasibility* thus includes the technical success of the task in dealing with the consequences of failure, while *economical feasibility* is only concerned with whether the task is an economical success. This makes the two primary decision criteria much simpler both to understand and work with. A full description of these and their meaning is extracted from Coetzee (1997/2).

Technical Feasibility

> Technical feasibility depends on the technical characteristics of both the failure mode and the task. The task must be able to prevent the failure mode to some specified level of certainty. This specification differs for the various failure consequences:
>
> - *Hidden failure consequence*: the task must reduce the risk of a multiple failure to an acceptable level. In the case of a hidden failure, the failure itself does not have the negative effect, but if it is not found and repaired it will eventually lead to a multiple failure which may or may not be worth preventing depending on the risk involved. The fact

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that the failure is hidden, does not necessarily imply high risk – the risk is high if the hidden failure can lead to a costly or unsafe multiple failure. On the other hand, if the hidden failure will not lead to a multiple failure or the resulting multiple failure is of no consequence then the risk involved is negligible (this is an example of a superfluous function - the specific function can in actual fact be removed). If a suitable task that reduces the risk to an acceptable level is not found then the initial default action is a scheduled failure finding task.

- *Safety or Environmental failure consequence*: the task should reduce the risk of the failure either totally or to a (very low) acceptable level. Where safety or environmental issues are at stake one cannot compromise. If a preventive task that reduces the risk of failure to a low enough level is not found, redesign is compulsory (the default action).
- *Operational and non-operational consequences*: the task should reduce the risk of failure to a low enough level so that the benefits of the preventive action are worth the cost of implementing it. If no suitable preventive task is found, the initial default action is corrective maintenance (no scheduled maintenance). Where-as in the case of hidden consequences and safety/environmental consequences, technical viability includes whether the prevention is successful, in this case it does not.

Economical Feasibility

Economical feasibility, as the name suggests, is only concerned with whether the task, which has already passed the sieve of technical feasibility, makes economical sense. The different failure consequence categories are dealt with as follows:

- *Hidden, safety and environmental consequences*: Here technical feasibility plays a much greater role than economical feasibility. The reason for this is that the consequence of failure in this area is in most cases detrimental to the health and life of persons and/or plant/business asset. Thus, one normally has to find a preventive task that works. However, one cannot disregard the cost of the proposed action altogether. In some or other way, one has to establish whether the proposed action is the only or least expensive way to solve the problem. This can entail comparing the cost of alternative preventive actions against one another or against the possibility of redesign to solve the problem.
- *Operational consequences*: In the case of operational consequences, the task is economically feasible if the total cost (cost of downtime + cost of failures incurred + cost of prevention) is at a minimum. That is, the cost of the preventive task per operational measuring unit is less than the cost of the operational consequences (in other words the value of production lost) plus the cost of repairing the failure per operational measuring unit.

- *Non-operational consequences*: In this case the answer to the question of economic feasibility is the same as for operational consequences, except that the cost of lost production does not feature (the failure does not affect the operation).

The technical feasibility criteria suggested by Coetzee (1997/2) and expounded above are not completely satisfactory for use in the operational and non-operational consequence categories. It still represents a mixture between technical risk and economic worth. This ambiguity should be removed to ensure that the term has a singular significance.

As a consequence of adding two additional task types to the task selection tree, MSG-3 (1993) has to address the 'applicability' and 'effectiveness' criteria of successfully selecting these tasks as part of the preventive strategy. The applicability criterion for *lubrication/servicing* tasks is stated as 'the replenishment of the consumable must reduce the rate of functional deterioration'. The effectiveness criteria differs for different consequence categories: for safety consequences 'the task must reduce the risk of failure', for operational consequences 'the task must reduce the risk of failure to an acceptable level', and for economic consequences 'the task must be cost-effective'. For the *verify operation* task (failure finding) the applicability criterion is that the 'identification of failure must be possible'. The effectiveness criteria again differs for different consequence categories: for safety consequences 'the task must ensure adequate availability of the hidden function to reduce the risk of a multiple failure', and for economic consequences 'the task must ensure adequate availability of the hidden function in order to avoid economic effects of multiple failures and must be cost-effective'.

As was mentioned previously (page 3-42), Harris (1985) shows that process degradation is not addressed adequately in the present versions of RCM. To address this problem, the cost of performance degradation should be added to the cost of lost production as described above.

Nowlan and Heap (1978) presented a 'quick and dirty' first order decision diagram for economic feasibility. This was improved by Coetzee (1997/2) and is shown in figure 3-33. As economic feasibility plays only a secondary role in the case of hidden failure consequences, as well as with safety and environmental consequences, this diagram is only applicable in the case of the operational and non-operational consequence categories.

3.2.7.5. *Technical selection criteria*

Referring to Nowlan and Heap's (1978) task selection decision tree (figure 3-26) and table 3.4 above, the primary technical selection criteria for the different task types are as follows:

- On-condition task: detection
- Rework task: reduction of failure rate
- Discard task: failure avoidance *or* reduction of failure rate

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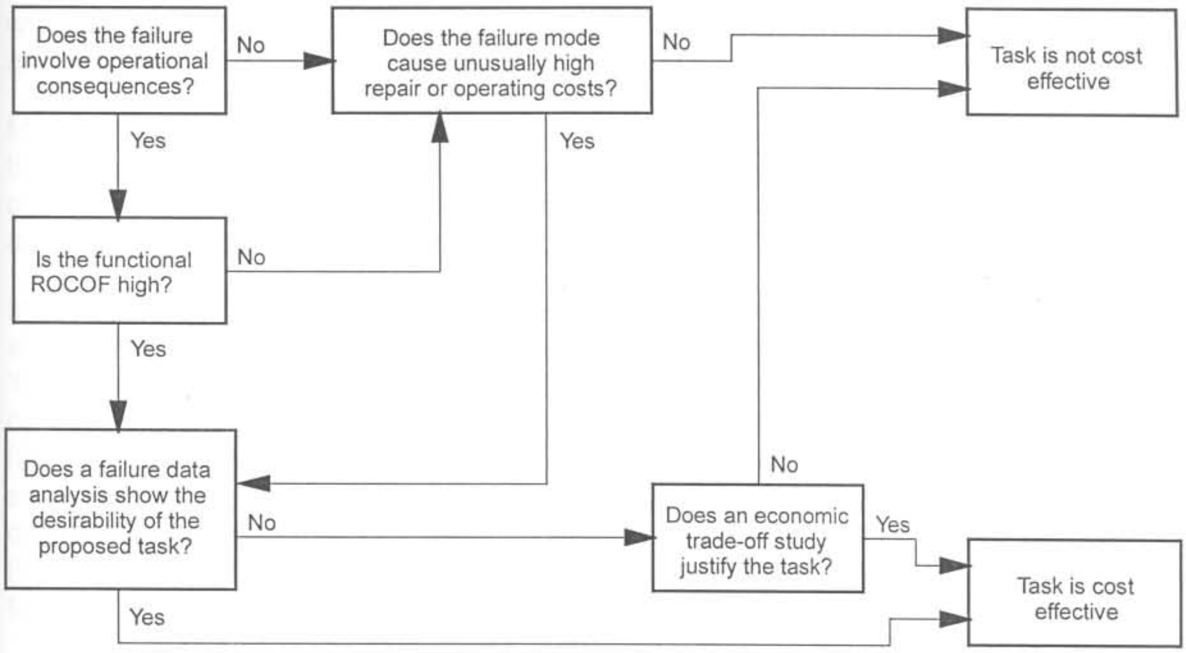

Figure 3-33: Cost Effectiveness Decision Diagram [Coetzee (1997/2)]

In the case of on condition tasks, all the authors concur that detection is the primary selection criterion. That includes the authors not specifically listed in table 3.4, because they mostly agree with the original Nowlan and Heap structure. The exception is Gits (1988), who does not agree with the Nowlan and Heap structure, having developed his own technique, but agrees that the primary selection criterion for condition-based tasks is detection (or the 'failure prediction property' (fpp) – see figure 3-28).

For rework/restoration/reconditioning tasks, all the authors agree that the primary selection criterion is the 'failure rate', although it is not totally clear that all of them appreciate the implication of that statement. The idea is that one can only practice Use Based Maintenance under conditions of IFOM[6] (Increasing Force of Mortality) or an increasing conditional failure rate (or Hazard Rate as Coetzee (1997/2) has it). The problem with the use of 'failure rate' here is that it can most probably be mistaken for an increasing ROCOF[7] (Rate of Occurrence of Failures) which will certainly increase in most cases of use based preventive action. A common problem with all of the authors (excluding Nowlan and Heap (1978) and Coetzee (1997/2)) is that they judge

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[6] The Force of Mortality typically gives the risk that a component will fail at a certain age. Under an increasing Force of Mortality (IFOM), it could thus be justified to replace or recondition the component at some age, as the risk of failure of the renewed component will be much lower than that of the component before renewal. Cost factors will determine at what exact age renewal has to take place.

[7] An increasing Rate of Occurrence of Failures (ROCOF) is typical of a system which consists of many components, many of which will be IFOM, others displaying random shock failure patterns (constant FOM) and some even running-in failure patterns (decreasing FOM). As time passes, more and more components start failing for the first time, thus causing an increasing ROCOF. This is called reliability degradation.

whether the 'failure rate' is increasing through discussion with plant operations and maintenance personnel rather than through proper failure data analysis.

Moubray (1991) uses failure avoidance as the primary selection criterion in the case of safety/environmental consequences, which is probably more correct as the purpose of preventive action in this case should be total failure avoidance, which is a more conservative rule than FOM reduction.

In the case of discard/replacement tasks, Nowlan and Heap (1978) uses two alternative primary selection criteria, namely failure avoidance and increasing 'failure rate'. It is not clear why they include failure avoidance here as they never explain themselves regarding this issue. It probably has to do with safe life limits imposed through statutory or regulatory requirements. All the later authors use only the second criterion, as is the case with rework tasks. The discussion above for rework tasks further holds fully for this category as well (including the previous paragraph's remark regarding Moubray's position on failure avoidance).

MSG-3 (1993) has nothing new to contribute in this area, apart from the criteria for the two new task types, as described in paragraph 3.2.7.4 above. For on-condition tasks, it specifies detection and P-F interval[8] consistency as criteria as is the case with most other authors. In the case of restoration and discard tasks, MSG-3 has in fact not progressed at all compared to the original RCM [Nowlan and Heap (1978)], as it still sticks to the idea of the bathtub curve. It thus sees technical applicability for restoration and discard tasks as being dependent on 'the item must show functional degradation characteristics at an identifiable age and a large proportion of units must survive to that age'. For restoration tasks, it adds 'it must be possible to restore the item to a specific standard of failure resistance'.

3.2.7.6. Default tasks

Although the task selection decision tree (figure 3-26) is principally the same for all consequence categories, the default action if no suitable preventive task was found differs considerably for each consequence category. Moubray (1991) coined the term 'default actions' for these consequence specific tasks. There is not much that warrants comparison in the different literature sources. The only author with a proper discussion of the default task area is Moubray (1991). A short discussion of the default tasks per consequence category from this source follows in the interest of completeness:

- Hidden failures – if no suitable preventive task is found in the case of hidden failures, the default action is a scheduled Failure Finding task (if it is possible to detect the failure through such means and if the task is technically and economically feasible). Should this possibility not be viable, and safety is involved, Redesign is compulsory – if safety is not

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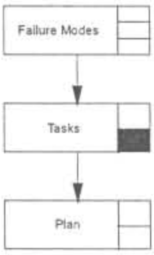
[8] The time between the point at which a Potential failure is identified using inspection or Condition Monitoring and the time at which the actual Functional failure occurs.

involved the default is Corrective Maintenance, with Redesign as an option.

- Safety/Environmental Consequences - if no suitable preventive task is found in the case of Safety/Environmental Consequences, the default is to consider a combination of preventive tasks (On-condition, Rework and Discard), as the failure mode with Safety/Environmental Consequences cannot be allowed to exist unchecked. Should this possibility not be viable, Redesign is compulsory.
- Operational and Non-operational Consequences – in the case of the so-called economic consequence categories, the lack of a suitable preventive action is not a crisis and the default action is Corrective Maintenance, with Redesign as an option.

3.2.8. Task Frequencies

3.2.8.1. Introduction



Maintenance task frequencies, especially concerning critical items, are a perpetual problem, as the task of maintenance is to prevent failures from occurring. The better the maintenance function fares regarding this objective, the less failure data will be available for analysis to determine scientifically calculated task frequencies. Nevertheless, one should do the best possible within the constraints of a scarcity of data. Fortunately, statistical methods allow for the use of suspended data in conjunction with the failure data that is available to enrich the data set. And, as the task decisions regarding rework and discard tasks require an increasing hazard rate, data analysis is essential if one does not want to choose your strategy from the On-condition category only, apart from a few statutory and regulatory life limiting tasks. The same analysis that leads to the hazard curves will also provide the task frequencies in the use based task categories. On-condition tasks and scheduled Failure Finding task frequencies, on the other hand, can be determined from past experience with similar equipment as well as manufacturer data, being very conservative in the setting of inspection intervals (typically only a small fraction of the assumed life) [Nowlan and Heap (1978), p. 324]. As the item's life gets nearer to the assumed failure point, the frequency of inspection is repeatedly increased. It is again important to note that accurate inspection frequencies also requires knowledge regarding the Mean Time to Failure and the variance of times to failure (i.e. the failure distribution must be known).

Nowlan and Heap (1978), (p.106) stresses the use of age exploration to develop task intervals as the equipment ages, especially in the case of On-condition tasks. For an On-condition task, three factors determine its technical feasibility. The first of these is the characteristics of the failure (especially whether the failure has a gradual onset). The second is the ability to measure reduced failure resistance and the third its ability to deal with the failure consequence. This third factor depends on the interval between

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inspections (the same is true for Failure Finding inspections). Thus, the intervals between inspections need to be conservatively short to ensure that the task is technically feasible, given the lack of experience/data. As the equipment gets older, this interval is even shortened further using the same reasoning. However, once in a while one of the items is left to fail without taking action, but monitoring it all the while, so to build up data/experience. The intent is to, over the longer term, increase the intervals based on operating experience (p.324 op.cit.).

For use based maintenance tasks Nowlan and Heap (1978), p.61 stresses the importance of the availability of failure data to determine task intervals. They argue that the only justification for an economic life limit is cost effectiveness, a fact that cannot be refuted. Cost effectiveness can only be proved if the failure distribution is known to predict how the age of preventive removal of an item will affect the cost-benefit ratio.

The task frequency selection approach of MSG-3 (1993) is very simplistic. It consists of the following three sources. The *first* concerns prior knowledge from other aircraft systems/powerplants and the *second* manufacturer's test data. *Thirdly*, if there is insufficient similarity between the previous and current systems, the task interval/frequency can only be established initially by an experienced working group and steering committee personnel using good judgement and operating experience in concert with accurate data.

Following this introductory passage, the various author's opinions regarding this important topic is explored.

3.2.8.2. On-condition tasks

Nowlan and Heap (1978) states that the task frequencies for On-condition tasks can be determined from past experience with similar equipment as well as manufacturer data. The approach is then to be very conservative in the setting of inspection intervals (typically only a small fraction of the assumed life) [Nowlan and Heap (1978), p. 324]. This high conservatism in the times between inspections is to ensure that the task is technically feasible, given the lack of experience/data. As the item's life gets nearer to the assumed failure point this interval of inspection is repeatedly even shortened further using the same reasoning. However, the intent is to increase the intervals – this is only possible based on operating experience. That is, accurate inspection frequencies requires knowledge regarding the Mean Time to Failure and the variance of times to failure (i.e. the failure distribution must be known). This is achieved through age exploration, i.e. once in a while leaving one of the items to fail without taking action, but monitoring it all the while, so to build up data/experience.

The original authors of RCM worked from a basis of developing a maintenance plan for new equipment, thus working from the premise of no experience/data. This is certainly one of the typical RCM scenarios (the one extreme). The other extreme is a situation where ample experience/data is

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available, and then one has all the possible situations between these two extremes, which possibly describes reality best.

Moubray (1991) following this practical experiential thought train states that On-condition task frequencies are governed by the P-F intervals (i.e. the time that expires between the point where a potential failure becomes measurable and the point of actual failure) (p.166). He suggests that a task interval of half the P-F interval should be conservative enough to ensure that the possibility of a failure is detected early enough.

Smith (1993) does not have anything substantial to add to the discussion and only echoes the thoughts of Nowlan and Heap given above in much shorter format. Gits (1988), on the other hand, just states that the inspection interval determines the cost of inspection, without even referring to the influence of the interval on task effectiveness.

Coetzee (1997/2) states that the effectiveness (and thus the technical feasibility) of an On-condition task to prevent failure from occurring depends on the following:

- It must be possible to unequivocally identify the potential failure through the condition monitoring or inspection method that was chosen.
- Normally when a component's condition deteriorates, it does so somewhat slowly in the beginning and then accelerates towards the point of functional failure. When we monitor such a deterioration process, it is important that the lag time between the point where our monitoring establishes that a potential failure exists and the point of actual functional failure is *firstly* reasonably consistent. It should, *secondly*, be more than enough to take preventive action (that is to prevent the failure completely or to limit the consequences of failure sufficiently).
- The condition monitoring or inspection frequency envisaged must be practically achievable. The time between inspections (condition monitoring) must be sufficiently less than the time interval between the point at which the potential failure becomes evident and the point of functional failure to ensure that the potential failure will be identified in time.
- The time between monitoring points should be set less than half the lead-time to failure (the time interval between the first identifiable indication of the potential failure and the functional failure). This will ensure that the potential failure will, with high probability, be identified in time for preventive action to be taken.
- In practice, it might sometimes be necessary to start monitoring at a higher frequency once the potential failure has been identified, to accurately predict when functional failure will occur. This is especially so in the case where the lead-time to failure spans a long time (sometimes weeks or even months).

3.2.8.3. Failure Finding tasks

Moubray (1991) is the only author to have a proper discussion on the frequency of Failure Finding tasks. He states that these frequencies are governed by the *consequences of the multiple failure*, which dictate the necessary availability of the hidden function, and the *mean time between occurrences of the hidden failure*.

He presents two approaches to determining the Failure Finding task interval. The first of these is the 'rigorous' approach, where the required availability of the hidden function is calculated from:

$$Av_h = P_m \times P_p$$

Av_h = Availabilty required of the hidden function
P_m = Acceptable probability of occurrence of resultant multiple failure
P_p = Probability of occurrence of failure of protected function during period under consideration

The required Failure Finding inspection interval can then be calculated from:

$$FF_i = f_i \times MTTF_h$$

FF_i = Failure Finding inspection interval
f_i = Failure Finding inspection interval fraction
$MTTF_h$ = Mean Time to Failure of hidden function

with the inspection interval fraction f_l corresponding to the calculated value of Av_h read from the following table (which is given without proof):

Av$_h$	0,995	0,975	0,95	0,93	0,91	0,89
f$_l$	0,01	0,05	0,10	0,15	0,20	0,25

His second approach is applicable to situations where the hidden function is not important enough to warrant the analysis effort. In such cases a decision regarding the hidden function required availability, Av_h is made directly and a value for f_l read from the table above, after which the Failure Finding inspection interval FF_l is calculated.

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3.2.8.4. Rework tasks

As was stated in the introduction above Nowlan and Heap (1978), p.61 stresses the importance of the availability of failure data for determining the task intervals of use based maintenance tasks. They argue that the only justification for an economic life limit is cost effectiveness, a fact that cannot be refuted. Cost effectiveness can only be proved if the failure distribution is known to predict how the age of preventive removal of an item will affect the cost-benefit ratio.

Smith (1993) proposes a method whereby the task interval is based on the Failure Distribution function (an acceptable risk of failure is chosen and then the corresponding age at which that cumulative percentage of failures have occurred read off) in the case where data is available. In other cases (no failure data available) he suggests an initial conservative intelligent guess regarding the task interval. Age exploration is then used to improve this interval over time. Each time that the task occurs, the unit and all its parts are meticulously inspected, its condition recorded, and its task interval extended by a percentage based on the condition of the suspended unit. In this way, the correct task frequency is eventually found, without initial experience/failure data availability.

Moubray (1991) suggests that the interval, in most instances, be determined by the 'useful life'[9] through the 'consensus of people who have the most knowledge of the asset' (p.225). He states that analysis of failure data is not worth doing for more than 1 to 2% of failure modes and then for operational and non-operational failure modes only. This is a very simplistic view and fails to see the benefit of (i) understanding the failure mode well through a proper reliability analysis and (ii) analysing the failures of the units with the highest failure rates (the problem cases). Even if it then amounts to as low as 1 to 2%, the benefit will be disproportionately high (much higher than the 1 to 2% suggests). Furthermore, the 'consensus of people' is a very dangerous (and subjective) quantity to base this decision on. The method that Smith suggests above is much more balanced.

It is clear that this area needs a more fundamental investigation. It is true that there is a dearth of proper failure data in industry (for the reasons stated in the introductory paragraph above). Better ways of extracting information from the combined knowledge base of the organisation (formal data and the experience of people) will have to be investigated, perhaps using Bayesian statistics.

3.2.8.5. Discard tasks

The argumentation for discard tasks broadly follows that for rework tasks above, with the only exception being safe life limit tasks. These are typically set by statutory or regulatory authorities and pose no problem in determining

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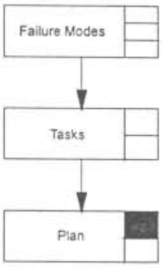
[9] That life at which there is a rapid increase in the conditional probability of failure (p.206).

the task intervals. The only problem with such tasks is that the intervals are often unnecessarily restrictive and costly. In such cases, it is beneficial to enter into age exploration as described in paragraph 3.2.8.4 above in co-operation with the statutory or regulatory authority involved with the objective of extending the relevant safe life limits without jeopardising safety.

When the organisation itself imposes safe life limits on certain items, the proven minimum life is often divided by a safety factor of as high as 3 to 4 [Moubray (1991), p.114]. Such a limit would then also be subject to careful age exploration as described in paragraph 3.2.8.4 above.

3.2.9. Task Packaging



Following the analysis presented above in paragraphs 3.2.2 to 3.2.8, the result is an endless list of individual tasks, which need to be grouped into logical work packets that can be done at suitable intervals. While performing the analyses, no regard should be given to any present intervals, practical limitations and own preferences. These issues should be resolved now during the task packaging exercise.

The task packaging procedure suggested by Nowlan and Heap (1978) starts by adding known non-RCM tasks to the total list of tasks from the analysis – in their case this included servicing and lubrication tasks specified by the manufacturer and scheduled zonal walkabout checks. These are now grouped into standard 'number check' and 'letter check' maintenance packages, each done at an increased number of flight hours. The typical check frequencies used at that time was:

- #1 Check – every stop at a maintenance station
- #2 Check – every long layover if the aircraft has flown more than 20 flight hours since the previous #2 check
- A Check – every 125 flight hours
- B Check – every 900 flight hours
- C Check – every 3 600 flight hours
- D Check – every 20 000 flight hours

One principle involved in the execution of these checks was that each higher check, when performed, will automatically include the work of the nearest lower work packages. Thus, a number 2 check will include the task content of a number 1 check, a A-check will include the nearest #2 check's content (and through that that of the #1 check), a B-check will include the A-check at 875 hours, and so on.

The process of task packaging then follows roughly the following principles:

- Each task in the task list resulting from the RCM-analysis is included in a work package with the objective of having as few different check intervals as is possible.

- The work package intervals chosen, like the task intervals, are chosen to be highly conservative.
- The individual task intervals are adjusted, if possible upwards (if that would not jeopardise the expected result), to fit in with the closest work package interval.
- If the workload of the larger work packets (i.e. C and D in this case) will cause too large fluctuations in the maintenance workload, these can be spread evenly amongst lower level packages. For example, the C-check's workload can be distributed evenly between the 4 B-packets between and including the C-check. This will have the effect that the B-checks are differentiated, such that a 900 hour B-check will only be repeated at 4 500 hours, and so forth. This creates an additional scheduling, planning and control complexity, but evens out the workload. In this instance, there will be no real C-check, but only a phantom C-check.
- A group of tasks that are particularly time-consuming might be distributed between successive instances of the same letter check.
- Both the task intervals and the work package intervals in an initial program is subject to age exploration, although the individual task intervals are typically extended through the extension of the package intervals. Other possibilities include moving the task to another work package and freezing the work package interval if a task interval cannot be adjusted and this specific task controls the package.

Moubray (1991) has nothing significant to add to the above, but adds the possibility to incorporate some tasks in the operating procedures. This, and a suggested modification (redesign) list, is shown in figure 3-34 [Moubray (1991), p.251].

The method of Gits (1988) deals quite comprehensively with the task packaging issue. He proposes a three-step process of task packaging:

- Clustering of tasks – in this step the tasks are grouped per common set-up[10] type. The benefit of this step is that the number of times that a specific set-up has to be performed is limited with the resultant production income benefit, with the possible adverse effect of shortening the intervals of certain individual tasks. The practice of the clustering operation is to group the tasks per set-up type and per task interval. Thus two groups of tasks with the same task interval will constitute two separate clusters if they do not share a common set-up type.
- Structuring of maintenance intervals – here the task intervals are fitted into the constraints imposed by the user organisation. This is similar to the task package intervals chosen in Nowlan and Heap's method above (principle 2) and then fitting the task intervals into the available package intervals. The typical application of this rule is the decrease of task

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[10] A set-up is an activity which must precede execution of the maintenance task. This includes production shutdown, opening up of the item, disassembly, administrative procedures.

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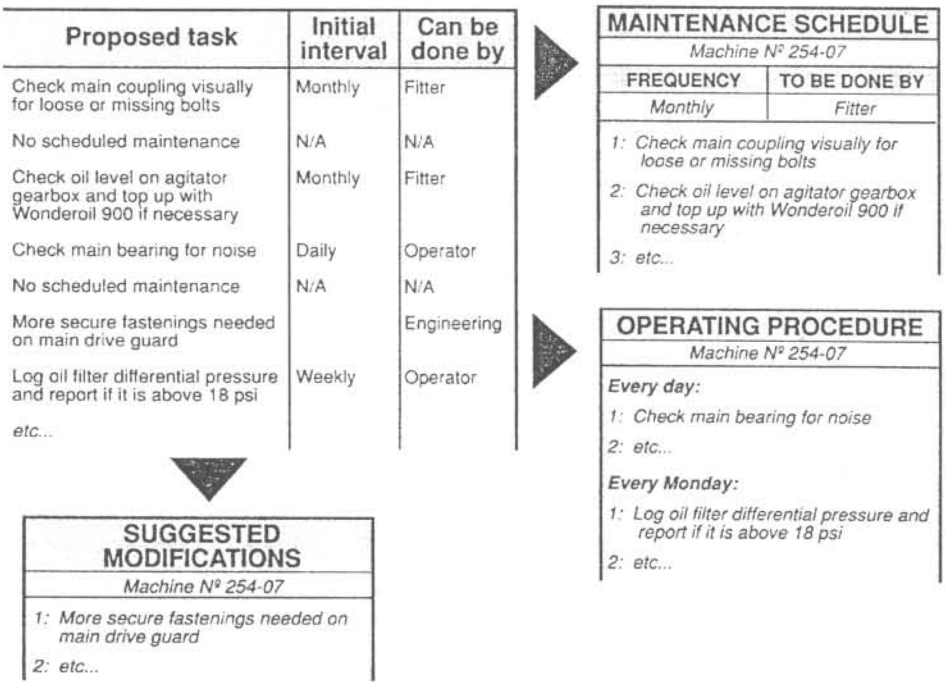
intervals to fit in with the work package intervals. This agrees with the approach of Moubray (1991), but disagree with that of Nowlan and Heap (1978) above, who suggested a preference for increasing the intervals if possible. This is not necessarily conflicting as the position of Gits and Moubray reflects the more conservative stance and that of Nowlan and Heap the more economic, which should be pursued if possible but not at the expense of task effectiveness.

- Grouping of work packages – the objective of this step is to smooth the workload within the organisational constraints. This is similar to the actions in the 4th principle of Nowlan and Heap above.



Proposed task	Initial interval	Can be done by
Check main coupling visually for loose or missing bolts	Monthly	Fitter
No scheduled maintenance	N/A	N/A
Check oil level on agitator gearbox and top up with Wonderoil 900 if necessary	Monthly	Fitter
Check main bearing for noise	Daily	Operator
No scheduled maintenance	N/A	N/A
More secure fastenings needed on main drive guard		Engineering
Log oil filter differential pressure and report if it is above 18 psi	Weekly	Operator
etc...		

MAINTENANCE SCHEDULE

Machine Nº 254-07

FREQUENCY	TO BE DONE BY
Monthly	*Fitter*

1: Check main coupling visually for loose or missing bolts

2: Check oil level on agitator gearbox and top up with Wonderoil 900 if necessary

3: etc...

OPERATING PROCEDURE

Machine Nº 254-07

Every day:

1: Check main bearing for noise

2: etc...

Every Monday:

1: Log oil filter differential pressure and report if it is above 18 psi

2: etc...

SUGGESTED MODIFICATIONS

Machine Nº 254-07

1: More secure fastenings needed on main drive guard

2: etc...

Figure 3-34: Task packaging [Moubray (1991), p.251, figure 11.2

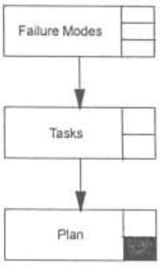
Kelly (1997) divides the maintenance tasks of a unit (typically sub-plant) into three groups:

- Work that can be done during production.
- Work of a minor character, which can only be done during production stoppages.
- Work of a major character that can only be performed during production stoppages.

The first of these is bundled together and grouped into 'on line routines', the second scheduled for production window opportunities and the third added to long term shutdown definitions. As a part of this process a spare parts needs analysis is also done to serve as basis for spare parts provisioning.

MSG-3 (1993) does not address the issue of task packaging at all.

3.2.10. Critical assessment of resulting program



The only authors (including MSG-3 (1993)) that have a proper section on the evaluation of the resultant maintenance plan are Nowlan and Heap (1978). This is difficult to understand, given the importance of the decisions taken in the process of analysis and the implications of wrong analyses. Compare this to financial auditing where quite small transactions are audited to prevent loss and it is still more difficult to understand. The problem is not necessarily that the analysts will make wrong recommendations on purpose, but that they necessarily have some biases and blind spots, which should be checked by an independent auditor.

Such an auditor in the case of the aviation industry is typically a member of the RCM project steering committee. This has the benefit that the auditor is aware of the scope of the project and the interfaces between different working groups/analysts. Coetzee (1997/2), p.81 suggests that the maintenance manager for whom the RCM analysis is done should also act as the auditor and final approval of the program. This has the benefit that he is involved in the process. The result of the maintenance effort is certainly in his interest.

Nowlan and Heap (1978) discusses RCM auditing in quite some detail. Instead of a long discourse, it would be beneficial if this part of the analysis is carried out in an itemised manner, highlighting the audit concerns in a question and/or statement format, following the pattern of Nowlan and Heap:

- Project auditing
  - Scope of project
    - Does the team have clarity regarding the system/equipment boundaries?
    - Does the team know which maintenance actions should be included? Does it include lubrication/servicing and walkabout checks?
    - Is there clarity concerning who/which team is responsible for interfacing functions/items?
  - Final product definition
    - What is the expected final product? A list of tasks (with/without intervals) or a finalised set of work packages?
    - Are the task detail and the amount of descriptive material to be included in the final product clearly specified?
    - Will the procedure writers be able to translate the analysis results into clear task instructions that reflect the purpose of each task?
  - Project timetable
    - Is the timetable realistic when compared to the workload, the analysts assigned and their experience?

  - Do the project milestones constitute logical points for project control?
  - Is the auditor clear on his scheduled involvement? He typically has to do auditing chores at the following checkpoints:
    i. When the overall plan is drafted.
    ii. When the program development team has been organised and trained.
    iii. When each working group has agreed on a list of significant items.
    iv. When analysis of the first few items has been completed.
    v. At the completion of each major portion of the program.
    vi. When the final product has been assembled and is ready for approval.
- ❖ Program-development team
  - Are the team capable (in terms of experience, qualifications and organisation) to complete this analysis successfully?
  - Are the team managed by a capable manager with experience on similar projects?
  - Does the project team have access to the necessary resources, both within and outside the organisation?
  - Are all the necessary disciplines represented in the team or available for consultation?
  - Are there organisational obstacles that may impede communication?
  - Is each analyst responsible for a complete analysis, or are various aspects of the job assigned such that it makes the work difficult to integrate?
  - Is the designer available to answer questions about specific failure modes and effects?
  - Is there someone available to each working group who has extensive knowledge of RCM techniques?
- ❖ Standards and Procedures
  - Are all participants of the project trained in RCM procedures and the specific standards utilised for this project?
  - Are RCM reference materials available for easy reference?
  - Does each analyst have a copy of the cost trade-off models to be used, including the costs imputed by the organisation to various types of operational failures?
  - What level of failure rates or repair expenses are considered high enough to qualify an item for analysis?

    - Have all analysts been supplied with the necessary stationary, schematics and descriptions of part relationships/ operation as is necessary?
    - Are reliability data available, either from developmental testing or from service experience?
    - Is there access to an actual production model of the equipment if further questions arise?

- Auditing the decision process
  - The selection of items for analysis
    - Has the group arrived at a common definition of *significant item?* (there is often a tendency to identify items as significant on the basis or their cost and complexity, rather than on the basis of their failure consequences).
    - Is the group clear as to what constitutes *operational consequences*? (because the actual economic impact will vary from one operating context to another and even from organisation to organisation, it is necessary to have a clear definition of the circumstances that constitute operational consequences and the relative costs imputed to those consequences).
  - Reviewing the information worksheets
    - Does the design of worksheets used allow the full functionality of RCM to be performed?
    - Has the analysis been performed at the right level? (see paragraph 3.2.2)
    - Has each item's functions been identified correctly? What about secondary functions? And hidden functions?
    - Is there any confusion between functional failures and failure modes?
    - Do the worksheets list failure modes that have never actually occurred?
    - Are the failure modes reasonable in light of experience with similar equipment?
    - Have any important failure modes been overlooked?
    - Does the description of failure effects include all the information necessary to support the analyst's evaluation of the failure consequences?
    - Are the effects of secondary damage stated, as well as the effects of a loss of function, and is it clear from the description whether or not the secondary damage is critical? (in the case of hidden functions the ultimate effects will usually represent the combined effects of a possible multiple failure).
    - Do the failure effects represent overreaction by inexperienced analysts?

  - Have all serious effects been included?
- Classification of failure consequences
  - Hidden functions:
    - Has the evident-failure question been asked, not for the item, but for each of its functions?
    - Has all instrumentation been included as a means of notifying the operating crew of malfunctions that would otherwise not be evident.
    - Have failures in replicated functions been identified as hidden?
    - Have the hidden functions of emergency items been overlooked?
    - Have hidden-function items with built-in test equipment been identified as being hidden regardless of the fact that failure-finding tasks are performed by the operating crew.
  - Safety Consequences:
    - Has a failure been identified as critical on the basis of multiple-failure consequences, rather than the consequences of a single failure?
    - Has the analyst taken into account redundancy and fail-safe protection that prevents a functional failure from being critical?
    - Was there a failure to identify secondary damage as critical when the system/equipment cannot be shown to be damage-tolerant in this respect.
  - Operational Consequences:
    - Is there a tendency to interpret failures that are expensive to repair as having operational consequences, or to ascribe operational consequences to failures that inconvenience the operating personnel?
    - A no answer to question 3 means that the failure in question has only non-operational consequences, and that function need not be protected by scheduled tasks in an initial program. If the item is subject to a particularly expensive failure mode, it will ordinarily be assigned to intensive age exploration to determine whether scheduled maintenance will be cost-effective. At this stage. however, any task analysis that falls in the third branch of the decision diagram is subject to challenge by the auditor and must be supported by a cost trade-off study based on operating data for the same or a similar item.
    - All answers to the first three task decision questions should be examined in detail, at least for the first few items completed by each analyst to ensure that the analyst fully understands the nature of the questions.
- Task selection: applicability criteria

  - Does the analyst understand the relative resolving power of the four basic types of task and the specific conditions under which each type of task is applicable?
    - On-condition task: If the task is merely an inspection of the general condition of the item and is not directed at a specific failure mode, it does not constitute an on-condition task. The failure mode must also be one for which it is possible to define a potential-failure stage, with an adequate and fairly predictable interval for inspection. It is also important to evaluate proposed on-condition tasks in terms of their technical feasibility. The failure mode may be one for which on-condition inspection is applicable, but is the item accessible for inspection? Is the task one that is feasible within the maintenance framework of the organisation? Does each inspection task include the specific evidence the artisan is to look for - if not, the procedures writers may have difficulty converting the task to the proper job instruction.
    - Rework task: have the age-reliability characteristics of the item been established by actuarial analysis? Is the failure mode one for which rework will in fact restore the original resistance to failure? Is there a cost-effective interval for this task? Has the item been assigned to age exploration to obtain the necessary information?
    - Discard task: the only discard tasks that should appear in an initial program, is for items that have been assigned life limits by the manufacturer. Safe-life tasks are applicable only to items subject to critical failures; hence, they should appear only in the safety branch of the decision diagram. The life limits assigned to hidden-function emergency items (which are not in themselves subject to critical failures) are adjusted based on failure-finding tests and in the strict sense are not safe-life limits. The auditor should question any safe-life discard tasks that are not supported by on-condition inspections (where possible) to ensure that the safe-life age will be achieved.
    - Failure-finding task: is there a failure to recognise that these tasks are the default? Is there a failure to recognise that these tasks are limited to the detection of functional failures, not potential failures? The intervals for such tasks should also be examined tor mistaken assumptions concerning the required level of availability. Does the level of availability properly reflect the consequences of a possible multiple failure? Has the analyst overlooked the fact that the interval is based only on the required availability of the hidden function itself? Have failure-finding tasks covered by routine crew checks been accounted for on the decision worksheets?
- ❖ Task selection effectiveness criteria
  - The applicability criteria for tasks pertain only to the type of task and are true for that task regardless of the nature of the failure

consequences. The effectiveness criteria however, depend on the category of failure consequences.

  - Some practical problems often come up in interpreting the effectiveness criterion for the safety branch. Do the tasks and intervals selected have a reasonable chance of preventing all critical failures? If not, what is the basis for judging that the remaining risk level is acceptable?
  - On-condition tasks provide control of individual units and therefore have a good chance of preventing all functional failures if the inspection interval is short enough.
  - Scheduled removals merely control the overall failure rate for the item. The auditor should therefore question the decision outcome of scheduled rework in the safety branch, because a reduction in the failure rate is unlikely to reduce the risk of failure to an acceptable level.
  - In the case of Operational Consequences, does the analysis show the basis for determining that the task will be cost-effective? What costs are imputed to the operational consequences and what is the source of these costs?
  - Cost effectiveness is far more difficult to justify in the Non-operational Consequences branch. If a task has been assigned, what is the basis for the cost-tradeoff analysis?
  - In the hidden-function branch a proposed task must ensure the level of availability necessary to reduce the risk of a multiple failure to an acceptable level. Is there a policy concerning this risk level that can be used to interpret adequate availability?

- Use of the default strategy (the term 'default' is here used according to the Nowlan and Heap (1978) definition):
  - Have failures, which may or may not always be evident to the operating crew, been classified as hidden?
  - Where it cannot he demonstrated that any anticipated secondary damage will not be critical, has the failure been assigned to the safety branch?
  - Have any opportunities been overlooked to assign on-condition inspections that may be partially effective in pre-empting functional failures?
  - Have all items for which the necessary information was unavailable been assigned to age exploration?
- General use of the decision logic:
  - One major problem is the tendency to select a familiar maintenance task and then work back through the decision logic to justify it.

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    - This handicaps the analysis in two ways: on one hand, more of the tasks tend to stay justified, and on the other, the possibilities of new tasks are not explored.
    - Some analysts may have a strong preference for rework tasks and will specify them whether they are applicable or not. Others will favour on-condition inspections under all circumstances.
    - The auditor should look for signs of individual bias during the progress-review meetings, and by actually counting the numbers of each type of task selected by the various analysts.

- Sundry auditing concerns
  - Analysis of systems items
    - The chief difficulty in analysing systems items is confusion about the appropriate level or analysis and the functions of the specific item under consideration.
    - In the case of aircraft, Nowlan and Heap (1978) states that if more than 500 systems items have been classified as significant at the aircraft level, the list is probably too long, and if there are fewer than 200, it may be too short. If any subsystem includes more than half a dozen functionally significant items, their classification should be re-examined.
    - Another problem is finding the dividing line between one system and another.
  - Non-RCM program elements
    - The zonal inspection program should be audited to ensure that all zones in the equipment are included.
    - Zonal inspections are general visual inspections; do the tasks clearly describe the elements in the zone to be inspected?
    - The servicing and lubrication tasks should be audited for completeness, and any deviations from the manufacturer's recommendations should be substantiated.
  - The completed program
    - Additional questions may arise when the program is examined as a whole.
      - Do the tasks for each portion of the equipment/system cover all levels of maintenance?
      - Do they still make sense when they are viewed together?
      - Are there any gaps or overlaps?
    - Packaging presents special auditing problems, since the standards to be applied depend on the organisation, and other factors such as the number and location of maintenance facilities.
      - Have these been taken into account?

    - Auditing the packaging of the tasks is primarily a matter of determining whether the tasks have been scheduled as efficiently as possible for a given set of circumstances.
    - The impact of the maintenance program on the intended use of the equipment should not be overlooked in the audit. Will the proposed maintenance schedule permit each equipment to have the longest possible uninterrupted production runs?
- ❖ Auditing the ongoing program
  - ▪ Certain information systems must be established before the equipment goes into service:
    - A system for reporting failures, their frequency, and their consequences.
    - An age-exploration system.
    - A system for controlling the addition of new scheduled tasks to ensure that they meet RCM criteria before they are accepted.
    - A system for periodic reevaluation of all tasks in the program to eliminate those which are no longer needed.
    - A system for reviewing the content of the work packages as the size of the fleet grows.
    - A system for evaluating unanticipated problems and determining the appropriate action.
  - ▪ Auditing an ongoing maintenance program may require different skills and experience from those needed to audit program development. At this stage the auditor may often find himself in an adversary situation and will have to be both inquisitive and objective.
- ❖ Auditing new RCM analyses for older plant/business systems/equipment:
  - ▪ Older equipment may not be as sophisticated or complex.
  - ▪ It often has fewer fail-safe or damage-tolerant features.
  - ▪ Much of the age-exploration information is already available.
  - ▪ It is especially important for the auditor to determine that the new RCM program is not being developed by an analysis of the existing tasks, but represents a completely independent analysis of the equipment.
  - ▪ There should be much data of actual operating experience. Often one has to delve to mine the wealth of data, as it mostly are not readily available. Thus one of the major differences in auditing the analysis itself is to determine that the data were in fact used and were used correctly. The auditor should make sure that rework tasks, for example, have not been selected without an actuarial analysis of the data for the specific item.

- The number of tasks in the program will ordinarily be somewhat greater for in-service equipment. These should be reviewed thoroughly to make sure they are necessary.
- Older equipment may require more rework tasks than new equipment:
    - First, the results of age exploration will show the economic desirability of some additional rework tasks.
    - Second, the older designs may actually have more assemblies that show a wear-out pattern.
- Older equipment may also have a larger number of scheduled tasks for hidden functions because of older design practices.
- The number of on-condition tasks for older equipment may be slightly higher because ways of exploiting these relatively inexpensive inspections will have been found by experience for a number of items.

This concludes the investigation of the RCM methodology as found in the literature. The next chapter will seek to build on this basis to suggest a proposed improved methodology that will serve the interest of industrial users better.

Chapter 4: Model Development

4.1. Introduction

4.1.1. Problems in the application of RCM

Apart from inherent flaws in the RCM methodology, the problem with the industrial application of RCM is often that the technique is not understood properly. It is thus either applied wrongly or to the wrong equipment or to the wrong failure modes. In addition, if there is not a problem in these areas, the wrong (or partly wrong) maintenance tasks are often selected. Most of these difficulties can be attributed to one or more of the following factors, which should be addressed in the design of a methodology to improve the present RCM methodology:

a. The RCM methodology is not understood within the correct conceptual framework, which includes the proper understanding of its role in helping to make the business successful. This understanding has to have as basis an appropriate grasp of the business objectives and the role of the maintenance plan in achieving such objectives. It thus also includes that RCM, if used correctly, produces a plan based on the preservation of *system function* and not *system operation.*

b. Maintenance management is often not committed to ensure success through the application of RCM. It is mostly seen as a technical panacea from outside the management sphere, rather than one of the elements needed for maintenance management success. Because of this, the RCM result is often not implemented properly. To counter this lack of commitment Coetzee (1997/2), p 236, recommends the use of a management champion.

c. The typical RCM text (i.e. Moubray (1991) and Smith (1993)) provides very little in terms of ways to limit the scope of the RCM analysis process. This often leads to a design task, which becomes so large that it is abandoned or the end result presents the organisation with such a high preventive workload that the RCM technique is discredited. For most industrial organisations, the technique used for setting up a maintenance plan must *firstly* not be heavy on resources and, *secondly*, the resultant maintenance plan should effectively decrease the total maintenance workload (preventive time plus corrective time) [Coetzee (1997/2)].

d. The process of the choice of maintenance tasks is a critical one. Often this is not understood well enough, leading to too many / inappropriate tasks being selected. People that are trained in the application of the technique easily becomes so motivated that they tend to be over enthusiastic in finding preventive tasks for every possible failure mode that could present itself during the life of the equipment [Coetzee (1997/2)]. To a large extent, this can only be addressed through

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the use of suitably trained analysts, but the process can also be streamlined through the use of suitable flowcharts and/or decision trees or the like.

e. The use and enforcement of the resultant maintenance plan mostly leaves much to be desired. This occurs due to a combination of a lack of understanding of the process at planner/supervisor/artisan level, a company culture that is not conducive to acceptance of improved methods/plans, as well as the communication gap in the maintenance management hierarchy [Coetzee (2000/2)].

These five factors play a major role in the relative non-effectiveness of the industrial application of RCM. Together with the specific shortcomings of the various implementations of the RCM methodology as identified in chapter 3, these factors will form the framework for the design of the improved RCM model presented in this chapter.

4.1.2. Chapter structure

To address the inherent problems in the industrial application of RCM, the remainder of this chapter is divided into the following parts:

- Conceptual Framework (§ 4.2) - most maintenance practitioners and persons involved with maintenance does not understand the conceptual framework of the maintenance function well enough to implement RCM well. In particular, the problems quoted in § 4.1.1 a) and e) will form the backdrop to the development of the conceptual framework.
- Component development (§ 4.3) - after putting RCM within the proper conceptual framework, the improved RCM model will be developed using the same structure as that used in chapter 3 (refer to page 3-1). Even the paragraph numbers are related to each other (e.g. § 4.3.3 relates to § 3.2.3) for easy reference to the literature study. Part of the problems quoted in § 4.1.1 c) and d) will be addressed in this paragraph.
- Application structure and methods (§ 4.4) - this paragraph assembles the various components into one logical whole. It also addresses the progressive application of RCM to achieve the optimum mix between the method and other techniques. It thus strives to solve all outstanding issues of the problematics quoted in § 4.1.1 c) and d) which were not solved in paragraph 4.3.
- Organisational issues (§ 4.5) - in § 4.1.1 b) the lack of management commitment and underestimation of the RCM implementation effort is pointed out. This aspect is covered in some of detail in this paragraph, ranging from the organisation of the effort to the training requirements, to the RCM database and its connection with the CMMS.

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4.2. Conceptual Framework

4.2.1. The Maintenance Cycle

The Maintenance Cycle model [Coetzee (1997/1)] describes the internal operation of the maintenance organisation. This model is a logical development of the Terotechnology model [British Ministry of Technology (1969)] and the TUE maintenance model [Geraerds (1990)], which both concentrated more on the maintenance function's relationships with the outside world and other functions in the typical industrial organisation. The Maintenance Cycle Model, on the other hand, explains the management and operational processes within the typical maintenance organisation. Thus, its accent is on the inner processes of the maintenance function, in which RCM plays a major role. The Maintenance Cycle model is depicted in figure 4-1.

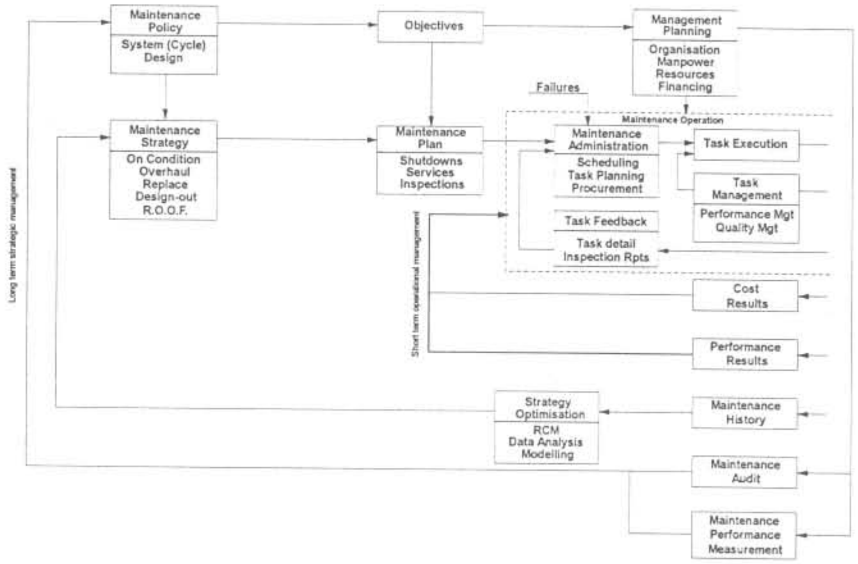

Figure 4-1: The Maintenance Cycle model

The maintenance cycle consists of two superimposed cycles, shown in figures 4-2 and 4-3 respectively. The outer cycle represents the managerial processes in the maintenance organisation, while the inner cycle represents the technical and operational processes. It is important to note that the outer and inner cycles do not represent different levels of management and/or operational staff, as the same persons will often operate both in the outer and the inner cycles.

The (managerial) sub-cycle has five embedded processes:

- Maintenance policy setting - the process during which the direction of the department is determined, as well as the broad game plan for achieving that goal - the policy is the driving force for the actions of the department.
- Objective setting - the process during which the maintenance management team determines and/or updates the department's objectives, which should be very specific in terms of both the results achieved and

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the target dates, and are in line with the framework as defined in the maintenance policy.

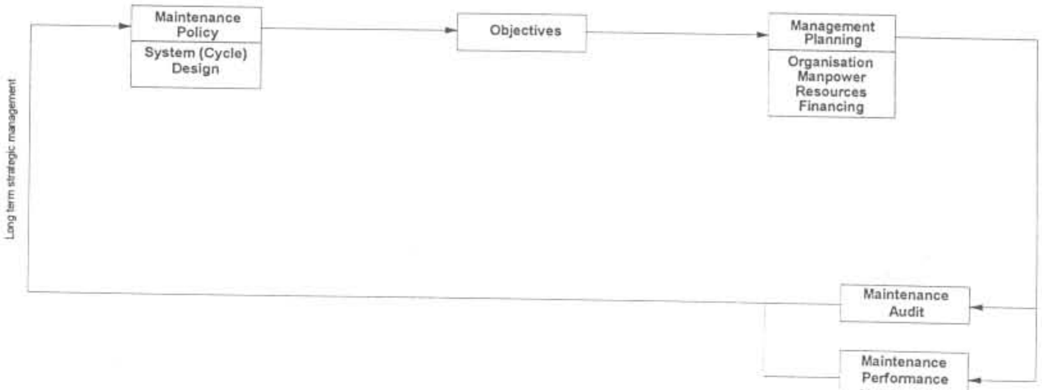

Figure 4-2: The outer (managerial) sub-cycle

- Management planning process - based on the policy document and the maintenance objectives, the maintenance management team plans the detail functioning of the maintenance organisation.
- Maintenance auditing - a formal audit process, which includes both hard and soft audits, forms the annual measurement process that completes the maintenance management cycle's control loop.
- Maintenance performance measurement - a measurement process that combines various performance measures into one single measure that gives an indication of the success with which the maintenance policies are being pursued.

The managerial cycle is a closed loop cycle and the process is repeated at a fixed frequency (normally annually).

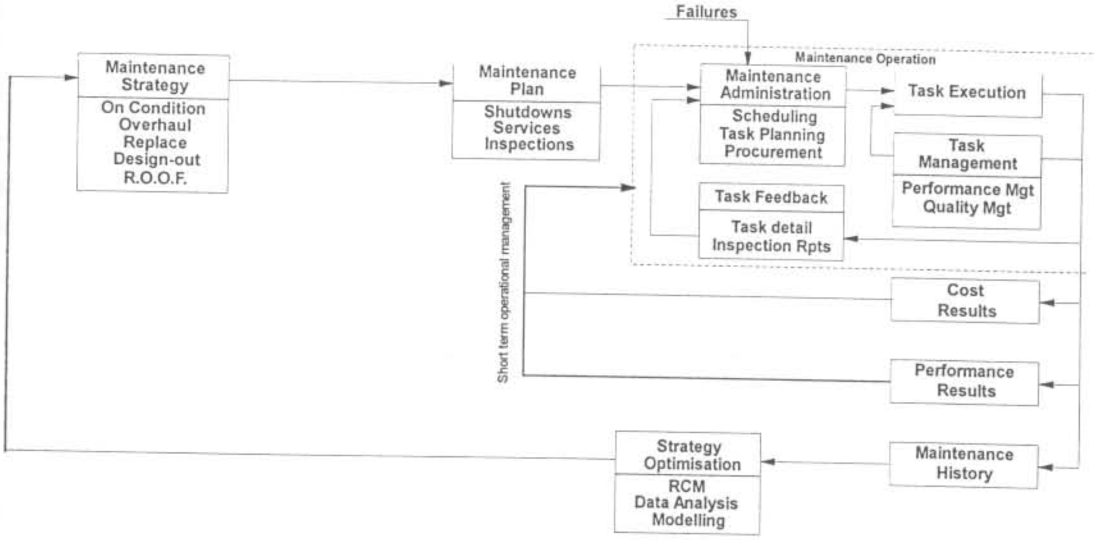

Figure 4-3: The inner (operational) sub-cycle

The second sub-cycle (the inner cycle) is concerned with the technical planning and operational part of the maintenance department's business. The inner cycle consists of two main processes:

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- Maintenance planning - this includes the three sub-processes Maintenance Strategy Setting, Maintenance Plan Development and Strategy Optimisation.
    - ❖ Maintenance strategy setting - in this process a decision is taken as to the maintenance strategy selected for each maintenance significant component of each machine.
    - ❖ Maintenance plan development - for each machine a maintenance plan is drawn up by combining the various component strategies into logical work units with specified scheduling frequencies.
    - ❖ Strategy optimisation - the selected strategies can be optimised at a regular (normally annual) frequency based on the aggregated machine history. Techniques such as Reliability Centred Maintenance[1] (RCM), maintenance data analysis and mathematical modelling are employed in this process.
- Maintenance operation - this process, contained within a dotted square, consists of the sub-processes Maintenance Administration, Task Execution and Task Management.
    - ❖ Maintenance administration - this sub-process, traditionally known as maintenance planning, involves all aspects of task scheduling, task planning, procurement, issue of task documentation and feedback of task data.
    - ❖ Task execution - the sub-process during which the maintenance worker (typically an artisan) performs the task as specified in the task documents.
    - ❖ Task management - the supervisory process, where the task is controlled. This includes task areas such as quality control, expert advice to workers, task follow-up, requisitioning, prioritising, backlog management, work efficiency management, budget control, safety and housekeeping and facility management.

The inner cycle is also a closed loop. Its has various feedback information and/or data sources, which result in operational management and supervisory action:

- Initiation of additional tasks, based on completed work feedback.
- Initiation of corrective maintenance tasks, based on failures of the business' assets. This is not a closed cycle feedback item in the strict sense, except if one considers the business as another process in the inner cycle.
- Managerial action in achieving optimal operational excellence and control based on cost and performance results.

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[1] RCM is inherently a macro optimisation methodology - if applied correctly, it results in the best maintenance plan (consisting of the best maintenance strategies) for the organisation.

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- Use of maintenance history to optimise maintenance strategies, thereby achieving an optimised maintenance plan.

The arrows connecting the outer and inner cycles in figure 4-1, show that there is interaction taking place between the outer and inner cycles. This interaction takes place primarily from the outer to the inner cycle - the managerial processes define the scope within which the inner cycle processes can take place. On the other hand, the results of the inner cycle processes in achieving the policy-guidelines and objectives are measured during the Maintenance Performance Measurement and Maintenance Auditing subprocesses in the outer cycle.

4.2.2. Maintenance a holistic 'problem'

Until fairly recently (the 80's), maintenance theory was non-existent. In the meantime, technology[2] was developing at such a pace[3] that present maintenance practices became obsolete. As possible maintenance 'solutions' became available, hungry maintenance practitioners seized them to solve their seemingly non-solvable situation. These 'solutions' include Reliability Centred Maintenance (RCM), Total Productive Maintenance (TPM), Condition Based Maintenance (CBM), Computerised Maintenance Management Systems (CMMS), Auditing Systems and the like. Most of these (apart from TPM and Auditing Systems) are aimed at the inner cycle of the Maintenance Cycle and will thus not produce the results envisaged, because of it not addressing the total complexity of the total maintenance function (outer and inner processes).

While each of the philosophies/techniques listed above play an important part in the solution, it must be implemented in a properly co-ordinated way. The problem with the fragmented 'solutions' towards improving the effectiveness of maintenance is that it does not assist the maintenance practitioner in positioning the technique as a part of a total maintenance strategy. The only exception to this is that of TPM, which is a philosophy addressing the total complexity, but which has had limited success in the western world due to a difference of managerial outlook.

The complexity of the maintenance function as depicted by the Maintenance Cycle requires an approach, which is strategically driven (from the outer cycle of the Maintenance Cycle). And this should include addressing important areas such as organisational climate, the suitability of personnel for their positions' requirements, training, facilities, operational and information systems.

The maintenance organisation, like all parts of the business consists of various parts that must function in full harmony to achieve a maximum contribution towards the goals of the business. This is not fully appreciated in most maintenance organisations, due to the accent on technical aspects in engineering tuition. Such harmony cannot be achieved by implementing highly

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[2] The technology built into the equipment or machinery or buildings that has to maintained.

[3] The information revolution and the later communication revolution is the major cause of this.

sophisticated (mostly technologically oriented and localised) solutions to problems experienced in sub-parts of this 'organism'. The only solution is a holistic approach that touches all the critical parts of the organisation at the same time.

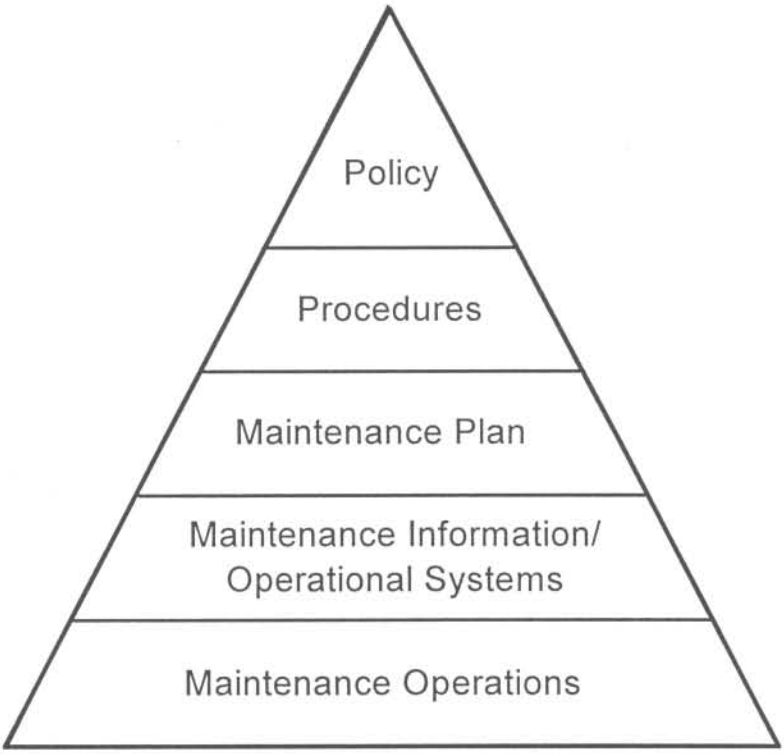

Figure 4-4: Maintenance Functional Hierarchy

Figure 4-4 is a diagrammatic representation of the various main areas depicted in the maintenance cycle. It shows the dependence of the various areas upon each other. The first level (the execution of maintenance work) is regarded by many as the heart of maintenance. However, this (bottom-most level) is dependent upon all the levels above it. Thus, the most important (and foundational) level is the maintenance policy, which dictates what procedures should exist and to which the maintenance plan is sub-ordinate. The maintenance plan is again necessary to effectively use maintenance information and operational systems, which in turn is necessary for effective maintenance operations.

4.2.3. Maintenance Risk

Maintenance risk consists of the different maintenance-related contributors to the non-achievement of production goals. The concept of maintenance risk (as defined by Jones (1995)) was introduced in paragraph 3.2.5 as a means for the prioritisation of failure modes.

Maintenance risk factors are typically measured in units such as downtime, percentage unavailability, units of production lost and increased maintenance cost. Risk is defined as:

$$R_i = P_i \times C_i \qquad 4\text{-}1$$

$$R_i = Risk\ attributed\ to\ the\ i^{th}\ risk\ consequence\ factor$$
$$P_i = Probability\ of\ occurrence\ of\ the\ i^{th}\ risk\ factor$$
$$C_i = Consequence\ of\ occurrence\ of\ the\ i^{th}\ risk\ factor$$

where the consequence C_I is expressed in monetary figures.

The different classes of maintenance risk are:

Risk consequence factor 1: Safety
Risk consequence factor 2: Lost Production
Risk consequence factor 3: Lost Quality
Risk consequence factor 4: Environmental Effects
Risk consequence factor 5: Maintenance cost

Each of these can be quantified and R_I calculated in monetary terms for the specific risk factor (i = 1 to 5 as shown above). The total risk for a particular (the kth) maintenance situation (such as a single piece of equipment to be maintained) can then be calculated from:

$$R_k = \sum_{i=1}^{5} R_i = \sum_{i=1}^{5} \left(P_i \times C_i\right) \qquad 4\text{-}2$$

The risk R_K of various maintenance situations can then be plotted on axis consisting of the two primary risk quantities P and C, where the different lines represent different levels of constant maintenance risk (or iso-risk[4] lines). The risk thus increases as shown in figure 4-5:

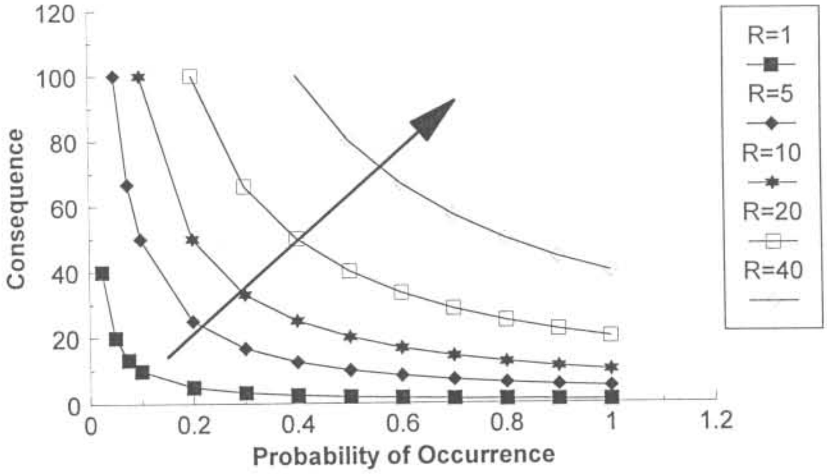

Figure 4-5: Increasing risk

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[4] Each of the joined points on the iso-risk lines in figure 4-5 represents points for which R = Consequence x Probability = constant.

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By plotting the various risks on the risk plot, the type of figure presented as figure 4-6 is obtained, with each risk being represented by one of the small asterisks and the average risk by the large asterisk. To improve (lower) the maintenance risk of the organisation, the risk represented by this large (average) asterisk must be managed downwards [Coetzee (2000/1)].

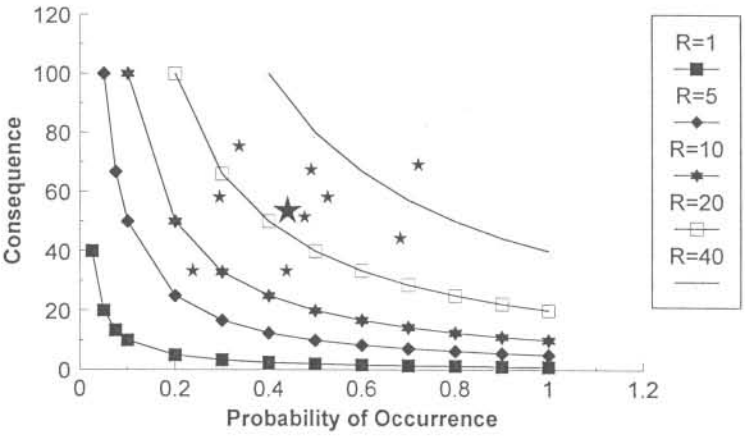

Figure 4-6: Risk plots

It follows that to reduce risk, it should be managed such that the average risk is moved to a lower total risk position on the risk plot [Jones (1995)]. This can be achieved through lowering either the consequence or the probability of occurrence for each individual risk point. The best approach is to lower both factors simultaneously, causing a decrease towards the origin (arrow A in figure 4-7). This is often not possible and the second best approach would then be a move in the direction of arrow C (a decrease in the consequence of individual risks, even if than means an increase in the probability of occurrence). Although the high rate of occurrence is a nuisance, the total risk will be reduced with the necessary beneficial effects on the organisation's profit. The worst situation is that represented by arrow B. This position, which reduces the probability of occurrence without a decrease in the consequence, has a beneficial effect on the total risk, but is not to be pursued if possible. This is due to the low predictability (due to the lack of statistical data following from a low rate of occurrence) which it provides of high consequence risks.

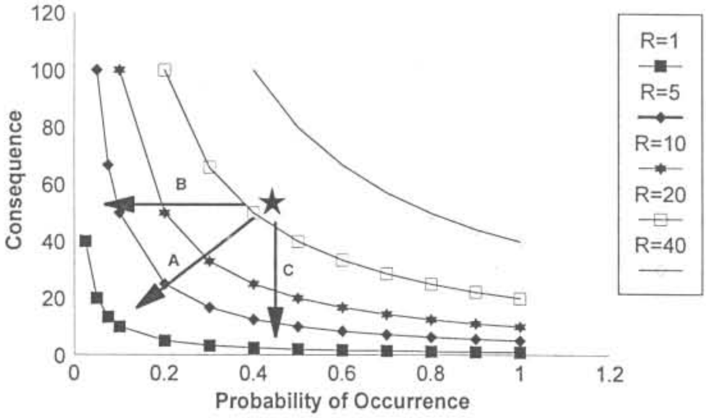

Figure 4-7: Directions of risk reduction

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Ways to reduce risk

With paragraphs 4.2.1 and 4.2.2 in mind, the principles of maintenance risk reduction as presented by Coetzee (2000/1) is introduced. There are two components in an integrated risk reduction effort:

a. **General risk reduction through proper maintenance management practice:** This is effected by putting in place the following managerial structure items (refer to the various sub-processes in the Maintenance Cycle, figure 4-1):
   - Maintenance policy/procedures
   - Maintenance business plan
   - Measurement processes
   - Maintenance Plan
   - Maintenance Administration principles and procedures
   - Maintenance Systems – effecting the systematic organisational behaviour, constituting the formal maintenance system (of which the CMMS is a part).
   - Development of the Maintenance Workforce – the workforce is developed in terms of knowledge, procedures and teamwork.
   - Management Excellence – this is achieved through a planned and concerted effort in applying good maintenance practice over a wide front in the organisation.

b. **Specific risk reduction through managing the risk of single high risk items downward:** This is an important facet of overall risk reduction. Although it is imperative that the management structures discussed above be put in place to have success, risks do not disappear by themselves, but through a concerted effort in reducing the risk of each major risk contributor. It is through these one by one risk reduction efforts, that most of the benefits of having proper policies, procedures and plans accrue.

4.2.4. Maintenance Strategy Options

Each time failure occurs, it affects the organisation negatively. The negative effects can be anything from losing output, quality, and timeliness to higher costs and threats to the safety of people or the environment. Sometimes the effect of the failure is not immediately evident (as in the case of the failure of non-fail safe safety devices), but can be the cause of a catastrophic multiple failure later. The organisation has to make a conscious decision regarding the prevention or not of each important failure mode. If a failure is not prevented, money will have to be spent on repairing breakdowns at a later stage. Thus a trade-off exists between the cost of prevention on the one hand and the cost of failure on the other (and such costs do not only include monetary costs). Depending on the severity of the failure (in terms of production lost, the cost of failure, the life of people or the effect on the environment) the organisation has to decide whether:

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(i) to prevent the failure from occurring *or*

(ii) whether the failure can be left to be handled when it occurs *or*

(iii) whether the failure has to be eliminated through design-out (the most costly option, both in terms of direct cost *and* organisational impact).

Reliability Centred Maintenance is concerned with the development of an optimal maintenance plan for the organisation, using well-excepted equipment reliability principles as basis. Such a plan consists of the total of all maintenance tasks to be performed for the various assets to be maintained. These tasks are based on and are derived from the most acceptable maintenance strategy options in each case, with the objective of minimising the negative effects of failure on the organisation. A suitable description of the various strategy options is found in Coetzee (1997/2), chapter 4. The present section is based on this source.

In principle there are only three main strategy options as depicted by the top structure of the strategy tree in figure 4-8. There are three options (in order of preference): prevent the failure from occurring; leave the failure to occur and then correct it; or redesign the system/component to remove the failure mode, if corrective maintenance is not an acceptable strategy. The first choice of strategy is thus always to either prevent the failure from occurring or to prevent its effects from affecting the organisation negatively. This is the most conservative strategy option. If *prevention* is not viable technically or economically (the two prerequisites for choosing prevention as strategy), the default strategy is *corrective maintenance* (except in the case of safety related failures). The last strategy option is design-out maintenance, which will be the default strategy for safety-related failures, and an economic choice (refer to the model in figure 4-28) in the case of other failures.

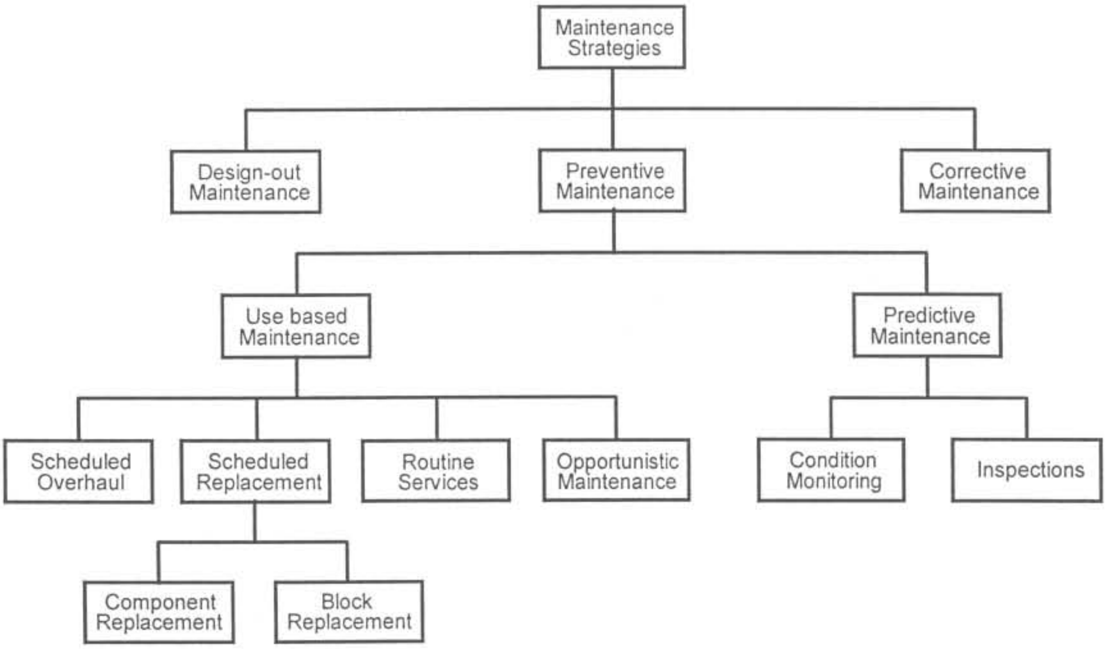

Figure 4-8: Maintenance Strategy Tree

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The three main strategy options and their sub-divisions are the following:

a. Preventive Maintenance

Preventive Maintenance can either be of the use based or the condition based variety. All maintenance strategies aimed at preventing failure from occurring or limiting the negative effects of failure are of the class Preventive Maintenance.

i. Use Based Maintenance

The traditional way of preventing failure from occurring is by replacing or reconditioning the item (sub-system or component) before failure occurs. The intuitive argument is that timely planned maintenance should lead to the prevention of unnecessary production delays, as it preserves the reliability of equipment. This technique is (wrongly) known to most people as Preventive Maintenance (P.M.) - as stated above, it is one of the class Preventive Maintenance, but not the only one. Contrary to intuitive belief, it is not universally applicable. This type of maintenance is only applicable (except in the case of use based routine services) to those cases where the risk to fail (force of mortality) increases with age. Prime examples are high wear, high corrosion or high erosion circumstances. Use based maintenance can in its turn be subdivided into:

Age based maintenance - maintenance actions are undertaken regularly based on the age of the equipment. Examples are scheduled maintenance work based on machine running hours, tonnage handled, production throughput and kilometres travelled.

Calendar based maintenance - maintenance actions are undertaken regularly based on expired calendar time, irrespective of production intensity. Examples are annual, bi-annual shutdowns to perform statutory work.

Use based maintenance tasks can further be classified into one of the following broad classes:

Scheduled overhaul - the machine or component is completely stripped and reconditioned to as near as possible to the as-good-as-new condition.

Scheduled replacement - the item (sub-assembly or component) is discarded and replaced by a new unit.

Routine services - the plant/business system/machine receives a service during which routine checks are made, oils and filters changed, greasing done and adjustments made.

Special categories of use based maintenance are:

Block replacement (or *group replacement*) - block replacement is based on the concept that similar components should have similar failure frequencies. Where the cost of lost production, plus the labour cost of replacing a component is high in comparison to the cost of the component, it might be worthwhile to consider block replacement. There are two main classes of block replacement. In the first, all similar components are replaced if one of them fails (corrective block replacement). Alternatively, all similar items can be replaced on a scheduled basis (preventive block replacement).

Opportunistic maintenance – sometimes, important scheduled work is identified as work that will only be carried out if the productive unit is down for some reason (e.g., breakdown). This is typical in cases where the continuous operation of the unit is critical and/or the loss incurred during plant/business system downtime is severe. Tasks is are scheduled for execution but are only carried out when the opportunity arises.

ii. Predictive (Condition Based) Maintenance

Predictive Maintenance is applicable to any failure mode where it is found to be technically and economically feasible - it has a special place in the cases where the risk of failure (hazard rate) does not increase with age, as Use Based Preventive Maintenance cannot be used in those cases. The condition of the equipment / component is measured at predetermined intervals, in order to determine when the risk of component failure becomes high. Only when the risk becomes unacceptably high will a replacement/overhaul be scheduled. Two main types of condition based maintenance can be identified:

Inspection - use is made of the five senses of a person to determine the condition of the equipment or component. This can include the use of instruments that enhances the use of the senses through amplification or benchmarking.

Condition monitoring - some parameter is monitored, using sophisticated measuring equipment, to detect signs of imminent failure. Examples of these are:

- Vibration
- Shock Pulse
- Oil condition
- Acoustic emissions
- Equipment Performance
- Thermography

iii. Corrective (Failure) Maintenance

This is a strategy of 'do nothing' or 'wait for failure' or 'repair only on failure (r.o.o.f.)'. It entails not trying to prevent the failure from occurring through either predictive or use-based strategies. This strategy is used when a preventive strategy is not technically or economically viable. Corrective maintenance can be further classified into the following three classes:

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Replacement - totally replace the component or unit upon failure.

Repair - repair the component or unit upon failure.

Delayed decision - either totally replace the component or unit upon failure or repair it, based on an *in loco* inspection following failure.

iv. Design-out Maintenance

This is, apart from the safety case (refer to the model in figure 4-28), the last resort strategy. The objective is to redesign the particular system or component to decrease the need for maintenance by removing unwanted failure modes. In the case of safety related failures, it is used by default to remove failure modes for which no suitable preventive tasks can be found. In all other cases, it is based on economic considerations when no suitable preventive task could be found and corrective maintenance (direct maintenance cost plus the cost of lost production) will be too expensive. A detailed economic trade-off study should always be done in such cases before proceeding with the design-out strategy. This should prove that the cost of the design work plus the consequential cost (manufacture, modification of existing machinery, system changes and stock changes) is less than the cost of corrective maintenance (direct maintenance cost plus the cost of lost production).

4.2.5. Reliability Centred Maintenance in context

The four sub-headings above (paragraphs 4.2.1 to 4.2.4) constitute the framework or context within which RCM has to be applied. Paragraph 4.2.1 presented the maintenance cycle, which shows *firstly,* that RCM is used in the inner or operational sub-cycle and *secondly,* that the technique provides one of the most important inputs to the maintenance operation itself, namely the maintenance plan. The second section (paragraph 4.2.2) pointed out that RCM forms part of one 'holistic' whole in terms of the maintenance organisation. It also showed that the methodology will not be effective (or not as effective) when used in an organisation where it is seen as only a part (albeit an important part) of the solution to the total maintenance 'problem'. Paragraph 4.2.3 gave a means for managing maintenance risk, a method that can be used very effectively to ensure that the RCM analyses leads towards a co-ordinated positive macro impact on the organisation. In particular, maintenance risk is a very important means for identifying the high-risk areas where RCM application will have the highest impact on profit. The maintenance strategy tree given in paragraph 4.2.4 is an essential element of the RCM process itself as RCM is a methodology for applying the best strategies to various maintenance situations to achieve an optimised maintenance plan.

The message of figure 4-4 is particularly important for the discussion of the context of the RCM methodology. This fundamental diagram shows that the maintenance plan is one of the central elements in the functional hierarchy of the maintenance organisation. *Firstly*, the methodology will not be effective, even when applied properly to the organisation's assets, if it is not applied in

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the context of an appropriately defined and implemented maintenance policy as well as the necessary supporting management procedures. The main reasons for this are:

a) that the RCM effort must be aligned with the organisation's strategic thinking *and*

b) that the RCM result will not be effectively put to use by the maintenance operational staff if they do not understand the rationale behind the RCM drive and believe in the end result.

Secondly, the RCM output constitutes one of the primary inputs to the maintenance operation. It is the main driver of planned maintenance actions and it follows that its success is critical to the success of the Computerised Maintenance Management System (CMMS) and the eventual result of the maintenance effort. Coming back to the fact that its position is a central one in the maintenance functional hierarchy, it could be argued that attempting to manage maintenance without designing a suitable maintenance plan is analogous to running a production concern without any production schedule or plan. The result is disaster, from both the organisational control and financial result perspectives.

4.3. Component Development[5]

4.3.1. Framework for component development

The principles underlying RCM are not complex at all. On the other hand, because of the number of concepts involved in the methodology, RCM is often perceived to be complex by users of the technique. It is thus expedient to introduce a simple overall structure, which serves to communicate the total concept in a palatable way. This structure can be used as a framework for the detailed development of the new methodology. The framework developed for this purpose in chapter 3 is adapted, and is shown in figure 4-9.

This RCM outline differs from the one introduced in chapter 3 in two important aspects. It *firstly* has two additional process blocks, that incorporates more of the formerly peripheral processes into the body of the methodology and thus improves understanding and ease of application. *Secondly*, it incorporates two formal feedback loops, which serve as reminders that RCM is not a once off process, but should become a continuous action in the maintenance organisation. Maintenance success is so central to the success of the typical manufacturing business that it will not succeed in a competitive world without a reasonably optimised maintenance plan.

The *first* additional process block comprises the implementation of the maintenance plan resulting from the RCM analysis. This block in turn consists of two sub-processes, the population of the task database and the performance

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[5] Refer to § 4.1.2 on page 4-2

of the resulting scheduled maintenance. The first of these comprises the input of individual tasks and task frequencies into the task database in the packaged format provided by the task packaging sub-process. The second sub-process involves the routine scheduling of the tasks for execution by maintenance operational personnel, including the feedback of relevant actual task data into the history base.

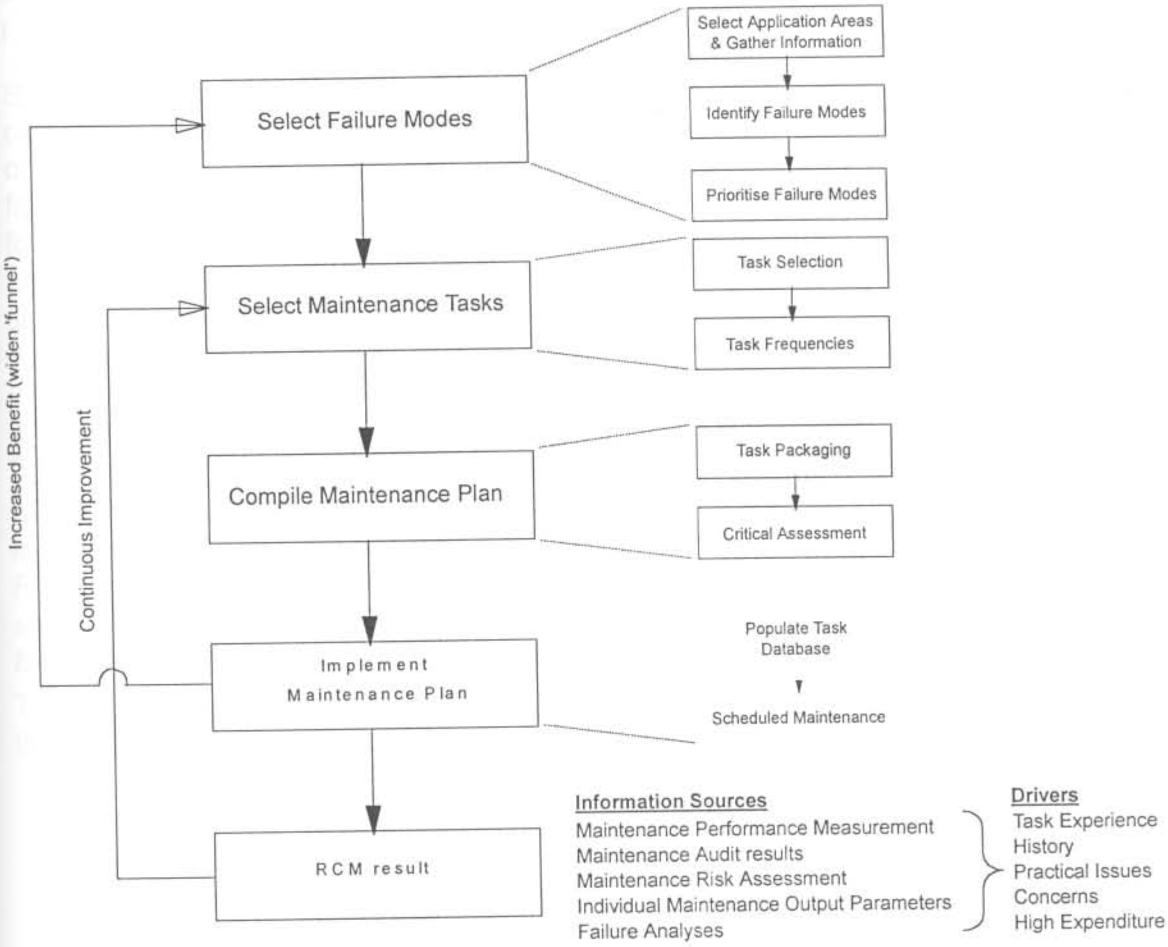

Figure 4-9: Outline of RCM process

The *second* additional process block depicts the result of RCM application. It pictures the process of continuously evaluating the result to initiate improvement action, as is necessary. This evaluation is based on information sources, such as Maintenance Performance Measurement [Coetzee (1997/2) chapter 11], Maintenance Audits [Coetzee (1998)], Maintenance Risk assessment as described above (paragraph 4.2.3), Individual maintenance measurement parameters and indices and failure analysis results. The drivers that cause improvement actions to be initiated are items such as:

i. Task experience (proving that a present task is not optimal).
ii. Task and life history (initiating failure analyses with resultant task and task frequency changes).
iii. Practical issues (requiring different task packaging or specification).
iv. Concerns (very often 'gut feel' that needs to be substantiated through detailed analysis).

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v. High expenditure.

The above-mentioned drivers are serviced by a Continuous Improvement feedback loop, which mostly re-initiates the Task Selection process to improve the Maintenance Plan based on new information as listed in points i to v above. The other feedback loop is used to achieve an increased benefit, based on an increased scope of application of the RCM methodology (see paragraph 4.4).

Something which must be reiterated here, and which cannot easily be included on the diagram, is RCM's accent on the *preservation of function* as opposed to the *preservation of equipment* (see paragraph 3.2.1). This is a facet of the RCM process that should be continually stressed, as it is normal for maintenance users of the methodology to think in terms of the equipment. One of the terms found in maintenance terminology is 'machine health'. One should change your view of maintenance to one of *preserving essential equipment function* instead of one of *preserving general equipment health*. When the equipment was originally bought, the organisation bought *function*. It is this function that must be preserved. The RCM handbook of the Naval Sea Systems Command (1983) accentuates this view by stating:

"*RCM is a methodology intended for use in developing … **the preventive maintenance program for a ship**. If you are involved … in the application of RCM, you should understand that intention. Otherwise, you may focus on some lesser level of assembly rather than **on how it, in concert with other hardware, provides all the function of the ship***."(accentuation added).

The focus should be the *ship* and its functions – that was what was bought in the first place, and that is what should be preserved.

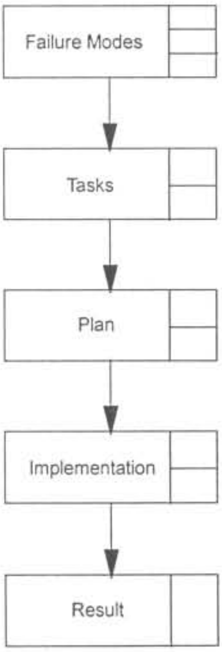

Figure 4-10: Tracking Diagram

To assist the reader in following the various discussion topics in this chapter, use will be made of a diagrammatic representation (like the one used in

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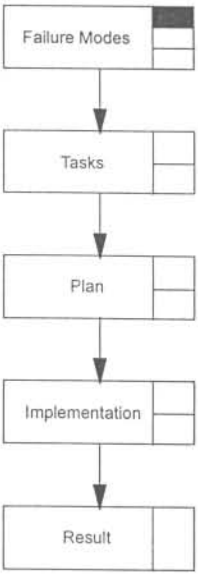
chapter 3) to assist him/her in understanding which part of RCM is being addressed. The framework of this diagram is shown in figure 4-10, where the smaller blocks on the right hand side of the process blocks represent the sub-process blocks as shown in figure 4-9. The smaller blocks will be individually filled to show which parts of the RCM process is currently being addressed.

4.3.2. Selection of Application Areas



In the analysis of paragraph 3.2.2 it was found that three methods of selection of application areas are in use. These are *firstly* partitioning [Nowlan and Heap (1978)], *secondly* use of the plant register [Moubray (1991)], and *thirdly* analysis at the systems level [Smith (1993)]. The most frequent used is the method of partitioning (breaking down) the equipment to a level which ensures, on the one hand, that no failure mode is missed and, on the other hand, that the failure modes selected have an impact on the equipment function.

Which one of these three methods to use depends on the technology involved and the business culture. Each user has to evaluate his/her situation and use that mix of the three methods best suited to his/her business. Nevertheless, the best way of analysis (in pure technical terms) is by combining elements of these three methods into one. In most businesses a plant register exists that can be used to identify the technical structure of equipment/infrastructure of the business. This plant register can at least be used to identify the top structure (divisions and systems – see figures 3-1 and 3-2). Smith's idea to work at systems level is a good one for identifying the various systems for which further analysis should be performed. Those systems can then be subjected to a partitioning process to identify the Maintenance Significant Items (MSI's). This approach will be the best in ensuring that no important failure modes are missed, to achieve the best version of optimised maintenance plan at any particular point in time.

In order to ensure that no important failure modes are missed *at any particular point in time* involves four issues. *Firstly,* it requires the correct identification method for the business' major systems - the plant register and Smith's method can be used to divide the business assets (or plant) into its major systems. *Secondly*, choosing the most important plant items (business assets), from amongst the ones identified in the previous step, for the application of RCM – a method for this is suggested by Coetzee (1997/2) as was described in the last sub-paragraph of paragraph 3.2.2. *Thirdly*, this last method (for choosing the most important assets) should be such that it allows a progressive increase in the number of assets included for RCM application. *Lastly*, a method to ensure that the analysis is carried out at the right level. The method used by Coetzee (1997/2), which was shown in figure 3-4, can be used as basis, but should be improved to include all the relevant comments of other authors as described in paragraph 3.2.2.

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4.3.2.1. Identification of major systems

Most businesses have an asset register (plant register) that can be used to identify the technical structure of the business. This register can at least be used to identify the top structure of the equipment/infrastructure (divisions and systems). This entails some or other combination of the use of the asset register and the identification of major systems. However, as different businesses' structure differs, this will also be reflected in the way in which this identification process is conducted. The identification process for four types of businesses is shown in figure 4-11.

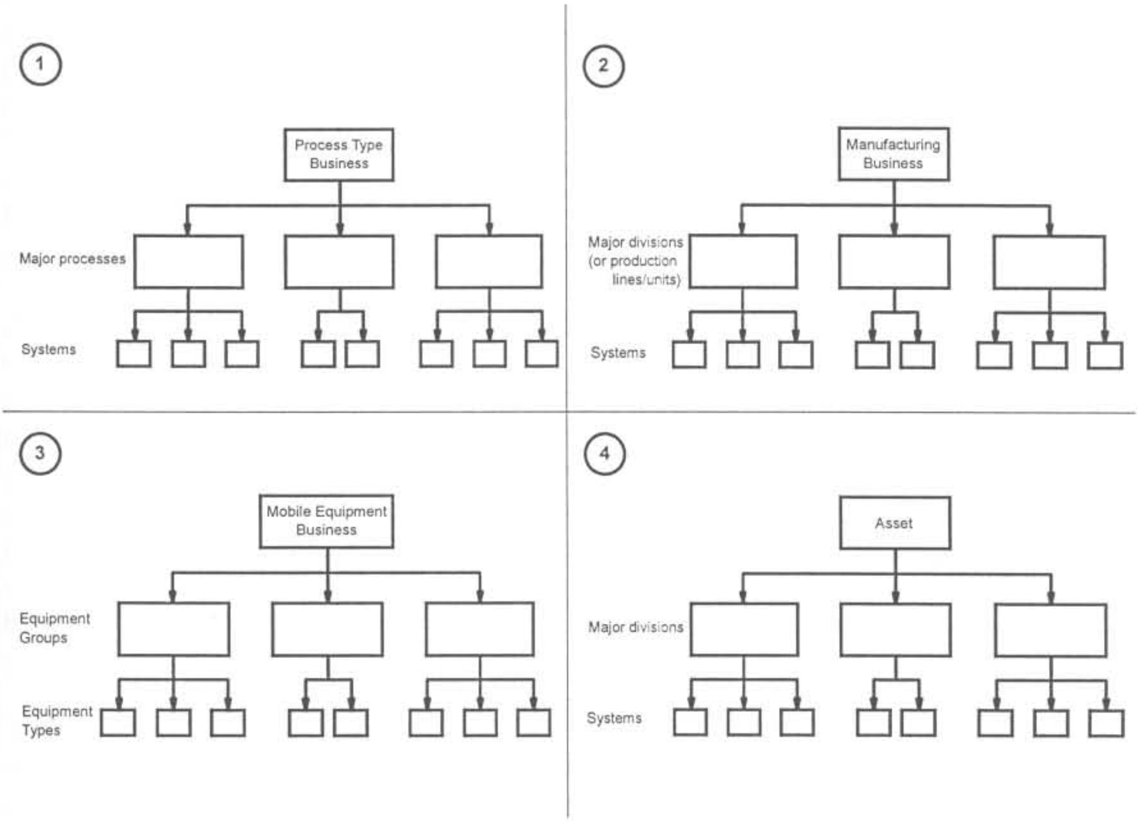

Figure 4-11: Identification of major systems for some business types

It is clear from figure 4-11 that there could not exist one simple formula for this top-level identification of major systems. It is not even plausible to always end with 'systems' as the bottom level result of this identification process (see case 3 in figure 4-11). The detail of this process really depends on the complexity of the business. In most complex businesses cases 1 and 2 will apply - the systems at the bottom level can each in turn be subdivided into individual equipment types using the structure of case 3, whereupon the equipment types can be subdivided into equipment subsystems using the structure of case 4. On the other hand, in mobile equipment type businesses (mines, quarries, civil works, transport businesses, farms) case 3 will apply – the equipment types can again be subdivided into equipment subsystems using the structure of case 4, if required. In the most simple case (such as the maintenance of a single building or building complex) case 4 will apply.

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The objective of this identification step is to identify systems (or units) at a high enough level to facilitate the next step, that of choosing the most important systems (or equipment types or assets) for further analysis. The resultant 'system' level must be high enough to easily determine the relative business impact of each such 'system', while being low enough to effectively limit the RCM analysis workload to a plausible one.

4.3.2.2. Choice of systems[6] for analysis

Following the identification of systems, a method must be devised to choose the most important of these for the application of RCM. Coetzee (1997/2) suggests that this should be done using the profit contribution of each of these units to prioritise the units in order of their relative contribution. Although this method is an improvement on the standard RCM methodology, it is imperfect. The main problem with the approach is that it accentuates profit only, without due regard to other impact parameters, such as safety and environmental effects. It also does not allow comparison with other impact parameters, due to a difference in measurement units.

Jones (1995) proposed the risk method presented in paragraph 4.2.3 as a way of quantifying the relative criticality of the various failure modes. This method is also suitable for the quantification of the relative importance of the different units. His method allows for the simultaneous evaluation of five impact-parameters in direct maintenance-related terms, using money as the common denominator. The parameters evaluated are lost production, lost quality and maintenance cost, as well as safety and environmental effects. A combined risk figure is then calculated for each unit – these figures can then be used, to identify the "20" % of units with the highest maintenance risk impact for further RCM application.

The specific method used for deriving the figures for this risk calculation is very business-specific. The method proposed for failure modes in paragraph 4.3.5 (table 4.2) may provide some insights.

4.3.2.3. Progressive application

The application of RCM should of course not stagnate at the "20" % level, as there is certainly much more benefit to be gained from better maintenance practices. The "20" % technique is only used to improve the short term gain and logistics of the RCM process. This "20" % window can and should be widened progressively following the successful implementation of the first "20" % of maintenance tasks – there should be a progressive increase in the number of assets included for RCM application.

The key is that the implementation must be progressive, that is, it should never be allowed to stop or stagnate. See the later discussion concerning the 'living RCM programme' in this regard (§ 4.4, p 4-59).

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[6] In the case of a mobile equipment business, these systems will be equipment types (see figure 4-11).

4.3.2.4. Partitioning process

The partitioning process suggested by Nowlan and Heap (1978) as described fully in paragraph 3.2.2 as well as their definition of 'Maintenance Significant Items' are well entrenched in the maintenance community and are sufficient to deal with this step in the analysis process. If one analyses the comments regarding the level of analysis in paragraph 3.2.2, it is clear that most authors agree with the Nowlan and Heap approach:

> *The resultant level of MSI's should be low enough that no failure possibilities are overlooked, but high enough for the loss of function to have an impact on the equipment itself.*

They predominantly put more accent on the importance of not analysing at too low a level, rather than not analysing at a low enough level. The emphasis is thus on making sure that failures at the level at which the analysis is carried out has a real negative effect at the equipment (or system) level. This was put strongly by the RCM handbook of the Naval Sea Systems Command (1983): "*RCM is a methodology intended for use in developing … **the preventive maintenance program for a ship**. If you are involved … in the application of RCM, you should understand that intention. Otherwise, you may focus on some lesser level of assembly rather than **on how it, in concert with other hardware, provides all the function of the ship**.*" (accentuation added). The focus point is the system function that was bought and that should be preserved. This necessitates fundamental changes to the diagram in figure 3-4 as was envisaged in paragraph 3.2.2 and reiterated above. The resultant new diagram is shown in figure 4-12.

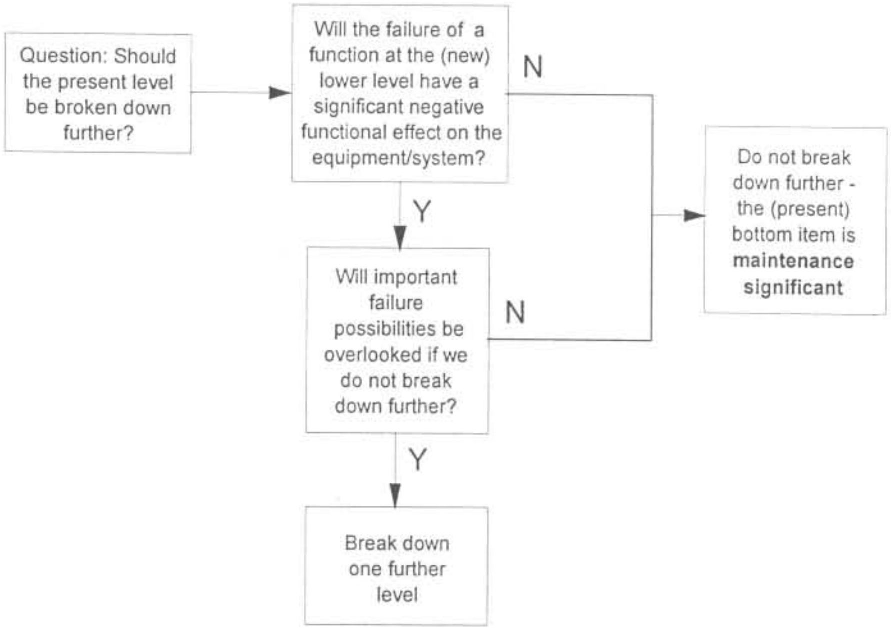

Figure 4-12: Item breakdown decision diagram

A few significant changes have been made to the original diagram in line with the available RCM experience. The *first* of these is that the block asking the question 'Is this the level at which we normally do maintenance?' in the original diagram has been removed. The aim of this block was to incorporate present maintenance experience regarding the right level to do maintenance at

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into the decision making process. With the accent on doing the analysis at a fairly high level, this block has become superfluous. The *second* change is in the wording of the second block where the words 'an impact' was replaced with 'a significant negative functional effect' to ensure that the partitioning process is stopped at a level that still has a significant impact at the equipment (or system) level. The other changes are smaller and was effected to promote clarity.

4.3.2.5. Prioritisation of MSI's

In line with Coetzee (1997/2), it is expedient to add another selection process to streamline the RCM process such that only the most important MSI's are subjected to detailed RCM analysis first. This prioritisation can be done using the risk approach outlined in paragraph 4.3.2.2, but will most probably, because of its detailed analysis, be difficult to apply at this level of the analysis. A more likely method is that of Coetzee, using the downtime contribution of each MSI to the downtime of the equipment (or system) to identify the "20" % of MSI's (using the Pareto principle) that contribute most to the downtime of the equipment (or system). Again, there should be progression, as with the first prioritisation process (see paragraph 4.3.2.3 above). Only, in this case the progression is even more important and should be effected over a much shorter period than in the case of the first prioritisation.

It is difficult to use a downtime prioritisation in all cases. For some equipment safety could, for example, be more important than downtime and then that factor could be used to prioritise the MSI's. The point is that the user of the RCM methodology should decide which single parameter or combination of parameters makes most sense for the prioritisation process. Another way of prioritisation could be to list the MSI's and then order them in order of importance based on such parameter or combination of parameters or heuristically (based on the 'gut feel' of the user).

These two prioritisation steps[7], together with the prioritisation process at the failure mode level (§ 4-28), constitutes a prioritisation mechanism, which serves as a means for achieving fast results from the RCM methodology. It acts as a 'funnelling process' to concentrate the RCM analysis on the more important units (prioritisation 1), MSI's (prioritisation 2) and failure modes (prioritisation 3). Each of these 'funnelling actions' is progressively more short term in nature, because the impact is higher at each lower level due to the effect of the higher level prioritisation. One would thus as soon as possible, following the initial RCM result, increase the failure mode funnel size from "20" % to 100 %, after which the MSI funnel size will be increased, and lastly the systems funnel size (§ 4.4). Only if both the lower priorities have been removed (full analyses performed on the equipment or system) will the first funnel (at the equipment / system level) be widened.

The prioritisation mechanism, as described above, is illustrated in figure 4-13

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[7] The systems prioritisation in § 4.3.2.2 and the present prioritisation of MSI's.

and in simplified format in figure 4-14. It results in approximately "1" percent of the failure modes of the business (the most important failure modes) being addressed during the first phase of the RCM process. These 'funnels' are then progressively widened as described above. Also, see the later discussion concerning the 'living RCM programme' (§ 4.4, p 4-59) in this regard.

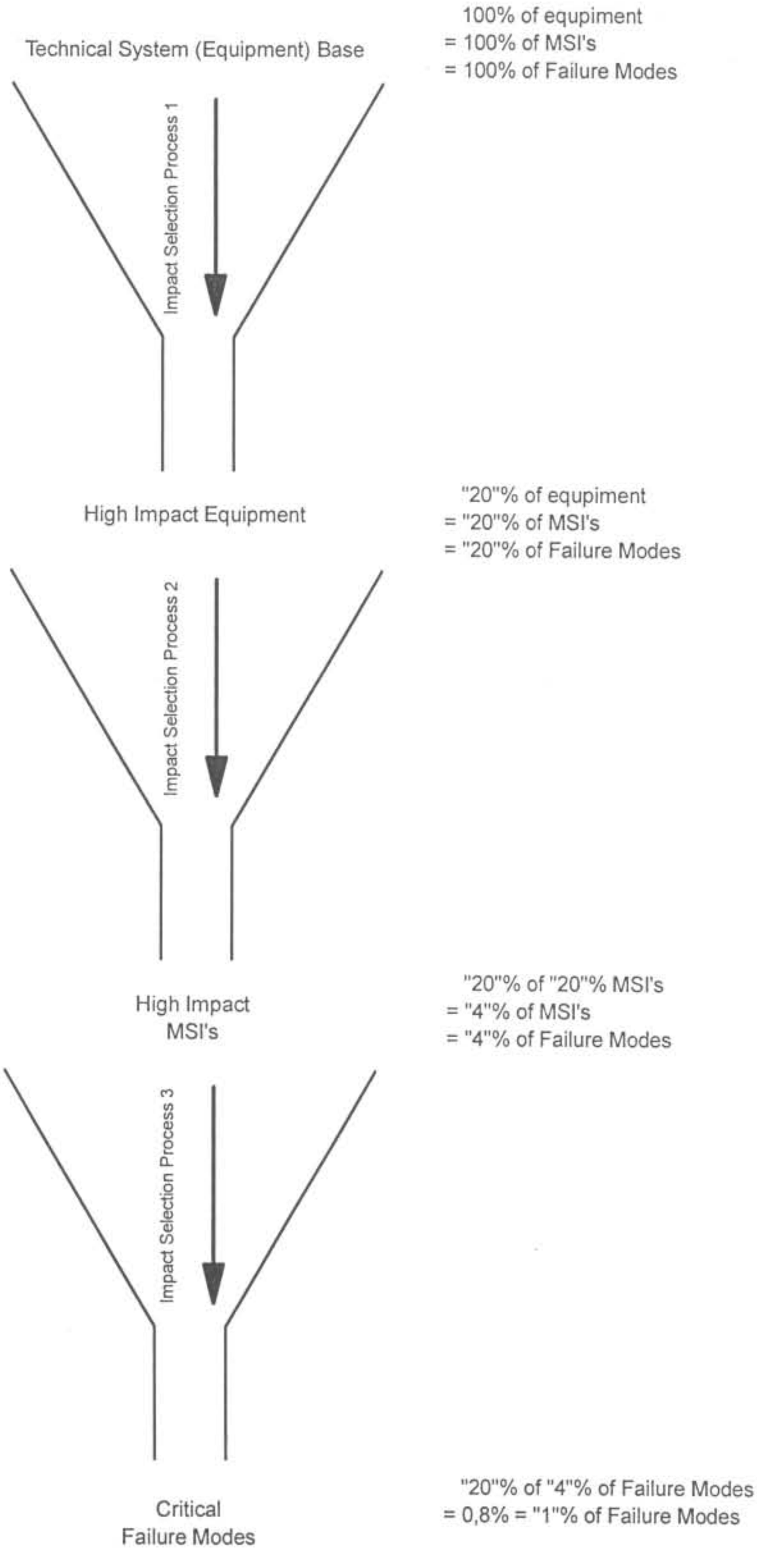

Figure 4-13: RCM prioritisation processes

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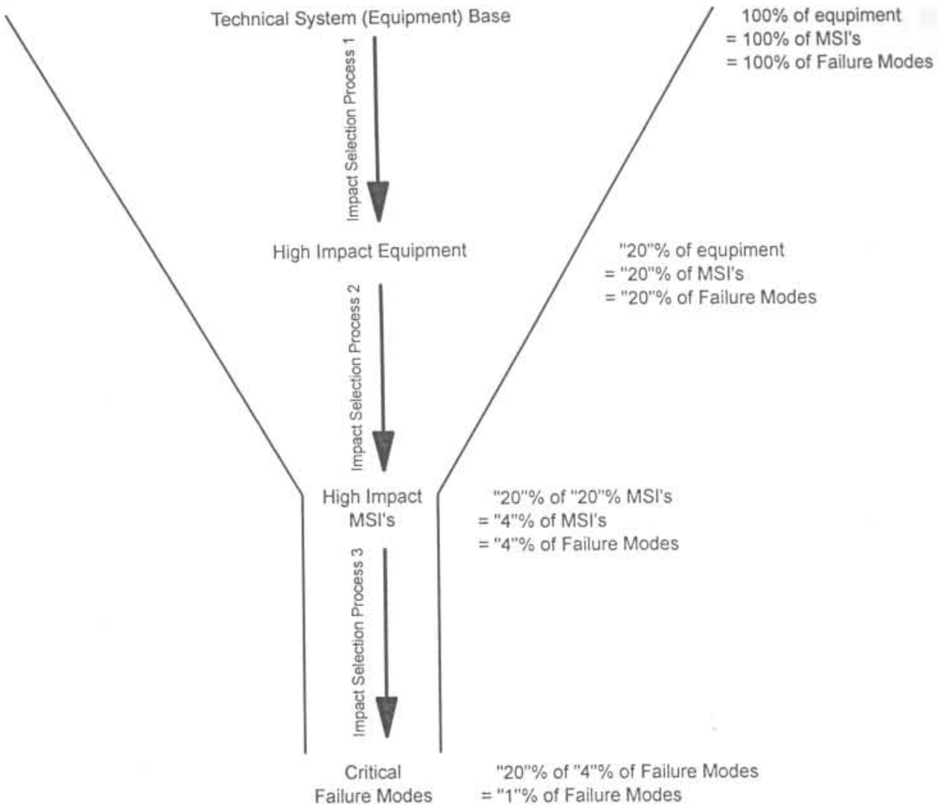
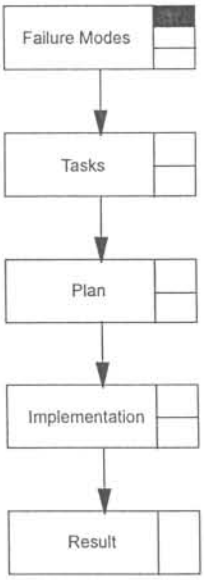


Figure 4-14: Summarised RCM prioritisation processes

4.3.3. Information Assembly



One of the most important steps in designing a maintenance plan for the organisation, is the assembly of information regarding the business. This is because RCM is very context-specific. The analyst thus has to understand the business, the technology involved and the operating context in order to design a plan that will be worthwhile.

The conceptual framework as described in paragraph 4.2 should be properly understood in the specific organisational context. The company mission and management philosophy should be obtained to ensure that the analysis is pitched for the specific company, thus increasing the probability of success of the resultant maintenance plan. To this should be added a study of the organisation's maintenance policy and maintenance management procedures to form the backdrop of RCM application.

This information assembly step and the previous step (selection of application areas) are very interdependent and should be performed in parallel. Through the process of the selection of application areas (§ 4.3.2) one should already have a view of the bigger picture, which will lead to the choice of information, which will be assembled in the present step.

The following table lists information that should be obtained to ensure that the RCM outcome is a scientifically valid maintenance plan. Each of the columns of this table contains a separate category-specific listing, so that no value should be attached to row context (each column represents a separate list or table).

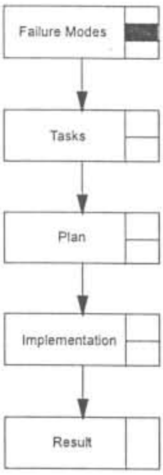
Table 4.1: RCM information requirements

General business operation	Asset-specific information	Maintenance information
Process flow diagrams	Design specifications	Present maintenance plan
Operations manuals	System schematics	Failure data
Operational procedures	Assembly drawings	Maintenance instructions
Asset register	Modification history	Maintenance procedures
Asset interdependencies		Maintenance manuals
Functional block diagrams		

As part of this step, a thorough study of the information at hand should be performed. One often finds that the process of information retrieval and analysis leads to additional understanding and insight into the business and the assets to be maintained. This leads to further direct added value in terms of improvement of operational and maintenance procedures, early fault identification, and asset reliability, operability, as well as maintainability improvements through redesign.

A valid concern, is that important failure modes may be missed through the application of the prioritisation processes. This is a further reason for the detailed study that this process step requires. Although the concern is real, it is unlikely that, in such a thorough study and the analysis that follows, any important failure modes will be missed. On the contrary, experience has shown that the most important failure modes tend to show up readily in this process of study and analysis.

4.3.4. Identification of Failure Modes



Paragraph 3.2.4 gave a description of the Failure Modes and Effects Analysis (FMEA) in its various variants. This is still the best and widest used technique for the identification of failure modes. Once the Maintenance Significant Items (MSI's) to which RCM must be applied are known, the FMEA technique is used to identify the failure modes and its effects for each such MSI. Even those methodologies claiming to be different from RCM (such as the method of Gits [Gits (1984)]) mostly uses an FMEA-like approach. The only exception is Kelly [Kelly (1997)], who

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does his analysis through a direct study of system functionality in lieu of the more rigorous approach of the FMEA.

The accepted structure for the FMEA used by most authors is item->function->functional failure->failure mode. This structure is inherent to the methods of Nowlan and Heap (1978), Moubray (1991), Coetzee (1997/2) and Smith (1993) (with small changes in Smith's case). No one of the other variants adds real value, as can be seen from the analysis in paragraph 3.2.4. We will thus use this accepted structure as the *de facto* standard. Furthermore, we will add failure effects at the local, system and unit levels in line with MIL-STD-1629A and Smith (1993), but using slightly different terminology. The use of a three-level effects-structure is deemed important to ensure that all possible effects of the failure mode are taken into account when doing task selection. The other columns in the standard FMEA, those of McDermott et al (1996) and Moubray (1991) are not deemed important and will not be used as they are very specific to certain classes of users and can be added as necessary. The only other data entities that should be used is a component reference number and a line reference number to cross-reference back to the specific FMEA analysis line from later parts of the analysis. As the severity class (MIL-STD-1629A) and RPN number [McDermott et al (1996)] are forms of criticality assessments, which will be covered in the next paragraph, they will also not be included in the FMEA. This is in line with the practise of Moubray (1991), Smith (1993), MSG-3 (1993), and Coetzee (1997/2).

The resultant FMEA analysis sheet is shown in figure 4-15. The heading *firstly* has space for the system name, system reference number and system function. In these spaces 'system' can mean a plant system (sub-plant), but can also be used for an equipment group, equipment type, equipment, machine or asset name and reference, depending on the need. The system function is incorporated to ensure that the analyst remains aware of the function that needs to be preserved. This is continually necessary to achieve a function-driven analysis. It *secondly* has spaces for the analyst's name (or that of the facilitator), analysis completion date, as well as the reviewer (auditor) name and approval signature. *Thirdly*, it has a space for a revision number, which is very important when the living (or ongoing) character of a properly implemented RCM programme is taken into account. *Lastly*, it has spaces for page numbering.

The FMEA table itself has only two extraordinary features. The *first* of these is the separate effects columns, which creates space for descriptions of local, system and unit effects, while still leaving enough analysis space in the main FMEA table. The *second* feature is the two reference columns, the first of which references backwards to an item number, while the second references forward to the effects column and to the further parts of the RCM analysis.

The item to which the table refers will typically be an MSI. Each item can have one or more functions (primary and secondary functions), each function

Reliability Centred Maintenance Analysis - FMEA

System:
Reference:
System Function:
Analyst:
Date:
Reviewer:
Rev No:
Approved:
Page of

XRef	Item	Function	Functional Failure	Failure Mode	FC	Comments	FRef

Failure Effects	FRef				
	Local				
	System				
	Unit				

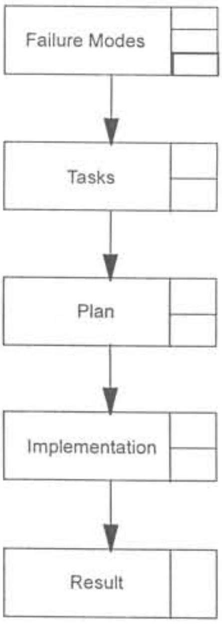
Figure 4-15: RCM FMEA analysis sheet

one or more functional failures[8] and each functional failure one or more failure modes, as is the case in standard RCM. In each case the resultant failure mode should be reviewed to make sure that it contributes to the main system function, thus keeping the analysis function-driven. For this purpose there is a functional check (FC) column, where a check will imply that the failure mode has an adverse effect on the system function. The FRef column carries a special reference number identifying the failure mode uniquely within the system. This can be used for the remainder of the analysis to identify the particular failure mode. It is also used to reference the special effects columns below the normal analysis.

The effects columns carries the failure mode reference (FRef) as heading and each has three spaces for local, system and unit effects. The local effects are those that the failure mode has on its own function (column 3), while the system effect is the effect of the failure mode at the system level and the unit effect, the effect on the total production unit (the **ship** that the RCM handbook of the Naval Sea Systems Command (1983) refers to). These effects are very important as they largely contain the information on which the further analysis regarding task selection will be based. There are only four effects columns, suggesting that such page will rarely fully document more than four failure modes. In some cases, there may be more than four failure modes, but then (due to the limited space in the primary table) some of them will typically be simple failure modes, not needing an effects analysis.

4.3.5. Prioritisation of Failure Modes

As was stated in paragraph 4.3.2.5, a last prioritisation step is needed to achieve the "1" % of the failure modes of the business (the most important failure modes) being addressed during the first phase of the RCM process. This, together with the previous two prioritisation steps, constitutes a prioritisation mechanism, which serves as a means toward fast results from the RCM methodology. It acts as a 'funnelling process' to concentrate the RCM analysis on the more important units (prioritisation 1), MSI's (prioritisation 2) and failure modes (prioritisation 3). The total prioritisation mechanism, as de-



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[8] Nowlan and Heap (1978) defined the three concepts *failure*, *functional failure* and *potential failure* as follows:

1. *A failure is an unsatisfactory condition.*
2. *A functional failure is the inability of an item (or the system/sub-system in which it is installed) to meet a specified performance standard.*
3. *A potential failure is an identifiable physical condition which indicates that a functional failure is imminent.*

While the second and third of these definitions are satisfactory, the first is not. It is far too wide and misleading. The following are better formulations of these three definitions:

1. *A failure is any condition which results in unsatisfactory performance or points to the fact that the instant of such unsatisfactory performance is near.*
2. *A functional failure is the inability of an item (or the system/sub-system in which it is installed) to meet a specified functional performance standard.*
3. *A potential failure is the imminence of the instant of functional failure. The presence of such potential failure is normally found through measurement of some physical parameter (detecting a deviation from its normal 'healthy' value).*

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scribed above, is shown in figure 4-13, where the prioritisation of failure modes is represented by the bottom-most 'funnel'.

As was explained there (paragraph 4.3.2.5), each of these 'funnelling actions' is progressively more short term in nature, because the impact is higher at each lower level due to the effect of the higher level prioritisation. One would thus soon, following the initial RCM result, increase the failure mode funnel size from "20" % to 100 %, after which the MSI funnel size will be increased, and so forth. Only if both the lower priorities have been removed (full analyses performed on the equipment or system) will the first funnel (at the equipment / system level) be widened.

This last prioritisation process can take place using any one, or a combination of, the methods explained in paragraph 3.2.5. In summary, there is the severity rating of the standard FMEA [MIL-STD-1629A (1980)], the Risk Priority Number (RPN) of McDermott et al (1996), the Seriousness Factor table of Gits (1988), the criticality rating of FMECA [MIL-STD-1629A (1980)] and the risk profile method of Jones (1995). As described in paragraph 3.2.5, only the last two methods should be considered in any serious failure mode prioritisation endeavour, as the other methods are too simplistic. On the other hand, the FMECA method tends towards a complexity that would be beyond many industrial users, whereas the beauty of Jones' method lies in the simplicity of combining five diverse consequence factors into one risk figure, using only cost and probability estimates as basis. A further benefit of Jones' method is that it does not oversimplify the prioritisation into one single risk factor, whereas FMECA does exactly that (it measures risk based on operating time or number of cycles used). The method used in FMECA is effective in achieving mission success in military operations. Even in this case (military application) the prioritisation result can be improved using Jones' method as basis. This is explained in the development of the proposed prioritisation method in the following paragraphs.

Whether one calls the prioritisation result a criticality figure or a risk figure is a matter of personal choice. The term 'risk' is familiar to maintenance practitioners in industry (as they use the same concept to calculate safety risk) and will be used for our purpose. The calculation of the risk involved regarding any single failure mode is based on the combination of the various risk factors using the formula:

$$\text{Risk} = R_t = \sum_{i=1}^{n} P_i \times C_i \qquad 4\text{-}3$$

where P_i represents the probability of the risk consequence factor C_i occurring and n is the number of risk factors. Jones (1995) suggests safety, lost production, lost quality, environmental effects and maintenance as the five risk factors, but any combination of valid risk factors in the specific maintenance environment can be used for this purpose. Furthermore, the consequence values can be measured in any valid single quantity to make the relative risks comparable. In the case of general industry this will certainly be money, but in the case of high risk operations such as military installations, nuclear installations or space programs this quantity could be mission time or some measure of integrity or some other result-related quantity. Various formulae for the calculation of individual values of P_i and C_i for a specific maintenance environment could also be devised.

In the light of the above, the following should be seen as an attempt towards a standardised way of determining relative values of risk of the failure modes of a system. This standardised method is aimed at the general commercial application of RCM and will have to be modified for other RCM applications.

Coetzee (1997/2) states the general objective of the maintenance function as follows:

> *It is the task of the maintenance function to* ***support the production process*** *with* ***adequate levels*** *of* ***availability***, ***reliability*** *and* ***operability*** *at an* ***acceptable cost***.

This objective statement has lately been modified to the following:

> *It is the task of the maintenance function to* ***support the production process*** *with* ***adequate levels*** *of* ***availability***, ***reliability***, ***operability*** *and* ***quality*** *at* ***acceptable*** *levels of* ***safety***, ***environmental effects*** *and* ***cost***.

This sets the scene for the general application of risk principles to the failure modes of a system in the general commercial maintenance world. The quantities representing real risk are unavailability, unreliability, inoperability, poor quality, safety risk, environmental risk and high maintenance cost. Thus, seven risk factors, of which Jones (1995) has identified five (he used lost production to combine the effects of unavailability, unreliability and inoperability). His approach is a very practical one, as long as one keeps in mind that 'lost production' consists of the effects of unavailability, unreliability and inoperability. A generalised method of calculating the risk for the various risk factors (all seven risk factors) is shown in table 4.2.

Table 4.2: Risk factor calculation

	Probability of Occurrence P_i	**Consequence C_i (Rand)**
Availability	{(% downtime)/100}	$\{P_r \times G\}$
Reliability	{(% loss)/100}	$\{P_r \times G\}$
Operability		
Quality		
Safety	$\{1/T_{Ls}\}$	$\{(P_r \times G \times t_{Ls}) + L_{cs}\}$
Environment	$\{1/T_{Le}\}$	$\{(P_r \times G \times t_{Le}) + L_{ce}\}$
Cost	{1/MTTF}	C_f

Apart from P_r (production rate in units/hour) and G (gain in Rand/unit), all of the above (table 4.2) refers to the specific failure mode, i.e.:

- % downtime = historical % downtime for particular failure mode

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- % loss = historical % loss for particular class and for particular failure mode
- T_{Ls} = historical time between safety incidents for particular failure mode (hours)
- T_{Le} = historical time between environmental incidents for particular failure mode (hours)
- MTTF = historical time between failure incidents for particular failure mode (hours)
- t_{Ls} = production time lost during safety incident (hours)
- t_{Le} = production time lost during environmental incident (hours)
- L_{cs} = capital loss during safety incident (Rand)
- L_{ce} = capital loss during environmental incident (Rand)
- C_f = Cost of repairing failure (spares + manpower)

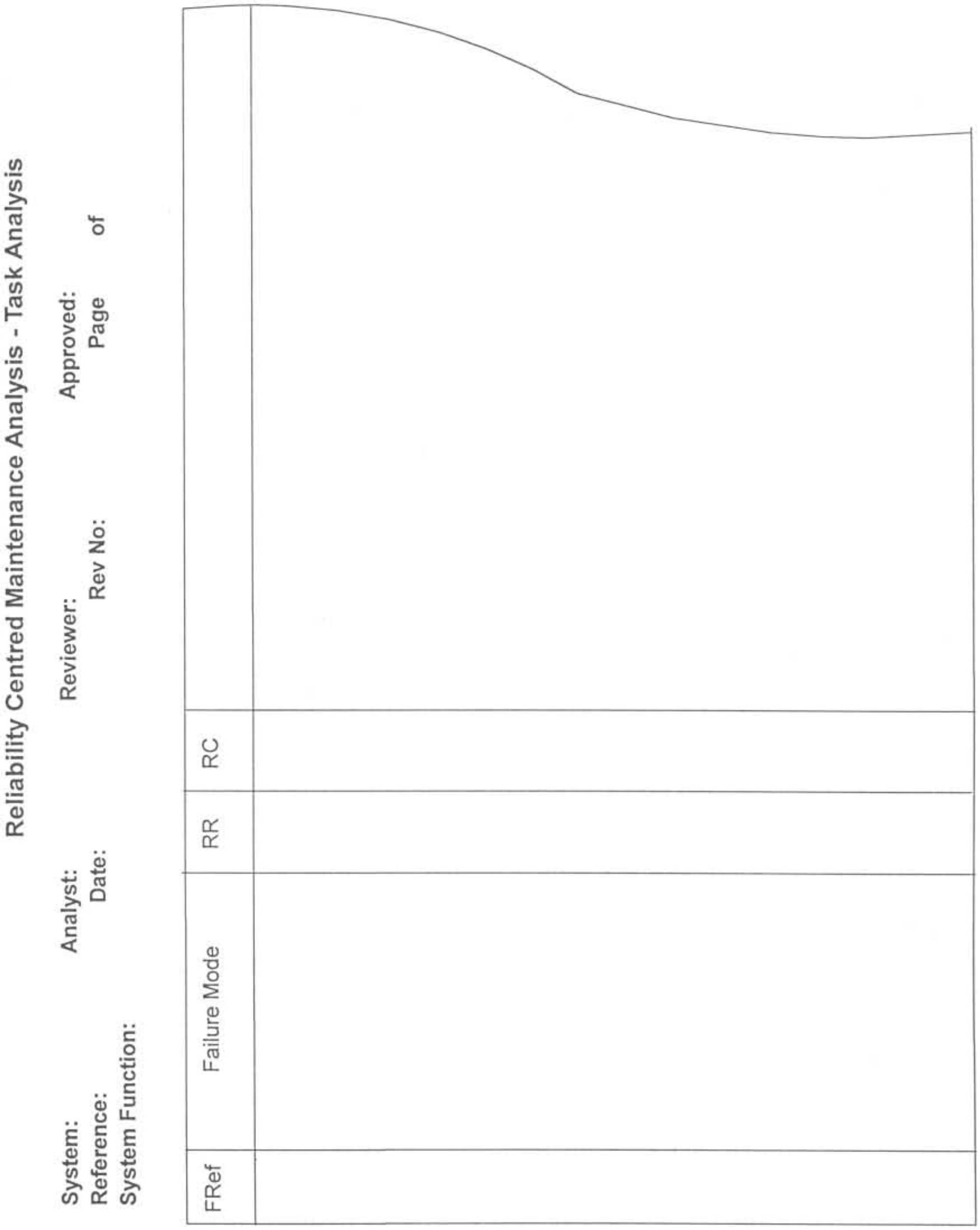
These are used in equation 4-3 to calculate the total risk (in R/h) for each failure mode. One could of course decide to use only some of the abovementioned five factors for the risk calculation, as some factors (e.g. safety and environmental) might not be relevant to a certain situation. Or, in an asset that does not contribute to production, the first two factors might not be relevant. Nevertheless, the technique provides both a practical way of prioritising failure modes and useful insights into the process of failure and its effects.

It is also handy for ease of comparing the relative risk involved in the various failure modes, to use a process of normalisation. This involves defining a level of risk R_{max} (R/h) that are deemed to be a 100% (or totally unacceptable) level of risk. Each failure mode then has a percentage risk equal to:

$$RR = \text{Relative Risk} = \frac{\sum_{i=1}^{n} P_i \times C_i}{R_{\max}} \times 100 \quad \% \qquad 4\text{-}4$$

It might be difficult to use the risk prioritisation presented above in some cases. For those equipment a single parameter or combination of parameters might make more sense for the prioritisation process. Another way of prioritisation could be to list the Failure Modes and then order them in order of importance based on one or more of the parameters listed in table 4.2 or otherwise using heuristics (based on the 'gut feel' of the user).

The first part of the documentation analysis sheet is for the above results is shown in figure 4-16. The sheet starts with the failure mode reference F_{ref}, which was described fully in paragraph 4.3.4 above, and a repeat of the failure mode column (for clarity). It then adds a column for the relative risk RR calculated using equation 4-4 above. This value is now used to select the "20%" of failure modes, which has "80%" of the risk impact, for further analysis. This could be done using standard Pareto analysis methods. Those failure modes that will be analysed further receives a tick mark in the risk check (RC) column. This prioritisation constitutes the bottom-most ‘funnel’ in figures 4-13 and 4-14.



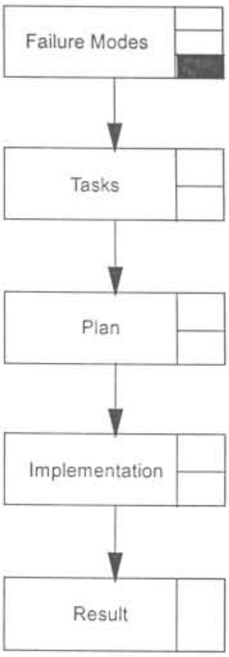
Reliability Centred Maintenance Analysis - Task Analysis

System: **Analyst:** **Reviewer:** **Approved:**
Reference: **Date:** **Rev No:** **Page** **of**
System Function:

FRef	Failure Mode	RR	RC	

Figure 4-16: RCM Failure Mode Prioritisation

4.3.6. Classification of Failure Modes



Before moving away from the area of failure mode selection (figure 4-9), we should deal with the only standard 'prioritisation' afforded by the original Nowlan and Heap (1978) version of the methodology. Reading Matteson (1989) one soon realises that this classification process, together with the task selection process, were really the heart of the technique in MSG-1 and MSG-2.

As stated in paragraph 3.2.6, the original version of the failure mode classification tree has weathered the further development of the technique well. Apart from Moubray (1991) who added the environmental sub-category to the safety category class and MSG-3 (1993) that added an extra question to discern between hidden consequences with safety and those with economical consequences, no changes were made to any official version of RCM. Harris (1985) did propose a further sub-division of the operational consequences category into mechanical consequences and process consequences, but this was not incorporated in any formal version of RCM. As stated in paragraph 3.2.6, it would not make sense to change the consequence structure, which is well established in the RCM world, by separating a single consequence category into two, based on a difference between the maintenance done by two disciplines of maintenance. Although his problem is a valid one, it is better addressed by adding an extra task selection step (see paragraph 4.3.7.1), rather than an extra consequence category.

The full classification structure looks like the one presented in figure 4-17. The structure is fully symmetric, with the two trees on the left and right being exact copies of each other, the only difference being the fact that the left structure shows the evident sub-structure and the right one the hidden sub-structure. The original version of RCM did not develop the right sub-structure at all, assuming that all hidden functions are safety-related by default. MSG-3 has now gone a step further by distinguishing between safety-related and economic-related (operational and non-operational) hidden functions. A logical question that poses itself is whether it would make sense to develop the hidden sub-structure further to differentiate between hidden operational and hidden non-operational failure modes. It would seem reasonable to expect that these failure modes, which is of no importance, will not show up following the prioritisation processes preceding this classification step. All failure modes that reach this step in the analysis process are important failure modes. The thinking behind MSG-3 is thus upheld, but it is clear that the hidden economic consequence category is really a hidden operational consequence category.

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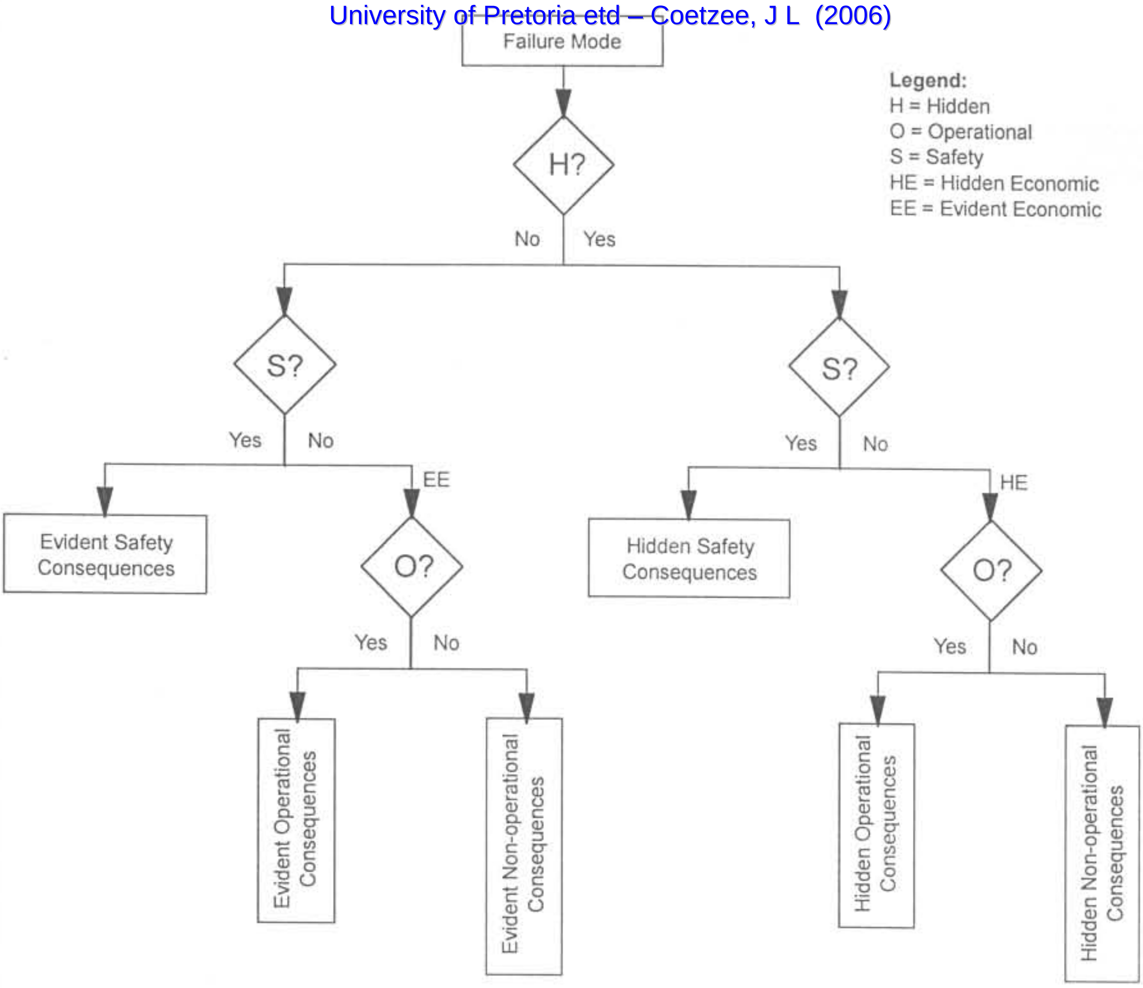

Figure 4-17: RCM inherent Failure Mode Classification structure

This thesis therefore proposes no fundamental changes to the consequence selection structure, apart from some small wording changes, in line with the best practice from table 3.3, and the two changes proposed by Moubray (1991) and MSG-3 (1993). The only change is that, in line with flow diagram convention, the rectangular question boxes have been replaced with diamond-shaped ones. The word 'evident' has also been left out in the names of the three evident consequence classes, in line with customary practice. The resulting decision tree is shown in figure 4-18.

The documentation of the Failure Mode Classification results is done on the extended Task Analysis worksheet as shown in figure 4-24. The results are written into the column headed 'Conseq Type' using the abbreviations H (Hidden Safety and Environmental Consequence), HO, S, O and NO (for meanings see figure 4-18).

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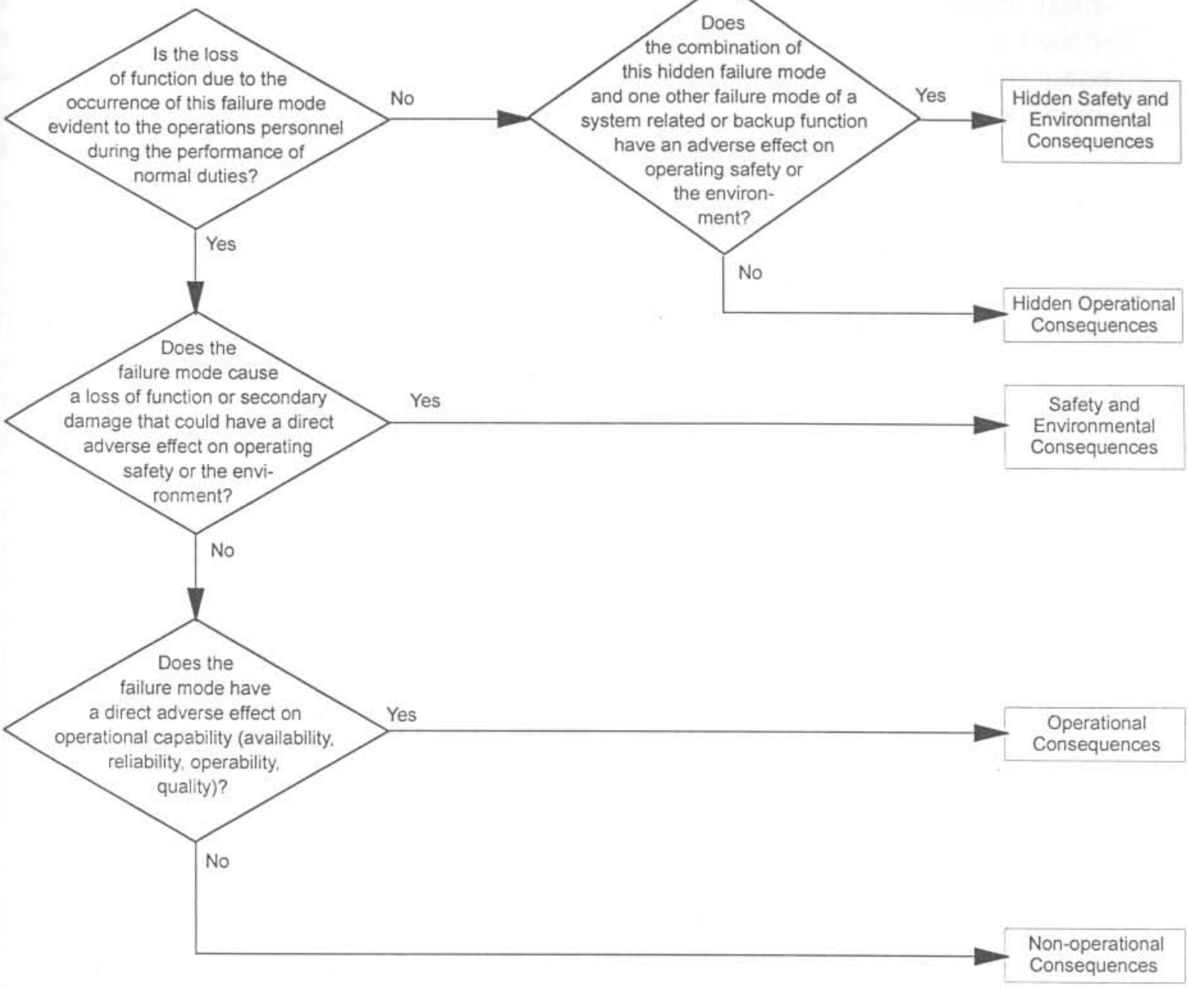
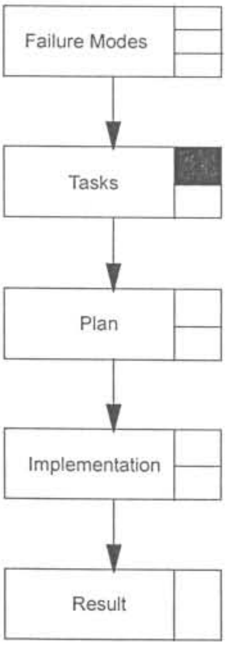


Figure 4-18: RCM Failure Mode Classification

4.3.7. Task Selection

4.3.7.1. Task Selection Process

Taking into account the full analysis in paragraph 3.2.7, it is again beneficial to think fundamentally about the process of task selection. For most users and authors of scripts on RCM, the principles in the task selection tree of Nowlan and Heap (1978) still holds today. These principles are *firstly* a conservatism in the order in which tasks are selected (see the second sub-paragraph in paragraph 3.2.7.3) and *secondly* the principle that the decision process is truncated once a valid task is found.



Gits (1988), Smith (1993), and MSG-3 (1993) all challenge the truncation principle. Smith applies a task selection without truncation for all failure modes, MSG-3 truncates for economical consequences and does not truncate for safety consequences, while Gits practices a mixture of the two based on four qualities ('hiddenness', seriousness, shape of F.O.M. and

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the possibility to detect a failure). The first Nowlan and Heap principle (conservatism) only makes sense if truncation does take place – this is the rationale behind Smith's change of the analysis order. Gits on the other hand loses a lot of the reliability logic (e.g. he only specifies the failure finding task possibility for hidden failures) by trying to provide a too simple decision tree).

The questions that now present themselves are whether the principle of truncation should remain and if the resultant answer should apply to all consequence categories. To the first question, one can categorically answer no. Taking into account the prioritisation process taking place before this analysis step (paragraphs 4.3.2.2, 4.3.2.5 and 4.3.5), one can make the statement that only important failure modes are handled (those with a high impact) in this step. For such failure modes it is obviously beneficial to consider all relevant maintenance options and then choosing the best task or combination of tasks. As far as the second question is concerned, it makes sense to apply such a rigorous approach only to the more important failure consequence categories. It would therefore seem logical to, in line with MSG-3, apply the more rigorous approach to the two safety consequence categories and to leave the choice to the user in the case of economic consequences, depending on his evaluation of the seriousness of the consequences. This would probably mean in practice that the non-operational consequence category will use truncation, while the user will choose between truncation or no truncation in the two operational consequence categories.

The reason why many RCM texts retain the truncation principle across the board is that they do not provide suitable mechanisms (this includes MSG-3) for prioritisation of failure possibilities and thus have to limit the number of task selection steps to contain the scope of the RCM analysis. This approach does not make sense at all. To apply the RCM principles over such a wide front that you are limited in not addressing the critical failure modes properly is foolish. The suggested principle of first selecting the "1%" most critical failure modes leads to an approach where one could look into all possible task options and/or task combinations when deciding on the best maintenance strategy. One thus makes certain that the most important failure modes are recognised and then spends enough time on the analysis.

As the prioritisation 'funnel' is progressively widened (refer to paragraphs 4.3.2.5 and 4.4), one can then use the less rigorous approach (truncation) more extensively. This slow shift in priorities as the analysis proceeds makes it non-preferable to only prescribe one or the other technique (truncation or not). Because of this fact, the conservatism in the task selection tree should be retained.

MSG-3 (1993) added a non-truncated lubrication/servicing task at the top of the task ladder. This was regarded by the original [Nowlan and Heap (1978)] version of RCM as a task that is added after the RCM analysis has been completed. However, as it is important to design the best maintenance strategy combination, this task and its role should be considered together with the standard RCM task train. The same argument holds for the suggestion of Harris (1985) that a Non-Maintenance Improvement task (see last subparagraph in paragraph 3.2.7.3) be added to the top of the task train (this time

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with truncation, if that applies). As was stated in paragraph 3.2.7.3, this Non-Maintenance Improvement task really implies some quality improvement action, and could be named a Quality Improvement[9] (QI) task.

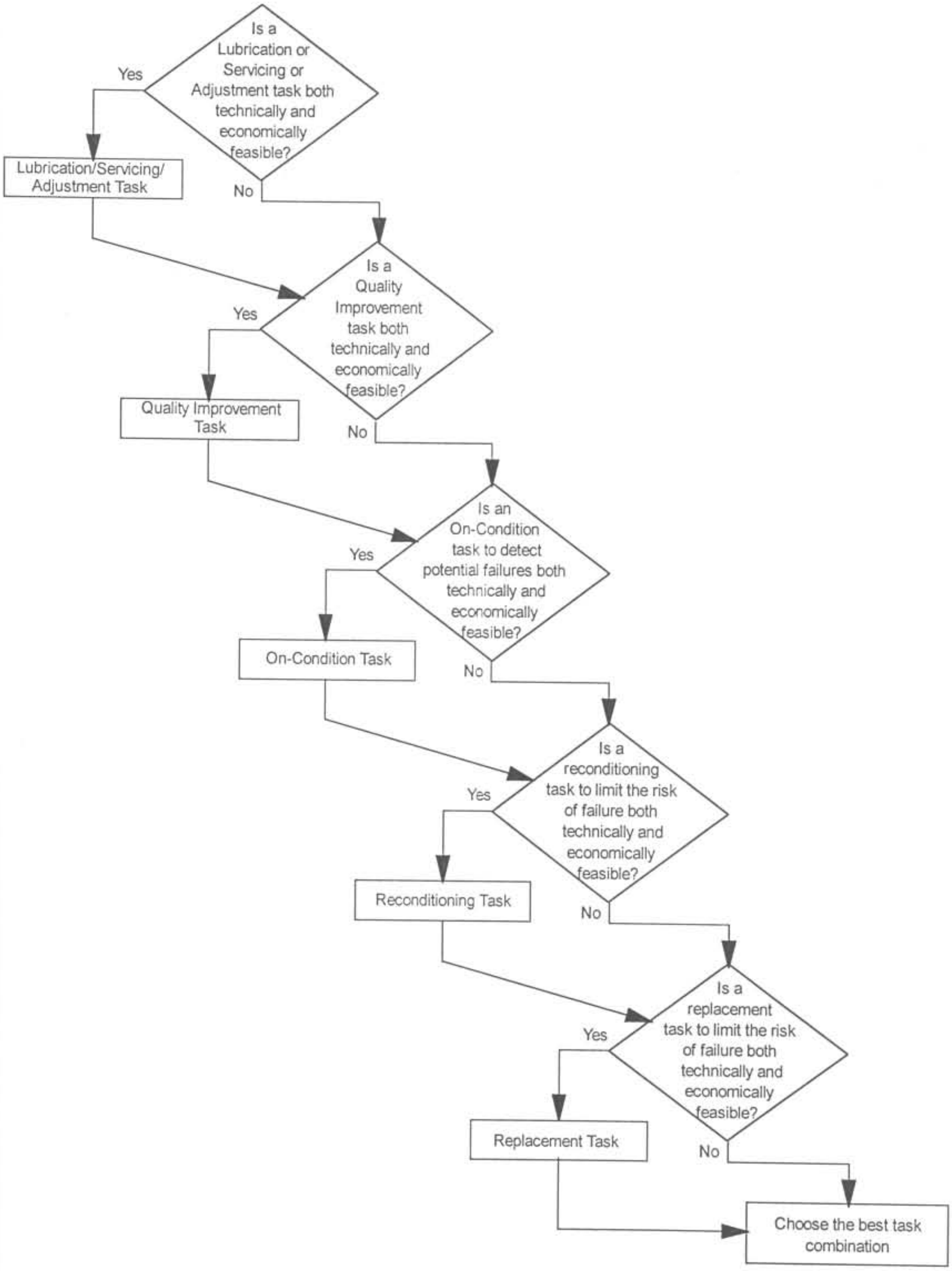

Figure 4-19: RCM Task Decision Tree 1 (without truncation)

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[9] The Quality Improvement Task is really a sub-class of the design-out category (the less expensive/intrusive part of design-out), applied early-on in the process. As such, this category of task is once-off (non-repetitive).

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The two resulting standard tree structures are shown in figures 4-19 (rigorous tree without truncation) and 4-20 (tree with truncation). These two trees are named 'Task Decision Tree 1' for the one without truncation and 'Task Decision Tree 2' for the one with truncation. Wording is based on the best practice from table 3.4. The scope of the servicing task is extended by the inclusion of adjustment.

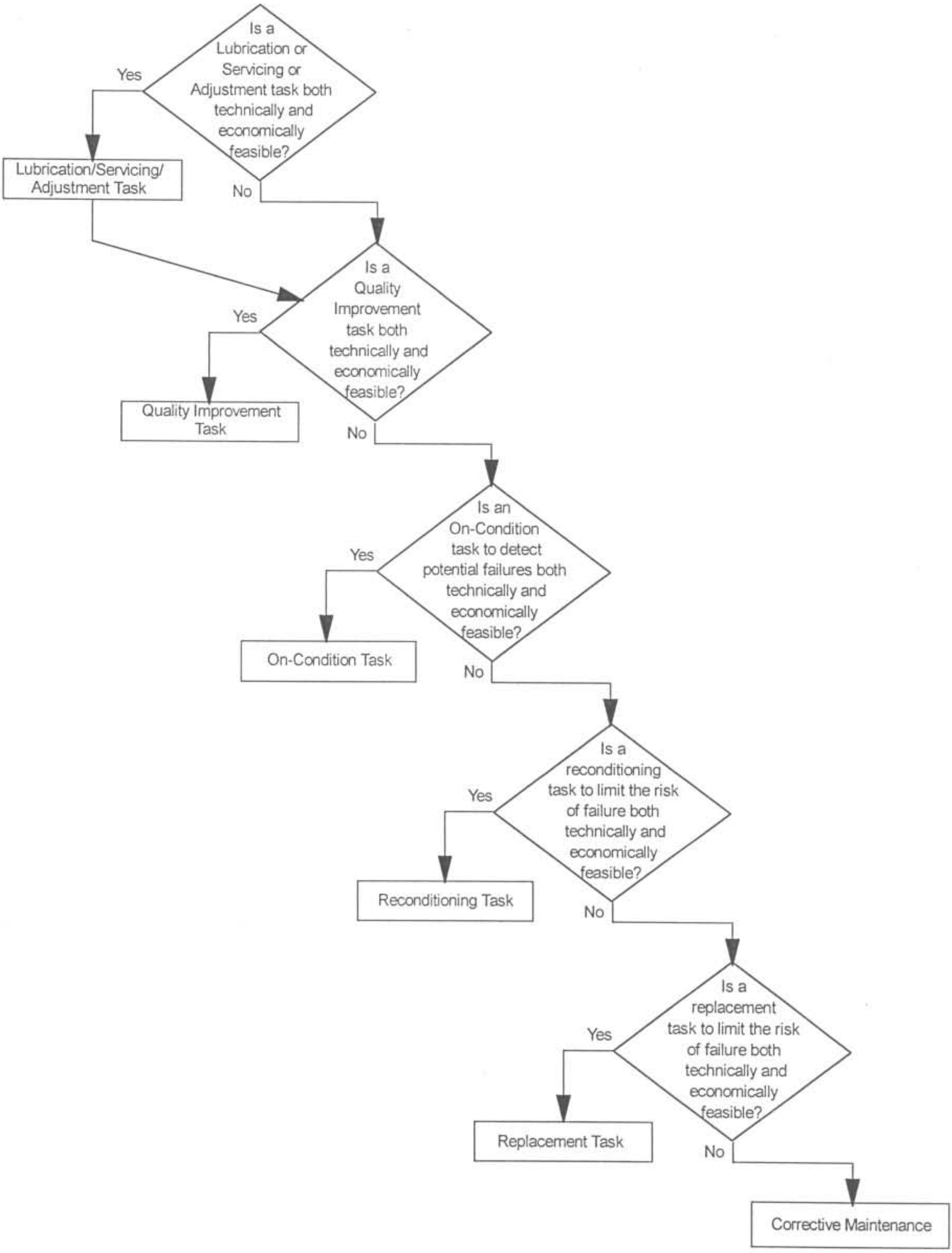

Figure 4-20: RCM Task Decision Tree 2 (with truncation)

When using these two decision trees for task selection in the case of hidden consequences, the failure finding task should be added after the lubrication task, resulting in the trees named 'RCM Task Decision Tree 1h' and 'RCM Task Decision Tree 2h'. These are shown in figures 4-21 and 4-22 respectively.

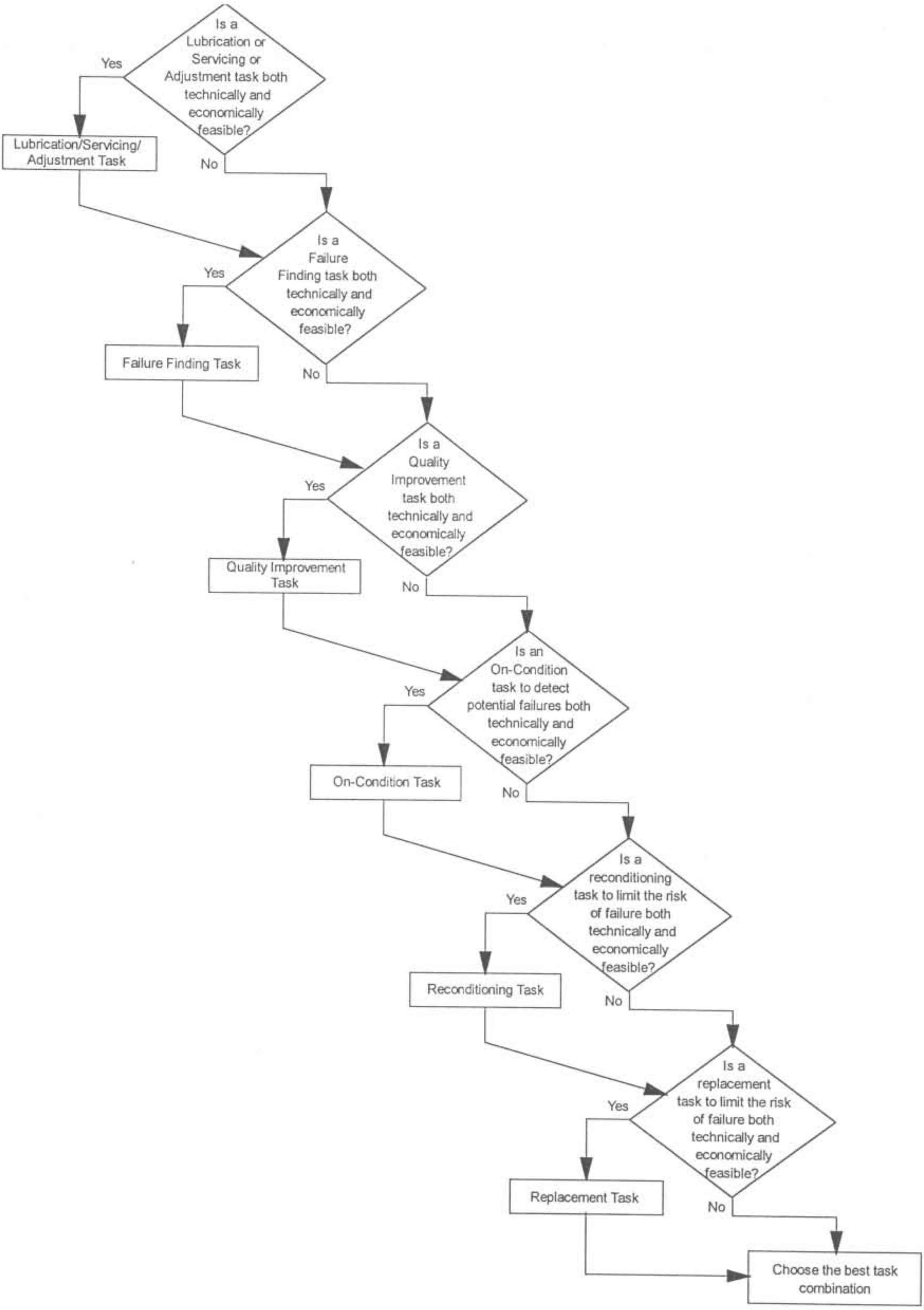

Figure 4-21: RCM Task Decision Tree 1h (without truncation)

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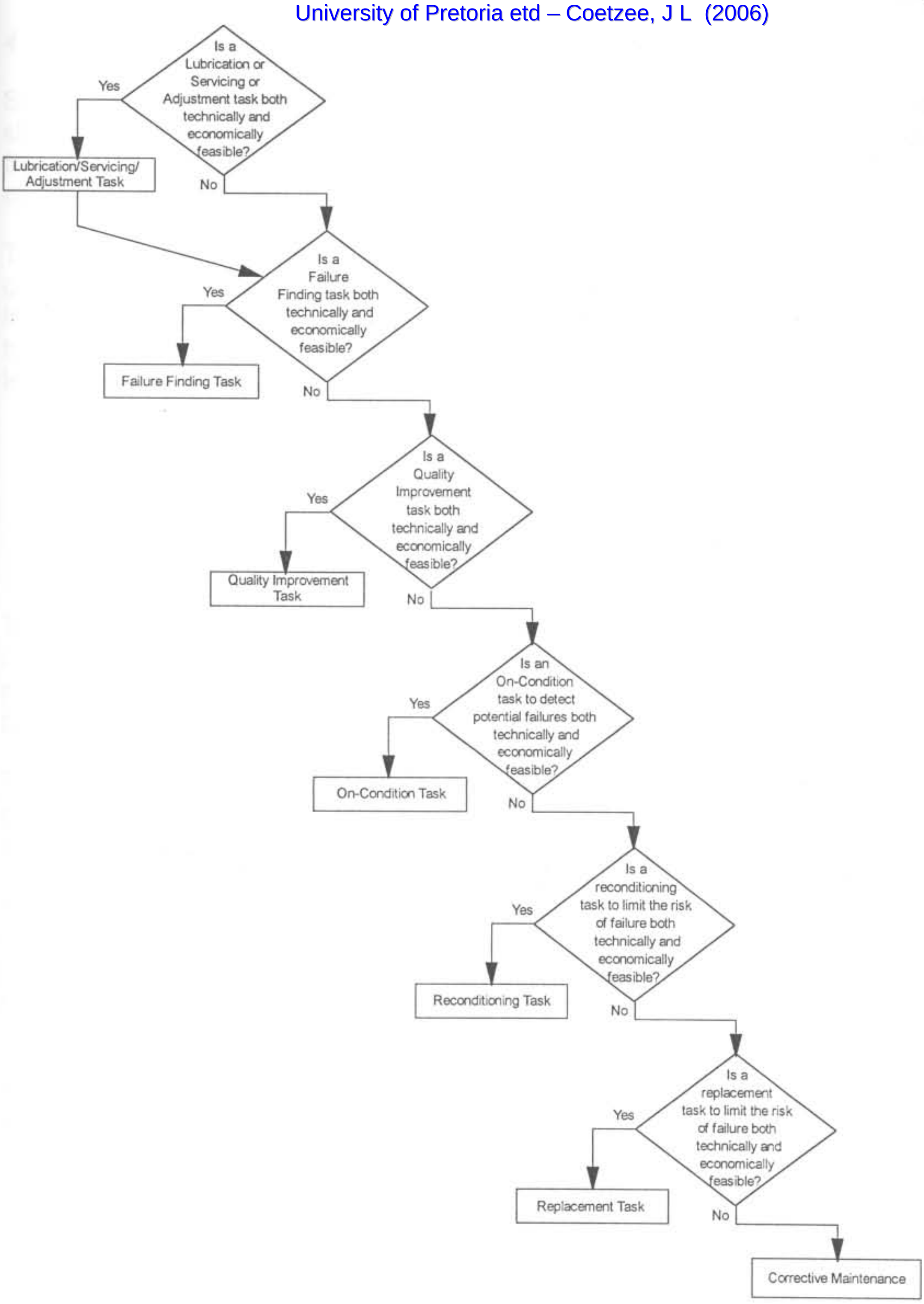

Figure 4-22: RCM Task Decision Tree 2h (with truncation)

The main RCM diagram is shown in figure 4-23. It features the Consequence selection tree of figure 4-18, choices between the various decision trees (figures 4-19 to 4-22) and the default action for each task outcome.

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4.3.7.2. Technical/Economical Feasibility

Summaries of the technical and economical feasibility characteristics are shown in tables 4.3 and 4.4 respectively. These are based on best practise from the various authors as analysed in paragraph 3.2.7 and taking into account the improvements suggested there.

Two factors complicate the use of these criteria in a mechanistic way as suggested by tables 4.3 and 4.4. The *first* of these is the fact that in all the more important cases it is now suggested that the task decision process not be truncated after a single valid task is selected. This has two effects on the selection criteria in tables 4.3 and 4.4:

a. The selection criteria for any one task can be applied less stringently, as the total effect can be obtained from a mix of tasks.

b. The total mix of tasks found from the last process block in the RCM decision tree 1 and 1h (figures 4-19 and 4-21) must be technically and economically feasible in terms of tables 4.3 and 4.4.

The *second* factor is that, especially in the case of non-safety items, one does not always have to prevent all failures to be successful. Often a less than perfect result will still contribute significantly towards a more optimised maintenance mix.

The decision criteria in tables 4.3 and 4.4 should thus be applied pragmatically. It must be stressed that pragmatic use of these criteria increases the need to support the decision process through thorough analysis.

4.3.7.3. Technical selection criteria

The technical selection criteria embedded in figures 4-19 to 4-22 and tables 4.3 and 4.4 have undergone subtle but important changes from the way it was used by Nowlan and Heap (1978) and other authors as analysed in paragraph 3.2.7.5. For condition based tasks the criterion is still detection as it makes total sense and there is full agreement between the various authors that this is the case.

However, for reconditioning and replacement tasks there is such a confusion between different authors, leading to even more confusion between users of RCM, that certain changes are necessary. The main change is due to the fact that most authors use an increasing 'failure rate' as a criterion, which could possibly mean an increasing force of mortality (hazard rate) or an increasing ROCOF (rate of occurrence of failures). In this thesis, this criterion has been replaced with whether the task will 'limit the risk of failure' (figures 4-19 to 4-22), which now means that there is a limitation on the FOM (force of mortality) for components and a limitation on the ROCOF for systems. In both cases such limit implies an increasing trend[10] in the quantity to be limited, because the level of risk must be lower after the action.

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[10] Refer Coetzee (1997/2), fig 5.8, p. 63.

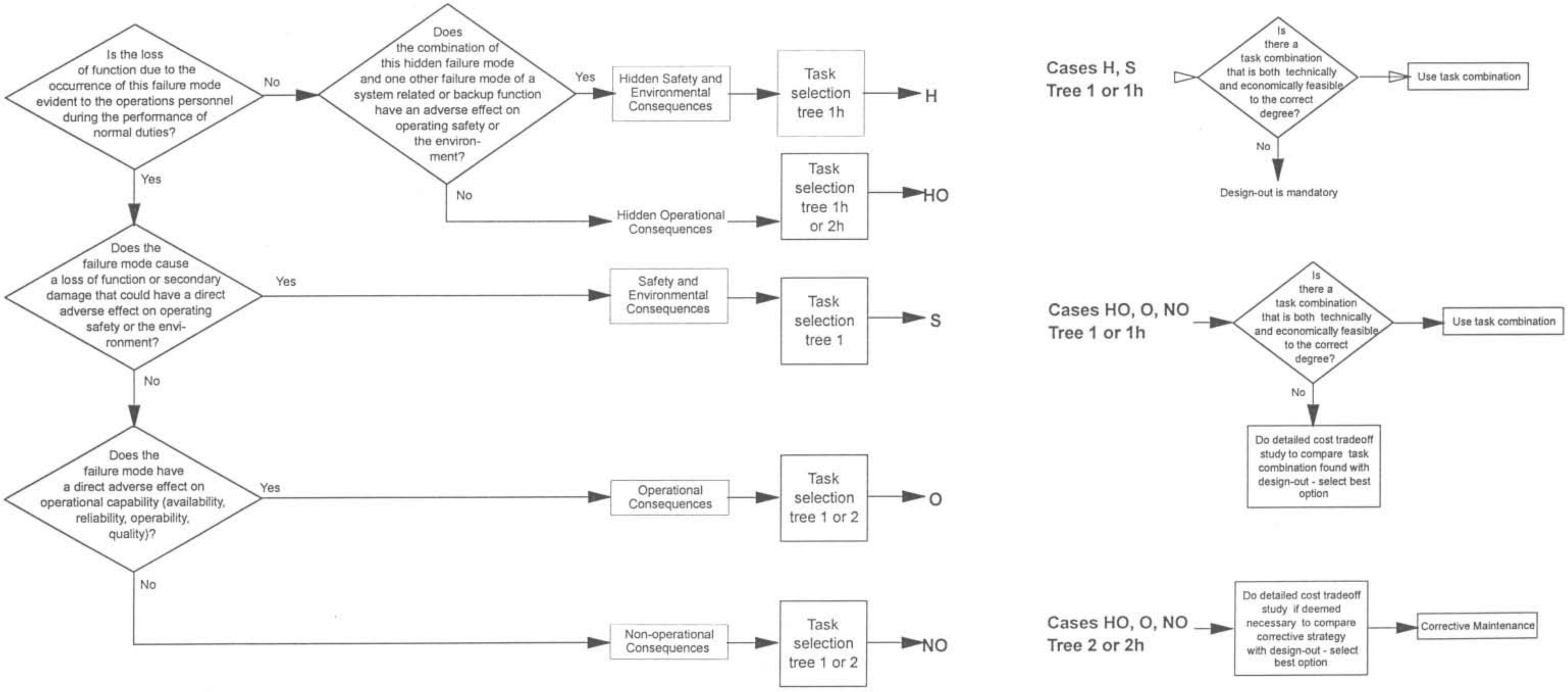

Figure 4-23: RCM Decision Tree

Table 4.3: Technical Feasibility characteristics

Task Category	Hidden	Hidden Operational	Safety	Operational	Non-operational
Lubrication / Servicing / Adjustment	The task must reduce the rate of functional deterioration.	The task must reduce the rate of functional deterioration.	The task must reduce the rate of functional deterioration.	The task must reduce the rate of functional deterioration.	The task must reduce the rate of functional deterioration.
Failure Finding	Identification of the failure must be possible *and* the task must ensure sufficient availability of the hidden function to reduce the risk of a multiple failure adequately.	Identification of the failure must be possible *and* the task must ensure sufficient availability of the hidden function.	N.A.	N.A.	N.A.
Quality Improvement	The task must, through improved quality of operation, maintenance or the installation reliability, ensure sufficient availability of the hidden function to reduce the risk of a multiple failure adequately.	The task must, through improved quality of operation, maintenance or installation reliability, ensure sufficient availability of the hidden function.	The task must, through improved quality of operation, maintenance or installation reliability, reduce the risk of the failure either totally or to a (very low) acceptable level.	The task must, through improved quality of operation, maintenance or installation reliability, limit the risk of the failure sufficiently to make the implementation of the task worthwhile.	The task must, through improved quality of operation, maintenance or installation reliability, limit the risk of the failure sufficiently to make the implementation of the task worthwhile.
On Condition	Timely detection of the failure must be possible *and* the task must ensure sufficient availability of the hidden function to reduce the risk of a multiple failure adequately	Timely detection of the failure must be possible *and* the task must ensure sufficient availability of the hidden function.	Timely detection of the failure must be possible *and* the task must reduce the risk of the failure either totally or to a (very low) acceptable level.	Timely detection of the failure must be possible *and* the task must limit the risk of the failure sufficiently to make the implementation of the task worthwhile.	Timely detection of the failure must be possible *and* the task must limit the risk of the failure sufficiently to make the implementation of the task worthwhile.
Recondition	The task must ensure sufficient availability of the hidden function to reduce the risk of a multiple failure adequately.	The task must ensure sufficient availability of the hidden function.	The task must limit the risk of the failure either totally or to a (very low) acceptable level.	The task must limit the risk of the failure sufficiently to make the implementation of the task worthwhile.	The task must limit the risk of the failure sufficiently to make the implementation of the task worthwhile.
Replace	The task must ensure sufficient availability of the hidden function to reduce the risk of a multiple failure adequately.	The task must ensure sufficient availability of the hidden function.	The task must limit the risk of the failure either totally or to a (very low) acceptable level.	The task must limit the risk of the failure sufficiently to make the implementation of the task worthwhile.	The task must limit the risk of the failure sufficiently to make the implementation of the task worthwhile.

Table 4.4: Economical Feasibility characteristics

Task Category	Hidden	Hidden Operational	Safety	Operational	Non-operational
Lubrication / Servicing / Adjustment	The most economical task combination that produces the right level of availability of the hidden function should be sought.	The most economical task combination that produces the right level of availability of the hidden function should be sought.	The most economical task combination that produces an adequate level of risk reduction should be sought.	The task should only be implemented if it reduces the total cost of failure plus quality improvement plus prevention.	The task should only be implemented if it reduces the total cost of failure plus quality improvement plus prevention.
Failure Finding	The most economical task combination that produces the right level of availability of the hidden function should be sought.	The most economical task combination that produces the right level of availability of the hidden function should be sought.	N.A.	N.A.	N.A.
Quality Improvement	The most economical task combination that produces the right level of availability of the hidden function should be sought.	The most economical task combination that produces the right level of availability of the hidden function should be sought.	The most economical task combination that produces an adequate level of risk reduction should be sought.	The task should only be implemented if it reduces the total cost of failure plus quality improvement plus prevention.	The task should only be implemented if it reduces the total cost of failure plus quality improvement plus prevention.
On Condition	The most economical task combination that produces the right level of availability of the hidden function should be sought.	The most economical task combination that produces the right level of availability of the hidden function should be sought.	The most economical task combination that produces an adequate level of risk reduction should be sought.	The task should only be implemented if it reduces the total cost of failure plus quality improvement plus prevention.	The task should only be implemented if it reduces the total cost of failure plus quality improvement plus prevention.
Recondition	The most economical task combination that produces the right level of availability of the hidden function should be sought.	The most economical task combination that produces the right level of availability of the hidden function should be sought.	The most economical task combination that produces an adequate level of risk reduction should be sought.	The task should only be implemented if it reduces the total cost of failure plus quality improvement plus prevention.	The task should only be implemented if it reduces the total cost of failure plus quality improvement plus prevention.
Replace	The most economical task combination that produces the right level of availability of the hidden function should be sought.	The most economical task combination that produces the right level of availability of the hidden function should be sought.	The most economical task combination that produces an adequate level of risk reduction should be sought.	The task should only be implemented if it reduces the total cost of failure plus quality improvement plus prevention.	The task should only be implemented if it reduces the total cost of failure plus quality improvement plus prevention.

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The idea of 'risk limitation' has also been carried into the detailed criteria of tables 4.3 and 4.4, to replace both the idea of an increasing 'failure rate' and the concept of 'failure avoidance', which are difficult concepts to grasp. Thus, the following criteria apply:

a. **Hidden consequences:** the task 'must ensure sufficient availability of the hidden function to reduce the risk of a multiple failure adequately'.

b. **Safety consequences:** the task 'must limit the risk of the failure either totally or to a (very low) acceptable level'.

c. **Economic (operational and non-operational) consequences:** the task 'must limit the risk of the failure sufficiently to make the implementation of the task worthwhile'.

4.3.7.4. Default tasks

Three factors make a total rework of the default task options necessary:

a. The failure finding task in the case of hidden consequences is no longer a default option but is amongst the first options considered.

b. The adaptability that the RCM tree now allows in terms of the specific task selection tree structure used in the case of non-safety items[11] needs a more flexible approach regarding default tasks.

c. The need to challenge the corrective maintenance default outcome of the operational and non-operational task categories.

These three factors led to the following three sets of default actions, which are shown in figure 4-23:

- Hidden (tree 1h) and Safety (tree 1) Consequence categories – following the last step (which involved choosing the best task combination), a check is made whether this task combination produces a solution that is 'both technically and economically feasible to the correct[12] degree'. The wording 'correct degree' again allows flexibility to cope with various circumstances and situations. If the answer is yes, the task combination is used, otherwise design-out is mandatory.
- Hidden Operational (tree 1h), Operational (tree 1) and Non-operational (tree 1) Consequence categories – this is the case where the more conservative approach (without truncation) was chosen. Following the last step (which involved choosing the best task combination), a check is made whether this task combination produces a solution that is 'both technically and economically feasible to the correct degree'. The wording 'correct degree' again allows flexibility to cope with various circumstances and situations. If the answer is yes, the task combination is

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[11] Any one of the four tree structures (1, 1h, 2 and 2h) can now be used in the case of hidden operational (HO), operational (O) and non-operational (NO) consequence categories (figure 4-23).

[12] Refer to tables 4.3 and 4.4 for

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used, otherwise a cost trade-off study is performed to compare the task combination found with design-out. The best option is then chosen based on economic realities.

- Hidden Operational (tree 2h), Operational (tree 2) and Non-operational (tree 2) Consequence categories – this is the case where the less conservative approach (with truncation) was chosen. The default in this case would traditionally have been corrective maintenance, with design-out as option. This is now modified to include a cost trade-off study if deemed necessary to compare the corrective strategy with design-out. The best option is then chosen based on economic realities. Note that it is still the prerogative of the user to bypass this step through the 'if deemed necessary' clause.

4.3.7.5. Documenting the results

The tasks found are documented on the extended Task Analysis worksheet as shown in figure 4-24.

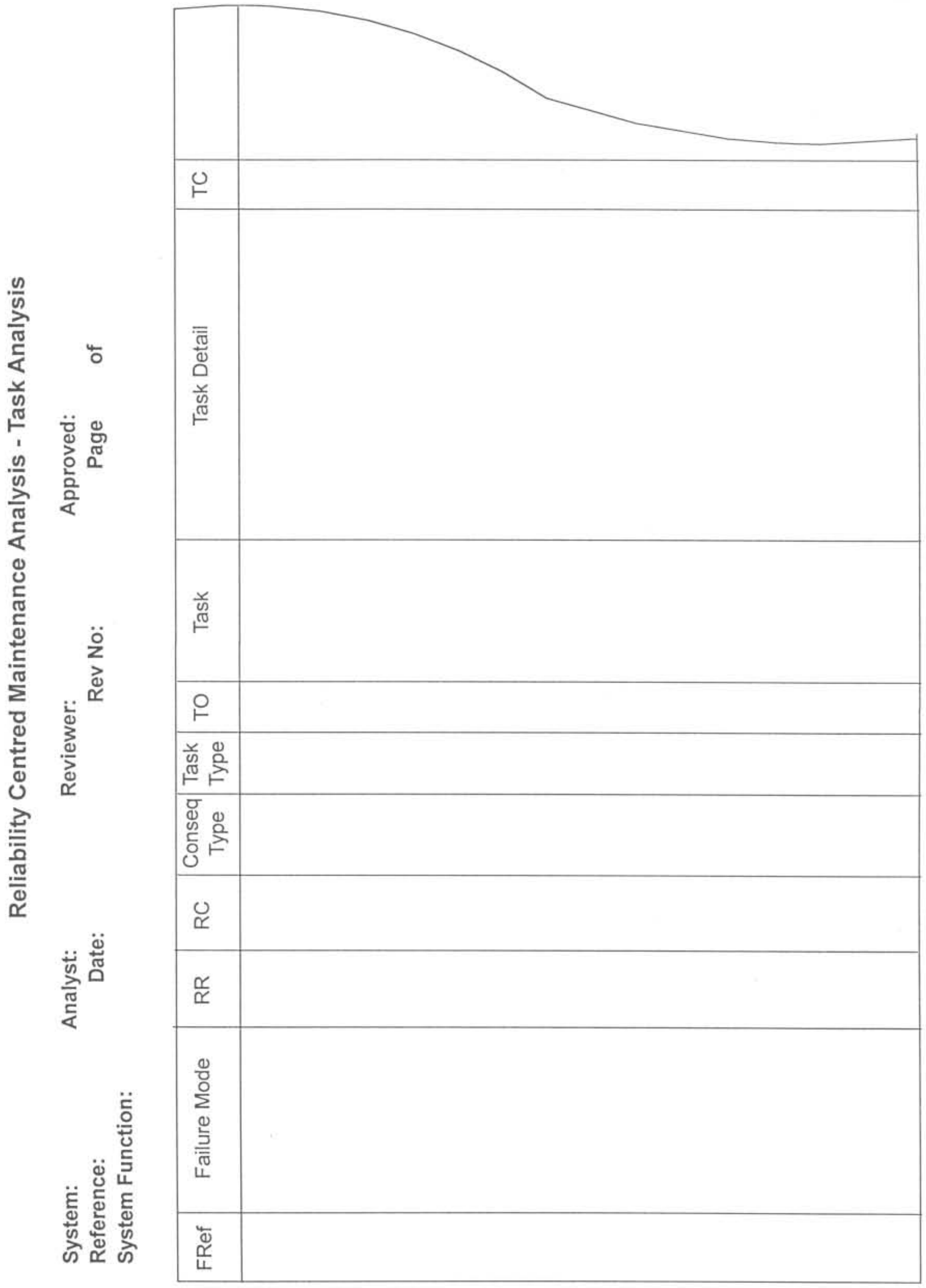
i. The column 'Task Type' is filled in using the abbreviations:

LSA	Lubrication, Servicing or Adjustment Task
FF	Failure Finding Task
QI	Quality Improvement Task
OC	On-Condition Task
Rec	Reconditioning Task
Rep	Replacement Task
CM	Corrective Maintenance Task
DO	Design-out Task

ii. The column headed 'TO' is used to document a cross-reference to the trade-off study, if applicable (see paragraph 4.3.7.4, as well as figure 4-23).

iii. The 'Task' and 'Task Detail' columns are reasonably self-explanatory – the first is used as either a short name for the task or a unique task identification number, whilst the second is used to fully describe the task, so that the artisan will know exactly what to do. This 'long' task description should consist of the full task action to be taken, any standards involved (e.g. measurement standards) and any feedback information required. The use of the 'Task' column for a unique task number is recommendable, as that makes task identification and history keeping much easier and more organised.

There is a consequence of the task selection process, which is not obvious at first. This is the fact that, because of the change in the process not to truncate after the task selection, a single failure mode might have a whole list of tasks listed next to it on the analysis sheet. All of these will be valid tasks, but would not necessarily all be used. During the last process on the decision tree (figures 4-19 and 4-21), the best task combination is chosen from the documented tasks.



Reliability Centred Maintenance Analysis - Task Analysis

System:
Analyst:
Reviewer:
Approved:
Reference:
Date:
Rev No:
Page of
System Function:

FRef	Failure Mode	RR	RC	Conseq Type	Task Type	TO	Task	Task Detail	TC	

Figure 4-24: RCM Task Documentation

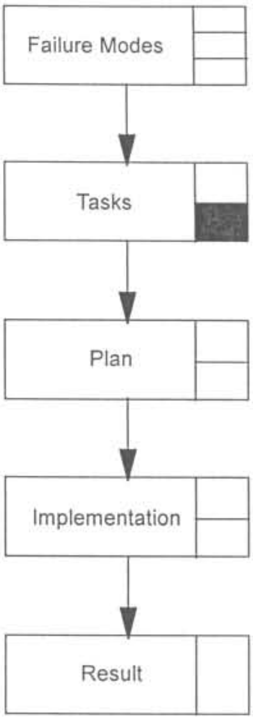
The tasks making up this best task combination is then checked in the TC (Task Combination check) column before handling the default part of the RCM decision process. Following the default analysis, this task combination will be confirmed by circles around the check marks if it survived the 'feasible to the correct degree' question. Otherwise, a further task, which can be a corrective task or a redesign task, will be listed with a circle next to it in the TC column to indicate that it was chosen.

4.3.8. Task Frequencies

It is not within the scope of this thesis to investigate and research better methods for the choice of task frequencies, but it will be one of the recommendations of the thesis that such efforts be promoted to enhance and add value to the RCM methodology.

There are many techniques available for the determination of task frequencies – some of these are shown in table 4.5. Many engineers, statisticians and operational researchers are doing research to find better ways of determining task frequencies. These efforts are invaluable, as it remains a challenge to find the correct task frequencies, given the scarcity of data in the typical maintenance environment.

It is recommended, that a company using RCM keep a list of standardised frequencies, which are acceptable to the organisation, either for the whole organisation or per workshop. This is in line with the third principle of Nowlan and Heap [Nowlan and Heap (1978)] and the second principle of Gits [Gits (1988)] (paragraph 3.2.9). The RCM analysts can then use such a frequency list to specify maintenance task frequencies, without having to change frequencies that are not acceptable later. Such list will typically consist of the frequency, the frequency unit of measure and a symbol representing the frequency.



The results of the frequency analysis will be documented on the Task Analysis worksheet by adding the specific standard task frequency symbol in the column headed 'F' in the Task Analysis worksheet (figure 4-25). At the same time the trade involved will also be added in the column headed 'T'. Possible trade abbreviations to be used are 'B' (Boilermaker), 'E' (Electrician), 'F' (Fitter), 'H' (Helper), 'M' (Millwright), 'R' (Rigger), 'W' (Welder), and so forth.

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Table 4.5: Listing of task frequency determination techniques

Lubrication Task:	Experience with similar equipment
	Manufacturer data
	Age exploration
Failure Finding Task:	Experience with similar equipment
	Manufacturer data
	Knowledge of the MTTF
	Knowledge of the variance in times to failure
	Age exploration
	Statistical Models (inspection)
	Moubray's method (paragraph 3.2.8.3)
Quality Improvement Task:	No frequency (once-off task)
On-Condition Task:	Experience with similar equipment
	Manufacturer data
	Knowledge of the MTTF
	Knowledge of the variance in times to failure
	P-F interval
	Age exploration
	Statistical Models (inspection)
Recondition Task:	Statistical Modelling
	Conservative estimation [Smith (1993)] (§ 3.2.8.4)
Replacement Task:	Statistical Modelling
	Conservative estimation [Smith (1993)] (§ 3.2.8.4)

4.3.9. Task Packaging

The principles of task packaging is simple: the individual tasks, which is the result of the RCM analysis, must be put together in logical work-packages, such that the work is grouped by:

i. plant/system/machine
ii. set-up type (step 1 of Gits [Gits (1988)])
iii. task frequency class
iv. trade
v. task timing [Kelly (1997)]

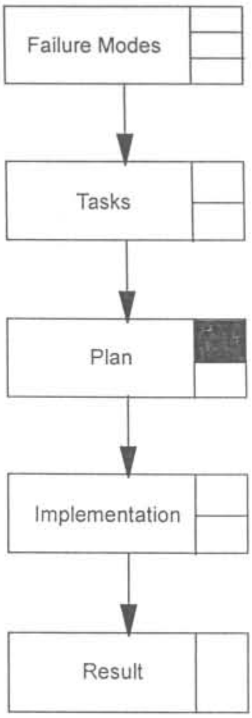
Reliability Centred Maintenance Analysis - Task Analysis

System: Analyst: Reviewer: Approved:
Reference: Date: Rev No: Page of
System Function:

Legend:
TO: Trade-off Study Number
TC: Task Combination Check
F: Frequency Group
T: Trade
ST: Setup Type
P: Production Indicator
SG: Schedule Group

FRef	Failure Mode	RR	RC	Conseq Type	Task Type	TO	Task	Task Detail	TC	F	T	ST	P	SG

Figure 4-25: RCM Task Analysis worksheet



The proposed RCM sheets (figures 4-15 and 4-25) are meant to be used per plant or system or machine, such that the tasks resulting from such an analysis will by definition be grouped according to the first grouping above. The traditional RCM analyses were also done in this way and additionally identified tasks per frequency and per trade. This then makes it easy: take all the weekly fitter tasks out of the RCM analysis and group them together. If there are too many tasks to be performed by one fitter, divide the tasks into two or more evenly spread work packages (typical work orders). This is an overly simplistic view of the process of task packaging.

The RCM Task analysis worksheet shown in figure 4-25 includes columns for starting the task packaging process. Some of them have already been discussed, but will be included in the following listing for completeness sake:

F	Frequency Group (refer § 4.3.8)
T	Trade Group (refer § 4.3.8)
ST	Set-up type[13]
P	Production Indicator[14]

The set-up type for the specific business has to be defined during the actual analysis process, as it differs from business to business. The production indicator, on the other hand, is reasonably standard and can be chosen from the following list [Kelly (1997)]:

P	Work that can be done during production
O	Opportunistic - minor work, to be done during production stoppages
SD	Major work to be done during shutdowns

The rest of the task packaging process now consists of considering these various classifications and grouping tasks into logical work packets based on the constraints imposed by them. This process is rather involved and does not lend itself to standardisation. The principles can however be expounded:

a. The task packaging process should normally be performed for the unit that was chosen for analysis (§ 4.3.2.2) to limit the complexity of the packaging process. After the tasks for the unit has been packaged

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[13] A set-up is an activity, which must precede execution of the maintenance task. This includes production shutdown, opening up of the item, disassembly, and administrative procedures. The benefit of this step [Gits (1988)] is that the number of times that this preparatory work has to be done is limited.

[14] The production indicator shows when the specific work can be performed, taking production constraints into account [Kelly (1997)].

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successfully, they can then be considered within the larger whole of which the unit is a component. This then allows integration of the task packages at the higher level to obtain additional logistical and scale benefits.

b. The tasks as listed in the Task Analysis worksheet should be sorted to obtain the logical work packages. This can be easily done if a spreadsheet was used in documenting the analysis results. The typical order of sorting would be: P | ST | F | T. This is different to the conventional T | F. This last (conventional) approach does not allow the grouping of the tasks of different trades, leading to a single co-ordinated task result. It is most often done correct in industry, but using heuristics. The order of sorting proposed in this paragraph effects a top to bottom approach in structuring task packages effectively.

c. Often different parts of the work done on a single unit, but utilising different trades, come from different operating units of the business (workshops typically) or even outside concerns. This does not pose insurmountable difficulties, but has an implication for task packaging in the area of achieving an acceptable level of task co-ordination.

d. The suggestion that the business keep a list of standardised frequencies, which are acceptable to the organisation, either for the whole organisation or per workshop (§ 4.3.8), embodies another important principle. The method of Gits [Gits (1988)] has as a formal task-packaging step, to structure the maintenance intervals such that it suits the business best (see the recommendation in paragraph 4.3.8). It is better, however, to structure these standard intervals beforehand and then only use standardised task frequencies in RCM analyses. Occasionally these standards may prove to be unacceptable, but then is the time to approach the higher management with a request to register another standard task frequency. After the change has been properly thought through, the principle accepted and no unacceptable adverse consequences having been discovered (and planning done to avert or mitigate any adverse consequences that may accrue), the standard list will be supplemented with the new standard task frequency.

e. Task intervals that affect the production process should be spaced as far apart as possible [Nowlan and Heap (1978) principles 1 and 2]. Even the other task intervals (those that do not affect the production process) should be spaced as far as possible apart to save manpower. On the other hand, the resulting maintenance plan must be effective (production output leading to profit is more important than manpower constraints).

f. Too large work packets result in a major impact on maintenance resources. Whenever large low frequency work packets occur, there should be an attempt to spread this workload amongst smaller higher frequency work packets, such that equalisation of workload is achieved without jeopardising the end result [Nowlan and Heap (1978), principle 4], [Gits (1988), principle 3].

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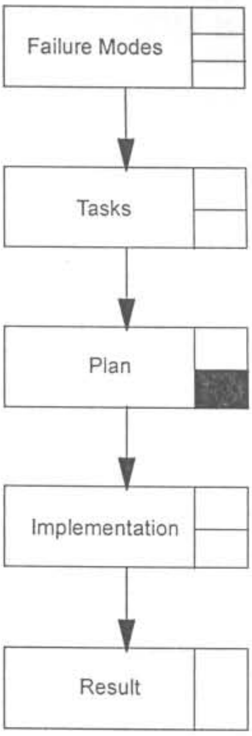
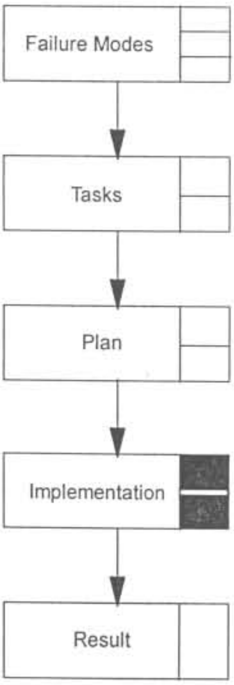
4.3.10. Critical assessment of resulting program



As was stated in paragraph 3.2.10, this is a very important area to ensure that appropriate results will be forthcoming from the RCM analyses, resulting in effective maintenance plans. Just as the RCM process should be driven by the maintenance manager for whom the maintenance plan is compiled, he or she should continuously be involved in the process, actually 'peeping over the shoulders' of the analysts to ensure that good results will be forthcoming. Whether such manager will involve him-/herself personally in the auditing of the RCM process and the RCM analyses is an open question, but he/she should at least ensure that the right level of auditing is taking place, improving the chance of success of the new maintenance plan. It is of no use to spend large sums of money to design new maintenance plans or improve the old ones if the result is not validated.

For this purpose, Nowlan and Heap wrote an extensive appendix on auditing the RCM analysis process and the resulting RCM analyses. The essence of that analysis was given in paragraph 3.2.10 and will not be repeated here, although that can form the core of a good (better than would typically be used by general industry RCM auditing contingents) audit approach. As the objective of this document is to improve RCM in the areas where it lacks, and the approach of Nowlan and Heap is more than satisfactory, this subject will be put to rest.

4.4. Application structure and methods



The RCM process itself was redeveloped in some detail in paragraph 4.3. Although this was done fairly completely, there now remains some questions regarding the coherence of the total model, practical implementation issues and the integration of the methodology into the organisation. The first two of these three topics will be addressed in this paragraph and the last in the next paragraph.

One of the major contributions of paragraph 4.3 lies in the process of limiting the number of failure modes to which the RCM task selection process is applied. This was done through the 'funnelling' concept (figures 4-13 and 4-14), which resulted in only "1 %" of the total number of failure modes being addressed during the first RCM analysis process. However, that causes other potential problems to spring to mind. What happens to the remainder of the equipment? What if some of the equipment outside the 'funnel' has important statutory or safety implications? These questions are so important that they may cause potential us-

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ers of the methodology not to use the method at all 'because it does not regard safety to be important'. Nothing can be further from the truth, but the fact remains that that can be the perception. The RCM methodology thus needs to be put in context regarding the whole maintenance plan. While RCM is used to design an excellent plan for "1 %" of the failure modes, there still needs to be something else in place for the other "99 %". In the traditional RCM approach, this was not a problem as the idea was to do RCM for 100 % of the equipment. But that was one of the major reasons why the technique was discredited in the first place.

The solution to this problem is not to see RCM as a methodology to totally replace the older mthods of setting up a maintenance plan, but as a technique for optimising the most critical parts of the maintenance plan. This ensures that the old plan is not discarded immediately, which would cause a high level of instability, but is gradually improved by the use of the RCM methodology. The principle is depicted in figure 4-26. The figure is another way of presenting the 'funneling' process of figures 4-13 and 4-14, but with the added feature that the other "99 %" is also shown. It shows that the "1 %" is analysed using the RCM methodology, while the other "99 %" is analysed using conventional methodologies. Those could include the Business Centred Maintenance method [Kelly (1997)], equipment manufacturer's recommendations, statutory requirements, NOSA standards and HAZOP studies. The point is that these last methodologies are typically those that were used previous to the introduction of RCM for determining what maintenance should be done. At the introduction of RCM to the business these are not discarded, but enhanced through the addition of the RCM methodology. The figure adds one further feature: the time deployment of the technique. It shows that the idea is to progressively widen the 'funnel' to further optimise the maintenance mix of the organisation.

The average maintenance manager and his/her personnel is often confused by the many ways used in the classification of maintenance tasks. This confusion is not improved upon at all through the implementation of the RCM methodology. Three of the main classification areas involved are given in the following listing:

a. The classification scheme used in figure 4-8, i.e. preventive versus corrective versus design-out.

b. Scheduled versus unscheduled work.

c. Planned versus unplanned work.

Figure 4-27 brings the relationship between these classifications, and with RCM, into focus. It can assist the end-user and the analysts in understanding exactly where RCM fits into the larger maintenance task management environment. It incorporates figure 4-26 and thus the relationship between RCM and other maintenance plan components. It clarifies the following:

1. RCM has as output three possible task options, i.e. *preventive, corrective* and *design-out*. This is explained further in figure 4-28. Although *failure finding* is part of *prevention* (figure 4-28), it is handled separately in figure 4-27 for clarity.

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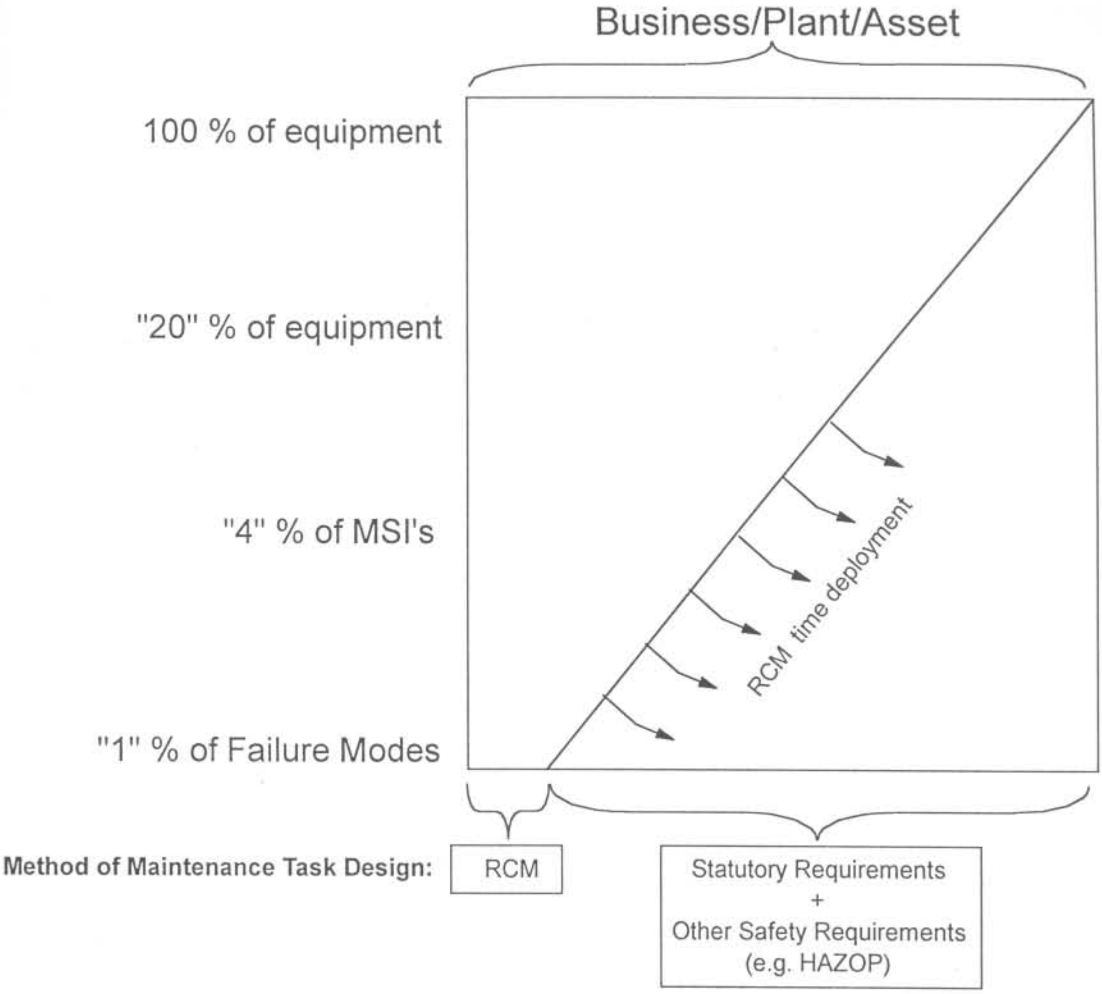

Figure 4-26: RCM versus other techniques

2. RCM is supported through *mathematical* (reliability) *modelling* in its decision making process.
3. Following design-out the redesigned unit (if design-out was an outcome of RCM) should be subjected to RCM analysis.
4. The output of the conventional maintenance plan design (the "99" %) is *'checklist-tasks'* and *corrective tasks*. All the important preventive tasks should be the result of the RCM analysis, and the conventional techniques should thus only result in inspection and servicing tasks, which are prescribed for some important safety or operations reason, as well as statutory life-limit tasks. These are mostly preventive in nature as well, but are dubbed 'checklist tasks' [Harris (1985)] to differentiate between the output of the two processes.
5. In most maintenance departments there will be some *ad hoc tasks*, ranging from convenience jobs to small modifications.
6. The preventive tasks and the checklist tasks together makes up the maintenance plan or the *scheduled work*. This work is scheduled as prescribed by the plan and task planning is then performed on it. The resulting work then makes out the larger part of the *planned work*.

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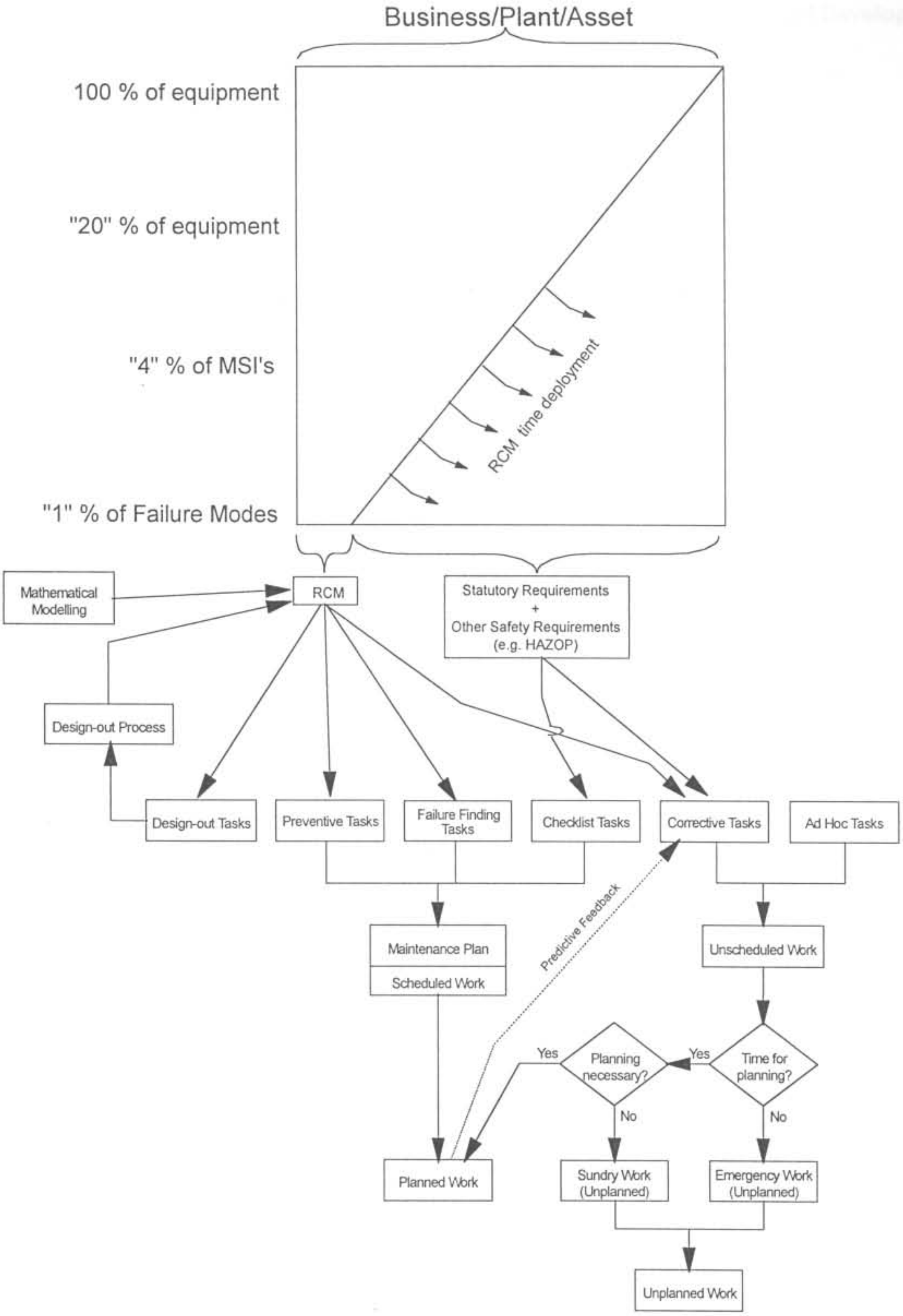

Figure 4-27: RCM in context

7. Corrective tasks and ad hoc tasks together makes up the *unscheduled work*. This work can be planned if time for planning is available and planning is necessary. It then makes out the smaller part of the *planned work*. The remainder of the unscheduled work is handled as *unplanned work*. These are further classified into *emergency work* (where a time constraint makes planning impossible) and *sundry work*. It is normally

this last class (sundry) that is used to build up a stable backlog for workload-balancing [Coetzee (1997/2) p.166-167].

8. A last comment regarding predictive work: if RCM prescribes a predictive task, it will result in a scheduled condition monitoring or inspection task. The outcome of this task will either be 'do nothing' (no potential failure was discovered) or 'correction is necessary' (typically a planned corrective task).

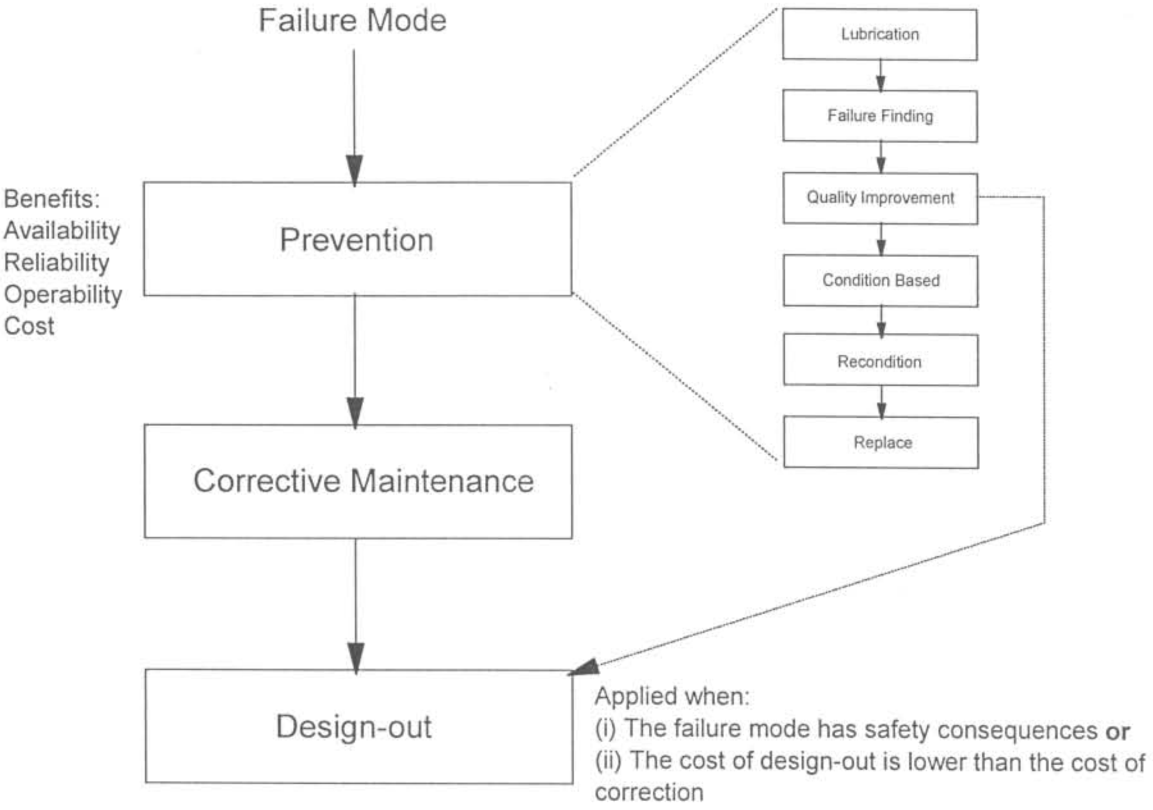

Figure 4-28: RCM task selection process summary

The second main topic of this section relates to some practical implementation issues. They are *firstly* the continuation of the process after it has been worked through once and *secondly* the continuous improvement process that follows after the full implementation of the first RCM maintenance plan. The first issue is addressed using figure 4-29 as basis. This uses the 'funnel' of figures 4-13 and 4-14 to further describe the process shown as the 'RCM time deployment' in figures 4-26 and 4-27. This shows that after the initial use of RCM to design a maintenance plan for the "1 %" of failure modes, the bottom-most failure mode 'funnel' is progressively opened until RCM has been applied to all the failure modes of the "4 %" of MSI's. Thereafter the MSI 'funnel' is opened further, again using a failure mode 'funnel' to progressively apply RCM to the 'new' MSI's, and so forth. After all the MSI's have been handled for the "20 %" of equipment, that funnel can be progressively opened.

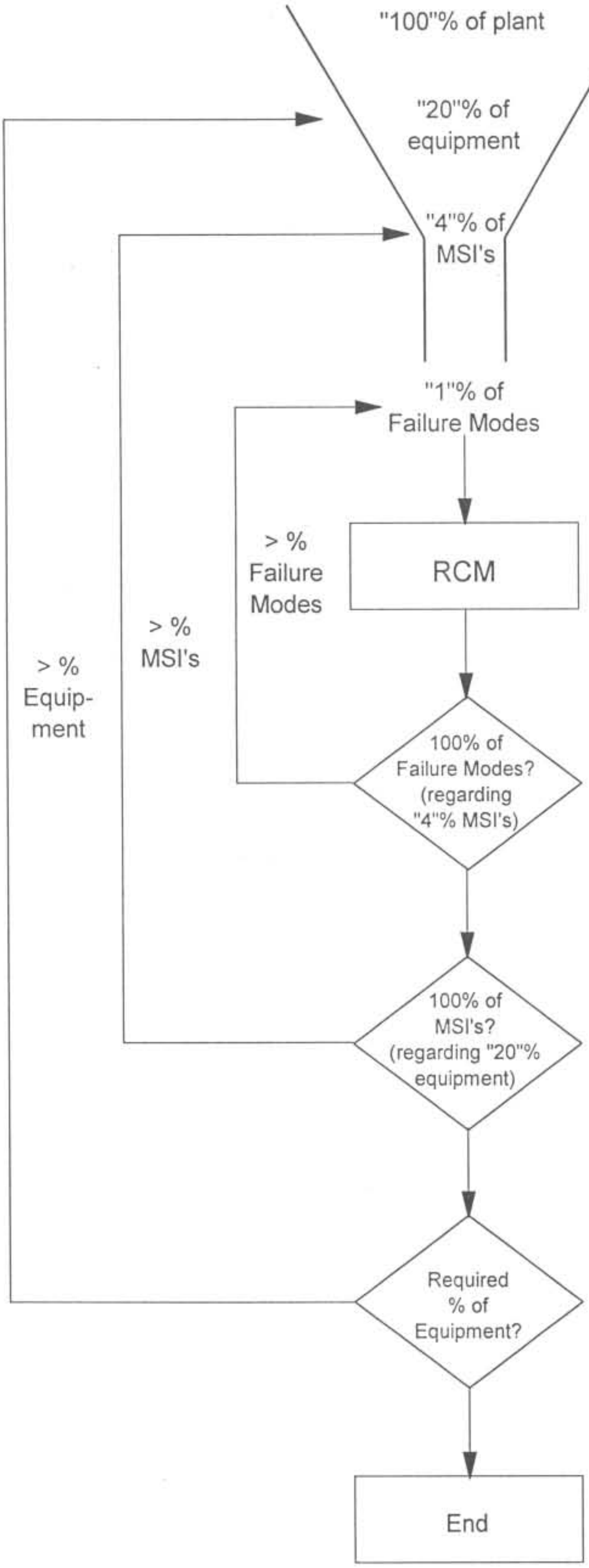

Figure 4-29: RCM progressive application

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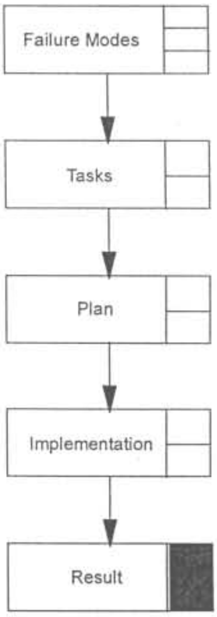
This opening-up process of the funnel is of course in the hands of the maintenance managers involved who should stop the process when it does not make economic sense any more. However, the process will normally not stop before the first "20" % of equipment have been fully analysed (that is, both the MSI and Failure Mode 'funnels' full open). The reason for this is that these "20 %" of equipment constitutes 80% of the organisation's maintenance risk – it would thus be irresponsible not to at least complete the RCM analysis for these units. For the other "80 %" of equipment one could use another way of selectively applying RCM to say the components with the highest ROCOF (using the Pareto Principle) or those with the highest cost (again using the Pareto Principle). The exact point at which you stop using RCM to your advantage is based on economics: if you overapply RCM, the marginal cost would exceed the gain achieved. On the other hand, if you stop too early you would not get the full benefit.

The outline of the RCM process shown as figure 4-9 is again included here for convenience as figure 4-30. It also shows the progressive application process discussed above as the 'increased benefit' feedback loop.

The second feature of importance in figure 4-30 is the feedback loop named 'continuous improvement'. This is what Smith calls the ***living RCM program*** [Smith (1993)]. It indicates that the RCM analysis process can never stop, due to the commitment that was made to continuous improvement of the maintenance plan (see §2.4). At the completion of the RCM implementation project (the 'funnels' have been opened up to their logical maximum opening) and all resultant tasks having been properly implemented, the Continuous Improvement loop is activated and a continued program of Maintenance Plan Improvement starts. This is normally driven through management activators such as a high ROCOF, high cost and catastrophic failure incidents, which indicates that further optimisation of the Maintenance Plan is necessary.

4.5. Organisational issues



One of the major reasons why RCM analyses in industrial organisations fail is because they underestimate the effort that goes into such a venture, as well as the implementation impact. They think that they can get by through using their existing organisation as is. Such an approach is bound to fail for a number of reasons:

a. The maintenance operational personnel in the typical maintenance organisation cannot appreciate, let alone implement RCM for the organisation. This includes most maintenance managers and engineers, simply because they do not have the time to study the technique properly.

b. Application of RCM is attempted using the present organisational structure without alteration. Taking into account point (a) above, this is a disastrous strategy. The typical maintenance organisation is so lean that it cannot in the first place afford to use its resources on a time consuming effort such as an RCM analysis. Secondly, the people concerned does not have the knowledge and experience of such an exercise. Thirdly, the people doing an RCM analysis need to be dedicated to that alone – it is impossible to handle both an operational job and be an executive member of an RCM analysis team (to just be part of a team of people supplying information is another matter altogether).

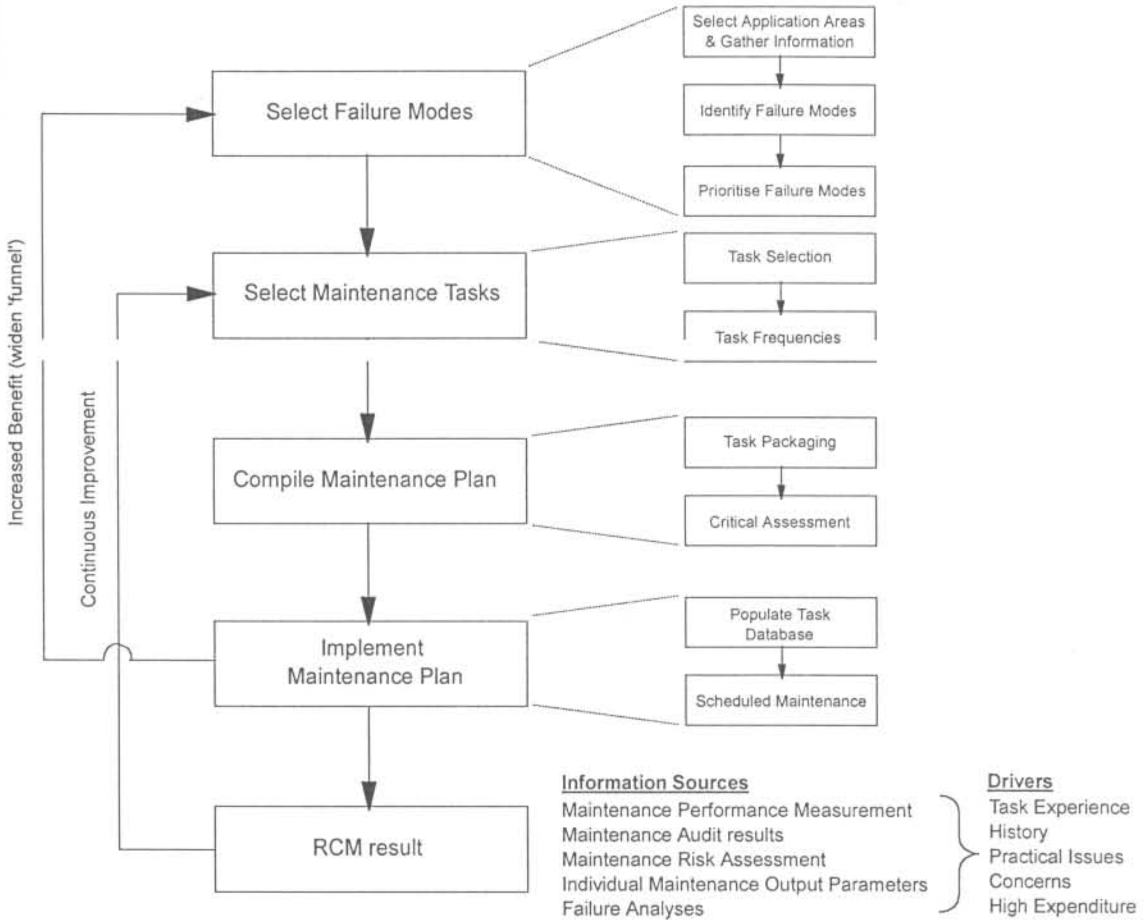


Figure 4-30: RCM Outline

c. The RCM process is not applied in its proper organisational and technical context – see paragraph 4.2.

d. There is no management sponsor or champion[15], who ensures that the process does not lose momentum.

e. The RCM analysis process stands completely separated from the CMMS – there is too much of a manual interface between the analysis and the actual maintenance operations.

f. The lack of formalisation of the management processes surrounding the RCM attempt. These include managing the process on a macro

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[15] A management champion is someone who truly believes in the cause and would, because of that, drive the process (provide energy). Also see paragraph 4.5.4 in this regard.

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scale using a steering committee, formal auditing arrangements, using highly skilled facilitators and analysts, and effecting suitable training for personnel at all levels in the organisation.

Also refer to the problem areas listed in paragraph 4.1 in this regard.

4.5.1. Applying the RCM analysis process in context

With reference to paragraph 4.2, which , which gave nceptual framework within which RCM is to be applied (the context), the following comments:

a. The full context within which RCM is to be applied must be understood properly by all personnel involved, but especially so by the steering committee, the management champion, the facilitator and all formally trained analysts. This includes understanding the maintenance cycle and the strategic position of the maintenance plan in that cycle, the holism of the maintenance function, the risk management process and the relationship between the different maintenance strategy options.

b. RCM must not be seen as *firstly* a once off exercise and *secondly* the only action required for success. If it not supported by a well thought through maintenance policy, management procedures, systems and a well-trained and motivated operational staff, even a perfect RCM effort will produce no results.

c. The RCM analysis process should be preceded by a risk analysis, which can then also be used for the first prioritisation process (see paragraph 4.3.2.2). This provides a 'base line' measurement against which later risk assessments can be compared to establish the success being achieved through the application of RCM.

d. The various maintenance strategy options and their implications, as well as their relationship to equipment reliability characteristics must be fully understood by all personnel involved, but especially so by the steering committee, the management sponsor or champion (see footnote on previous page), the facilitator and all formally trained analysts.

4.5.2. Conducting RCM training

A basic level of RCM training precedes almost all RCM projects in general industry. The problem is that the maintenance plan is such a critical output and is so interwoven in the organisational objectives (as exemplified by paragraph 4.2 and figure 4-4) that most of the maintenance organisation must undergo at least some RCM training. The training must not just consist of a single RCM course, but should include differentiated training for different functionaries in the maintenance organisation. Suggested RCM training-requirements are listed as table 4.6.

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Table 4.6: Suggested RCM training requirements

	Basic Awareness	Standard RCM	Contextual Awareness	Advanced Reliability	Advanced RCM	Managing the RCM process
Management Champion		x	x	x	x	x
Steering Committee members		x	x			x
Managers/Engineers		x	x			
Facilitator		x	x	x	x	
Auditors		x	x	x	x	
Analysts		x	x	x	x	
Supervisors		x				
Planners		x				
Artisans	x					
Typical duration (days)	1	3	2	2	3	1

→ Order of course presentation

4.5.3. Steering Committee

Nowlan and Heap (1978) suggested the use of a steering committee to steer the RCM project. MSG-3 (1993) has even a stronger accent on the central role of the steering committee. Despite this suggestion, industrial application of RCM is mostly done without this mechanism.

MSG-3 describes the purpose and composition of the steering committee as follows: "The management of the maintenance program development activities shall be accomplished by an Industry Steering Committee composed of members from a representative number of operators and representatives of the prime airframe and engine manufacturers. It shall be the responsibility of this committee to establish policy, set initial goals for scheduled maintenance check intervals, direct the activities of Working Groups or other working activity, carry out liaison with the manufacturer and other operators, prepare the final program recommendations and represent the operators in contacts with the Regulatory Authority. The ISC should see that the MSG-3 process identifies 100% accountability for all Maintenance Significant Items (MSI's) and

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Structural Significant Items (SSI's), whether or not a task has been derived from the analysis."

From this, we can get certain guidelines, although both the purpose and the scope of work of industrial Steering Committees will differ considerably from its General Aviation counterpart. The industry steering committee will typically consist of the top maintenance management of the concern, with the maintenance chief as chairperson and will typically convene on a monthly basis. The purpose of the steering committee is:

a. To organise, fund and control the RCM project.
b. To appoint a Management Champion, a facilitator, auditors and RCM analysts.
c. To set task frequency standards (§ 4.3.8).
d. To take critical decisions regarding the RCM variant used, the logistics of the process, approval of completed programs, order of RCM analyses (which sections/sub-plants get attention first), the 'funnel' percentages, the 'funnel' feedback loops, Continuous Improvement and so on.
e. To direct the RCM process and ensure consistent and acceptable progress.
f. To make sure that the analyses are of a sufficient standard (through the auditor(s).
g. To oversee the implementation of the resultant maintenance tasks, receive feedback of problem areas and take corrective action if necessary.

4.5.4. Management Champion

Most successful business interventions have behind it the drive of one or more visionaries who are willing to put their reputation at stake for the prize to be won. This drive is necessary to provide meaning to the effort, and excitement in regard to the expected results [Berlew (1984)]. The role of such visionaries, according to Berlew, is to:

1. Develop a common vision of what the future could be, which is shared by the workforce.
2. Create value-related opportunities, such as 'a chance to be tested' (self-actualisation), 'a chance to do something well' (excellence), and 'a chance to change the way things are' (responsibility), for key individuals in the process, which would make them willing to 'walk the extra mile'.
3. Make organisation members feel stronger and more in control of their own destinies through believing in them, having high expectations of them, rewarding rather than punishing them for sub-standard performance, encouraging collaboration, helping only when asked, and creating success experiences.
4. 'Walk the talk', that is, to behave in ways that are consistent with the values and goals they are articulating.

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Such individuals have to demonstrate expertise in the particular field and should take active roles in remaking the task environment to succeed, according to Lieutenant-General William P.Pagonis, who led the 40 000 people who ran the theatre logistics for the Gulf War [Georgiades and Macdonell (1998)].

4.5.5. Facilitator

RCM analyses are typically performed under the guidance of an RCM facilitator. These are persons that are well versed in the technique of RCM, reliability principles and the leading of small groups of technical experts. They should have the ability to lead group discussions towards consensus decisions and should have such a 'feel' for technology that they know when to make use of any specific and relevant internal or external expertise. Their role, according to Moubray (1991) p 237, is that of asking structured questions, ensuring that the group achieves consensus, and recording the answers on RCM worksheets. In this process, they have to decide at which level the analysis is carried out, ensure that meetings are conducted professionally and ensure that the RCM process is applied correctly.

The organisation should thus have at least one *well trained R.C.M. facilitator* [Coetzee (1997/2)] (if the organisation does not have such a person, a trained facilitator can be hired from an R.C.M. consultant). This person should be a well trained and experienced maintenance engineer, with a very good knowledge of maintenance theory (with the accent on failure theory - physical and statistical). He/she must be able to assess and analyse failure situations accurately through the collection of information from operating and maintenance staff, as well as from failure data. He/she must also be an expert in the application of the R.C.M. technique. This person should be used to lead all the R.C.M. sessions as facilitator. In these sessions, it is his/her task to get as much as possible information about the failure behaviour of the specific equipment on the table. He/she is not to participate in contributing technical knowledge regarding the specific situation. His/her role is rather to ensure that the R.C.M. technique is applied maximally to the available information, so to develop the best possible maintenance plan (having a lean but effective content), using as few man-hours as is possible in the design process. It is clearly not easy to find such a person, as he/she will probably be promoted to a management post before contributing much towards the development of a maintenance plan. However, that depends on the seriousness with which the individual organisation regards the maintenance plan. After all, this plan **is** pivotal in determining whether they will be successful in their maintenance approach.

4.5.6. Auditor

Nowlan and Heap (1978) sees the task of the RCM auditor as that of independent reviewer of the final result and of keeping the 'project on track' (p 350). They state that members of the steering committee, who also have overall responsibility for the RCM project, perform the auditing function in the air-transport industry. Similarly, Coetzee (1997/2) suggests that the mainte-

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nance manager, for whom the plan is developed, should perform the audit personally (p 81). Although this principle is reasonable, it is questionable whether this will realise in practice. He/she should, however, at least ensure that the right level of auditing is taking place, so improving the chance of success of the new maintenance plan. Moubray (1991) agrees with the foregoing principles.

4.5.7. Failure data

The availability of failure data is necessary for developing a proper and accurate maintenance plan. One can, *firstly*, not identify those MSI's which contributes most to the failure process if one does not have failure data to calculate the relevant ROCOF (§ 4.3.2.5). *Secondly*, the prioritisation of failure modes also rests heavily on the availability of failure rate data (§ 4.3.5). *Thirdly*, use based maintenance tasks can only be selected in IFOM situations (increasing hazard function) - the presence of an increasing risk to fail can only be detected through the analysis of operational failure data (§ 4.3.7.1). Failure data is, *fourthly*, also necessary to determine economically sound maintenance frequencies in the used based maintenance category, while it is advisable to have at least data regarding the MTTF available when determining the frequencies of services and inspections (condition monitoring, manual *and* failure finding inspections) (§ 4.3.8).

Although various authors (e.g. Moubray (1991) pp 218-222 and Smith (1993) p 102) dismiss the use of quantitative data, because of the difficulties in gathering / obtaining such data, it is an absolutely necessary requirement for developing an accurate maintenance plan as was explained above. This is where the failure database of the maintenance information system and computerised failure analysis tools come into the picture.

4.5.8. Database / Connection with CMMS/Analysis Software

As was stated above (§ 4.5.7), failure data is an essential part of understanding failure mechanisms and determining the most effective maintenance tasks. Nevertheless, that is not the only part of the maintenance history database that is of interest to the RCM analyst. The different failure modes encountered, as well as the concomitant factors that play a role in the occurrence of each of these failure modes, can often be best determined from the different failure classification codes and text history in the database.

In maintenance practice, this is one of the main factors preventing full success being achieved through the application of RCM. The lack of full management involvement in systems installation and application leads to databases of which the information can often not be trusted to the extent necessary to base maintenance plan decisions on it. This puts a tremendous burden on the team of analysts to discern between data that is valid and those that are not. This often leads to a bias to disregard the total database. However, that would lead to valuable and often indispensable information not being used for the analysis.

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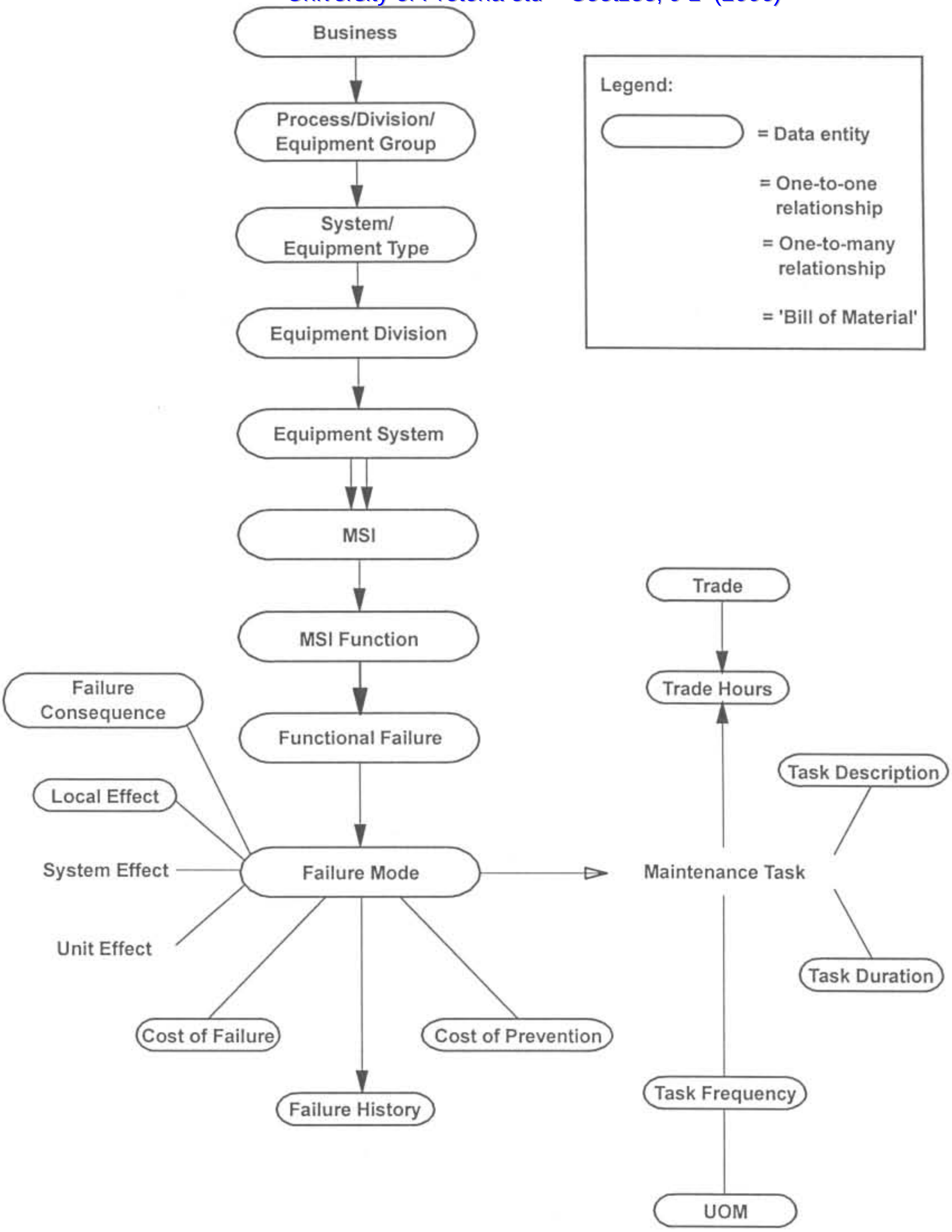

Figure 4-31: Proposed RCM data model

On the other hand, the lack of analysis information during the analysis process often leads to an increased awareness regarding the criticality of keeping proper failure history. This, combined with the fact that the prioritisation processes in RCM will identify the more critical MSI's and failure modes, then leads to a focus on these high priority items for future data collection. The popular view, which stresses the enormity and unrealisable proportions of the data collection process, is thus greatly mitigated.

One of the complicating factors in applying RCM, apart from the incomplete information in maintenance databases, is the fact that information for RCM

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analysis must be extracted from the database manually (often by designing purpose-made reports or data transfer interfaces, using report-writers or database tools such as MS Access ™). The ideal would be to have the RCM analysis process and the statistical failure analysis process integrated seamlessly into the CMMS. The present generation of CMMS's as well as the available analysis tools does not have this ability, which is a substantial shortcoming and which limits the extent to which RCM can be used effectively in the typical industrial situation.

Although it is not the objective of this thesis to specify the design of a CMMS, figure 4-31 shows a proposed data model that can be used as a basis for the integration of the three processes, i.e. the maintenance/operational process, the RCM process and the statistical failure analysis process. It is based on combination of the data requirements of the essential parts of these three processes from a proposed CMMS and the RCM/failure analysis capability of M-Analyst ™[16].

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[16] A system built and marketed by M-Tech Consulting Engineers, a company active in the fields of maintenance knowledge transfer, maintenance consulting and maintenance software distribution.

Chapter 5: Model Testing

5.1. Description of test system

The test system selected is a quench reflux pump in the VCM (Vinyl Chloride Monomer) plant of Sasol Polymers. The product of this plant (VCM) is the primary feedstock for the PVC (Polyvinyl Chloride) plant. The PVC plant produces PVC powder, which is sold to converters producing products such as piping, electric insulation, extrusion mouldings, flooring and sheeting. The specific pump set consists of two parallel pumps, numbered GA-1402 A and GA-1402 B, of which the one is normally in operation and the other one is on standby. The purpose of the quench reflux system is to control the quality in the quench column (a distillation column). The pumps were installed in 1994 and displayed low reliability, which is at least partly due to the severe duty to which it is exposed. Typical problem areas include the shaft sleeve, bearings, the mechanical seal, high system pressures and poor installation.

The plant's availability of historic data is very characteristic of the typical situation in industry. The plant changed over from one maintenance information system (a system they called MMS, which was based on the Fluor Daniel system of the late 1980's, with some modifications) to another (SAP/R3) in 1998. The history in the MMS system was not transferred to the SAP/R3 system. This is the typical situation found in the average industrial concern (a shortage of failure history due to loss of history during system changes). The raw data as supplied from the SAP/R3 system is shown in table 5.1.

Facts that become obvious when looking at table 5.1 are the following:

- The problems of the pump seem to be mainly related to the mechanical seal and its accompanying shaft sleeve.
- A secondary problem area is that of the sealing fluid accumulator - these failures are typically due to the pumped medium getting into the seal fluid system when the mechanical seal/shaft sleeve fails.
- The history is very difficult to interpret for the following reasons:
  - There is no information regarding the work done during overhauls.
  - The cost of overhauls (and other activities) is not consistent, which does not help the interpretation.
  - The 'type of work' column descriptors (which are supplied by the artisan) are not used consistently. This accentuates the comments of the company's artisans that the failure codes should be simpler to interpret.
- Most of the work was on pump A. This fact could be insignificant, but it could also point to the real problem - see later comment on page 5-14.

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- These tables do not supply any information regarding pump lives (which is of course crucial to determine the lives of the various components).

An assembly drawing of the pump is shown in figure 5-1, while a cut-through drawing of the mechanical seal used in the pump is shown in figure 5-4. Figure 5-2 shows two photographic views of the pumps with some important parts highlighted while figure 5-3 shows a piping schematic of the seal-oil system. A part - breakdown structure for the pump is shown in figures 5-6 to 5-8.

The pump pumps a mixture of Ethylene Dichloride (EDC) and Anhydrous Hydrochloric Acid (HCl), which is later separated, at a discharge pressure of 2500 kPa. It uses an API plan 53 (figure 5-3) barrier fluid arrangement with an API seal arrangement 3 (double mechanical seal). The environment is protected from leakage by circulating a barrier fluid, which also provides lubrication, at a pre-set pressure of 2 700 kPa. To pre-charge the seal fluid system to the pre-set pressure, the system is equipped with a hand charge pump. The mechanical seal includes an internal screw pump arrangement (item 1.4 in figure 5-4) to pump this circulating fluid. To compensate for day/night temperature differences (to ensure that the pressure is maintained), the system is equipped with a compensating accumulator.

The accumulator failures evident in table 5.1, were caused by product getting into the barrier fluid. That was caused by the operations personnel allowing the barrier fluid pressure to fall below the product pressure. By upgrading operational vigilance and ensuring that the correct pressure gradient (ΔP) is maintained these failures were stopped. This highlights the fact that problems are often permanently solved during the RCM analysis process, because the various failure modes are systematically analysed.

5.2. Maintenance plan analysis results

5.2.1. Analysis using standard RCM

A previous RCM analysis, using the RCM 2 version of Moubray (1991), was done for the plant, the applicable analyses being given in Appendix A on pages 5-35 to 5-37 (for the pump) and Appendix B on pages 5-38 to 5-43 (for the mechanical seal).

When one contemplates utilising RCM in a practical manner for the design of a maintenance plan for an industrial facility, it immediately becomes clear that you have to limit the scope of the analysis in some or other way (refer to § 4.3.2.2, § 4.3.2.5 and § 4.3.5 in this regard). Some practitioners do this by simplifying the analysis process (the adherents of 'streamlined RCM' and 'reverse RCM'), while others use the approach of 'generic' RCM analyses as is apparent in this case. The thinking behind this is that 'a pump is a pump' and 'a mechanical seal is a mechanical seal.' A generic RCM analysis for all single stage centrifugal pumps was thus performed (pages 5-12 to 5-14) and another for normal double balanced mechanical seals' (pages 5-15 to 5-20).

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Table 5.1: Failure History GA-1402 A&B Quench Reflux pumps

Line No	Pump No	Description	Type of work	Date	Cost R
1	A	Capture cost angle bracket	Preventive - General	20-Nov-98	R 1 683.50
2	A	Return spares to store	Predictive - General	17-Dec-98	-R 2 250.00
3	B	Install spare pump **and send defective unit** for overhaul	Predictive - CM	20-Jan-99	R 13 315.49
4	B	Replace accumulator bladder	Reactive - Planned	21-Jan-99	R 651.54
5	A	Install spare pump **and send defective unit** for overhaul	Predictive - CM	21-Jan-99	R 1 210.00
6	A	Overhaul spare pump in workshop	Proactive - Precision Rebuild	26-Jan-99	-R 8 482.70
7	A	Recondition Accumulator	Reactive - Planned	27-Feb-99	R 7 850.00
8	A	RTS hand refill pump	Reactive - Planned	28-Feb-99	R 0.00
9	A	Replace mechanical seal on spare pump	Proactive - Precision Installation	1-Mar-99	R 9 601.75
10	A	Recondition Mechanical Seal	Preventive - Recondition	25-Mar-99	-R 6 271.00
11	A	Recondition Accumulator	Reactive - Planned	19-Apr-99	R 7 850.00
12	A	Replace Mechanical seal	Reactive - Planned	31-May-99	R 11 088.82
13	B	Recondition Accumulator	Reactive - Planned	9-Jun-99	R 7 850.00
14	A	Overhaul spare pump in workshop	Predictive - CM	21-Jun-99	R 5 988.99
15	A	Recondition Accumulator	Reactive - Planned	5-Jul-99	R 7 850.00
16	A	Repair seal	Predictive - Work Generated from Inspections	10-Jul-99	R 9 945.96
17	A	Replace bearings	Reactive - Planned	3-Aug-99	R 319.00
18	B	Replace accumulator	Reactive - Planned	20-Sep-99	R 7 850.00
19	B	Replace mechanical seal	Reactive - Planned	19-Nov-99	R 9 307.00
20	A	Recondition Mechanical Seal	Reactive - Planned	17-Jan-00	R 1 566.00
21	B	Replace mechanical seal	Predictive - CM	18-Jan-00	R 10 685.05
22	A	Replace mechanical seal	Predictive - Work Generated from Inspections	31-Jan-00	R 11 036.92
23	A	Replace mechanical seal	Predictive - Work Generated from Inspections	6-Feb-00	R 11 596.59
24	A	Repair clamp plate	Reactive - Planned	10-Feb-00	R 570.00
25	A	Repair & sort out seal failure	Reactive - Planned	15-Feb-00	R 6 977.47
26	A	Replace mechanical seal	Predictive - CM	10-Apr-00	R 10 253.54

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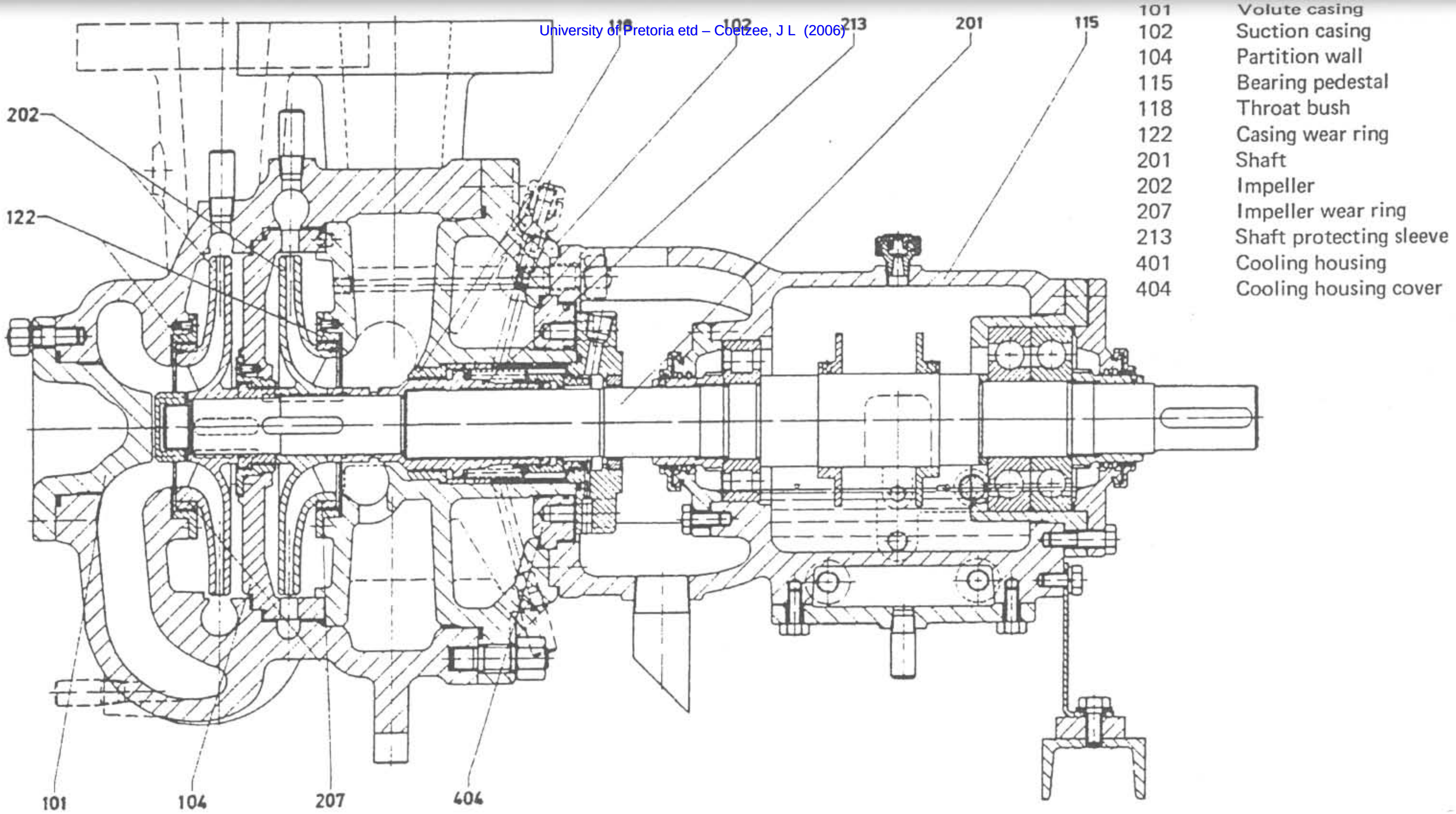
Table 5.1: Failure History GA-1402 A&B Quench Reflux pumps (continued)

Line No	Pump No	Description	Type of work	Date	Cost R
27	A	Recondition Mechanical Seal (2 off)	Reactive - Planned	26-Apr-00	R 1 434.00
28	A	Replace mechanical seal	Reactive - Planned	26-Apr-00	R 11 435.00
29	A	Replace mechanical seal (callout)	Predictive - CM	24-May-00	R 20 982.55
30	B	Recondition Mechanical Seal	Reactive - Planned	8-Jun-00	R 4 150.00
31	B	Repair leaking seal	Preventive - Replace	15-Jul-00	R 10 840.50
32	A	Repair leaking seal	Preventive - Recondition	8-Aug-00	R 22 244.99
33	A	Replace mechanical seal	Predictive - CM	22-Aug-00	R 11 404.49
34	A	Replace shaft and mechanical seal	Reactive - Planned	28-Aug-00	R 820.73
35	A	Replace mechanical seal	Preventive - Replace	19-Sep-00	R 10 840.50
36	A	Replace bearings	Preventive - Recondition	22-Sep-00	R 13 325.99
37	A	Replace mechanical seal	Predictive - CM	12-Oct-00	R 1 736.00
38	A	Recondition Mechanical Seal	Reactive - Planned	16-Oct-00	R 22 111.50
39	A	Recondition Mechanical Seal	Reactive - Planned	23-Oct-00	R 12 517.00
40	A	Recondition Accumulator	Reactive - Planned	8-Nov-00	R 5 980.00
41	B	Replace mechanical seal	Predictive - Work Generated from Inspections	14-Nov-00	R 0.00
42	B	Replace mechanical seal	Predictive - Work Generated from Inspections	16-Nov-00	R 4 476.90
43	A	Recondition Mechanical Seal	Reactive - Planned	24-Nov-00	-R 15 079.00
44	A	Recondition Mechanical Seal	Reactive - Planned	24-Nov-00	R 0.00
45	B	Replace non-return on seal pot	Reactive - Planned	24-Nov-00	R 932.00
46	B	Recondition Mechanical Seal	Reactive - Planned	24-Nov-00	R 1 130.00
47	A	Replace mechanical seal	Preventive - Gnl	28-Nov-00	R 1 745.74
48	B	Recondition Mechanical Seal	Reactive - Planned	7-Dec-00	-R 20 403.50
49	A	Spare hand refill kit	Reactive - Planned	11-Jan-01	R 2 653.00
50	A	Spare kit for oil hand pump	Reactive - Planned	7-Mar-01	R 0.00
51	A	Replace leaking seal	Reactive - Unplanned	6-Apr-01	R 9 556.50



101	Volute casing
102	Suction casing
104	Partition wall
115	Bearing pedestal
118	Throat bush
122	Casing wear ring
201	Shaft
202	Impeller
207	Impeller wear ring
213	Shaft protecting sleeve
401	Cooling housing
404	Cooling housing cover

Figure 5-1: Sectional drawing KSB RPH 40-231

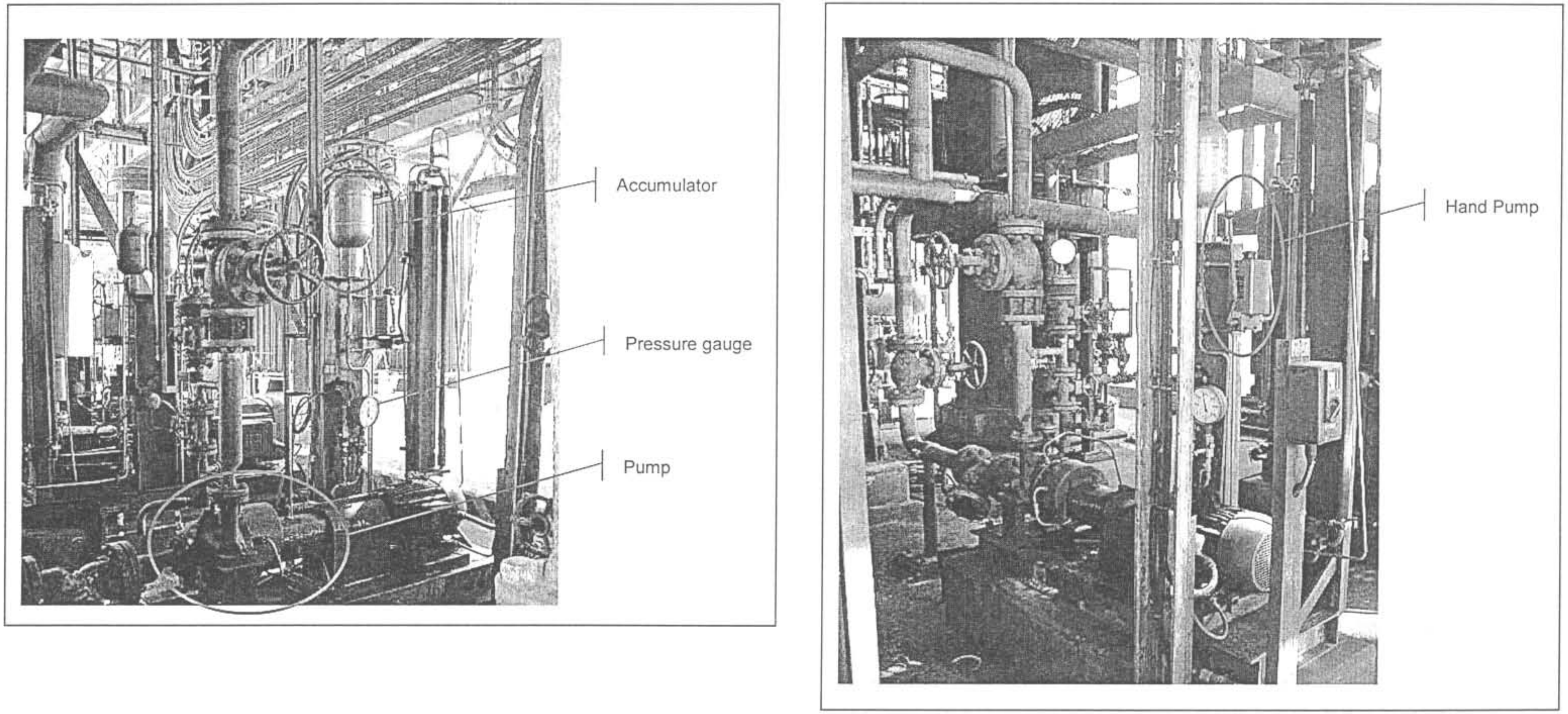


Figure 5-2: GA-1402 pumps

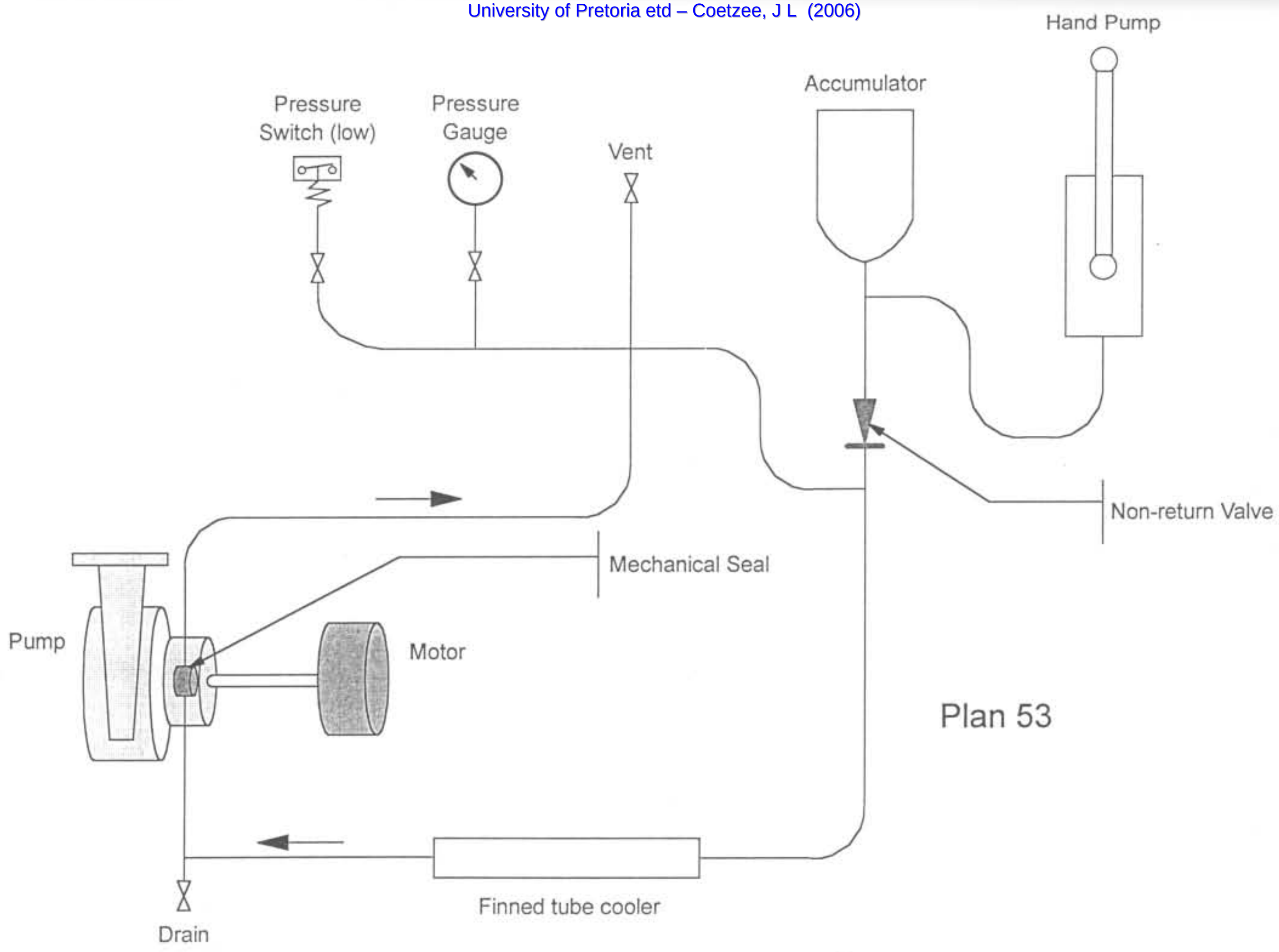


Figure 5-3: GA-1402 pumps seal-oil piping schematic

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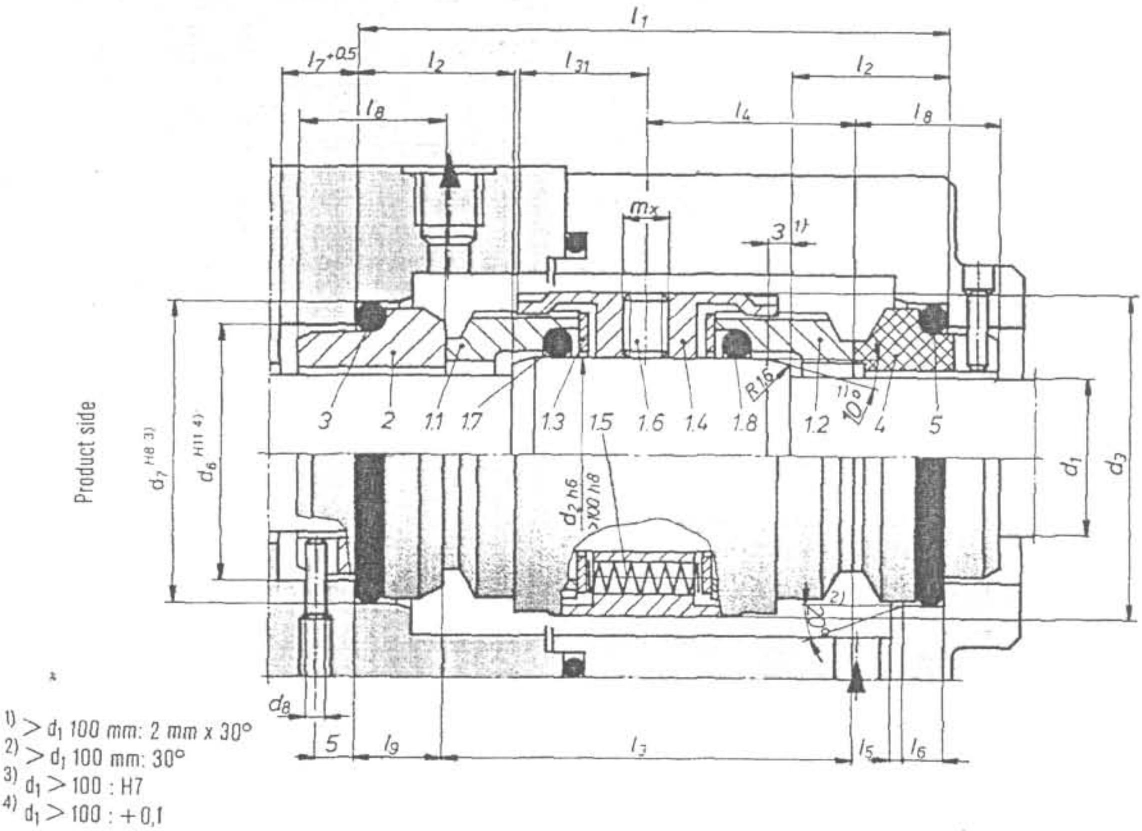

1) > d_1 100 mm: 2 mm x 30°
2) > d_1 100 mm: 30°
3) d_1 > 100 : H7
4) d_1 > 100 : +0,1

Figure 5-4: Sectional drawing of mechanical seal

Thus, while the risk involved can differ greatly from pump to pump (due to the difference in applicatory detail and operational circumstances), a 'generic' solution for the maintenance of all such units is proposed to limit the extent of the analysis to such an extent that it remains doable. This is grossly insufficient, taking into account the high safety risk involved in a plant of this nature. In order to make this type of approach work, the generic maintenance plan is then pitched to work for a high risk pump. This means that all pumps in the plant (44 pump pairs with mechanical seals) have to be maintained in the same rigorous way. The plant maintenance management's argument in defence of this is that they handle a product, which is many times as explosive as TNT. They would thus rather prefer to be overly rigorous. This makes sense, as is their second argument, that they do not want to confuse the workforce with too many versions of a specific type of unit's maintenance plan, to limit the negative effects of wrong maintenance actions. They concede that this is not very cost effective.

From experience, this type of approach can have serious implications for the long-term success of the maintenance plan, especially in less dangerous plants:

- It *firstly* proposes a plan that is resource intensive and,
- *Secondly*, both maintenance management and artisans will soon discover this fact and then only pay lip service to the plan (that is, if they do not actively disband it, as so often happens).

The major part of this analysis is probably perfectly valid for our two pumps, as they represent a high-risk situation in this plant. However, the fact remains that the outcomes from RCM analyses differ even from operating situation to operating situation utilising identical equipment, but with different fluids pumped and different pressures and flow rates.

5.2.2. Analysis using proposed improved model

One of the improved features of the proposed model is its funnelling approach, whereby the RCM energy is expended on items for which it matters most. For a first level prioritisation, refer to the Pareto analyses in figures 5-5 and 5-9. The first of these is a life-to-date Pareto cost analysis, while the second is a year-to-date Pareto cost analysis. For the life-to-date picture, the Pareto 'elbow' occurs at the fifth cost item, while it occurs at the fourth cost item in the year-to-date case. It is clear that the priorities in terms of high cost items have shifted somewhat over the longer term, indicating a change in priority based on cost profile. The results are shown in table 5.2

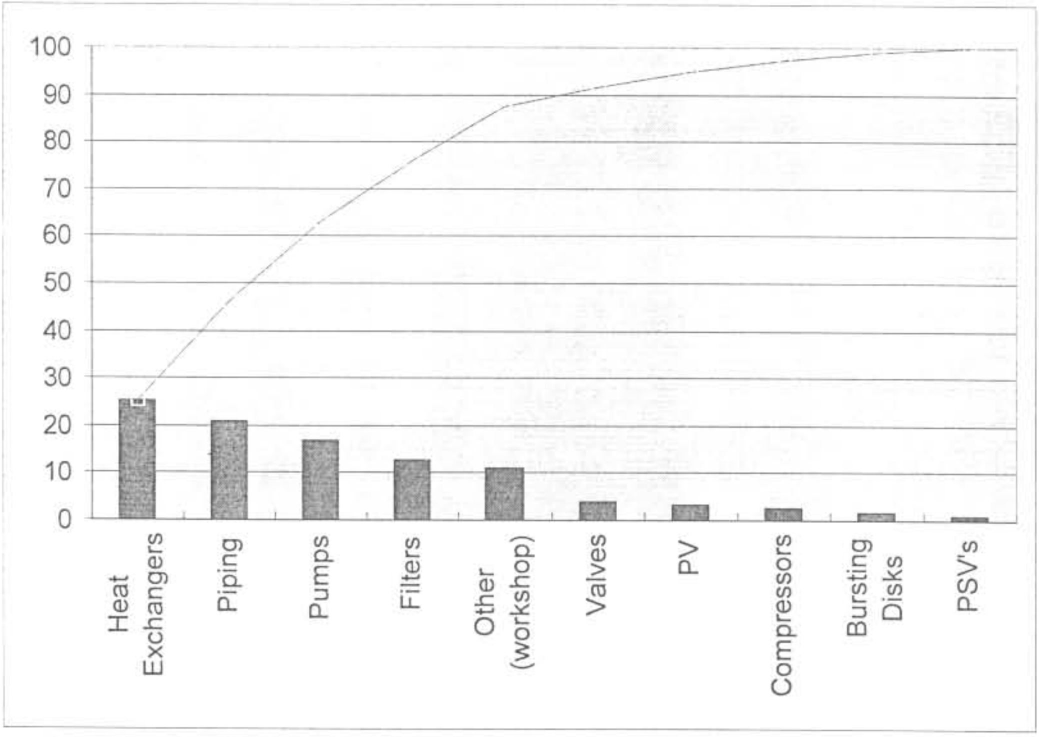

Figure 5-5: Life to date Pareto

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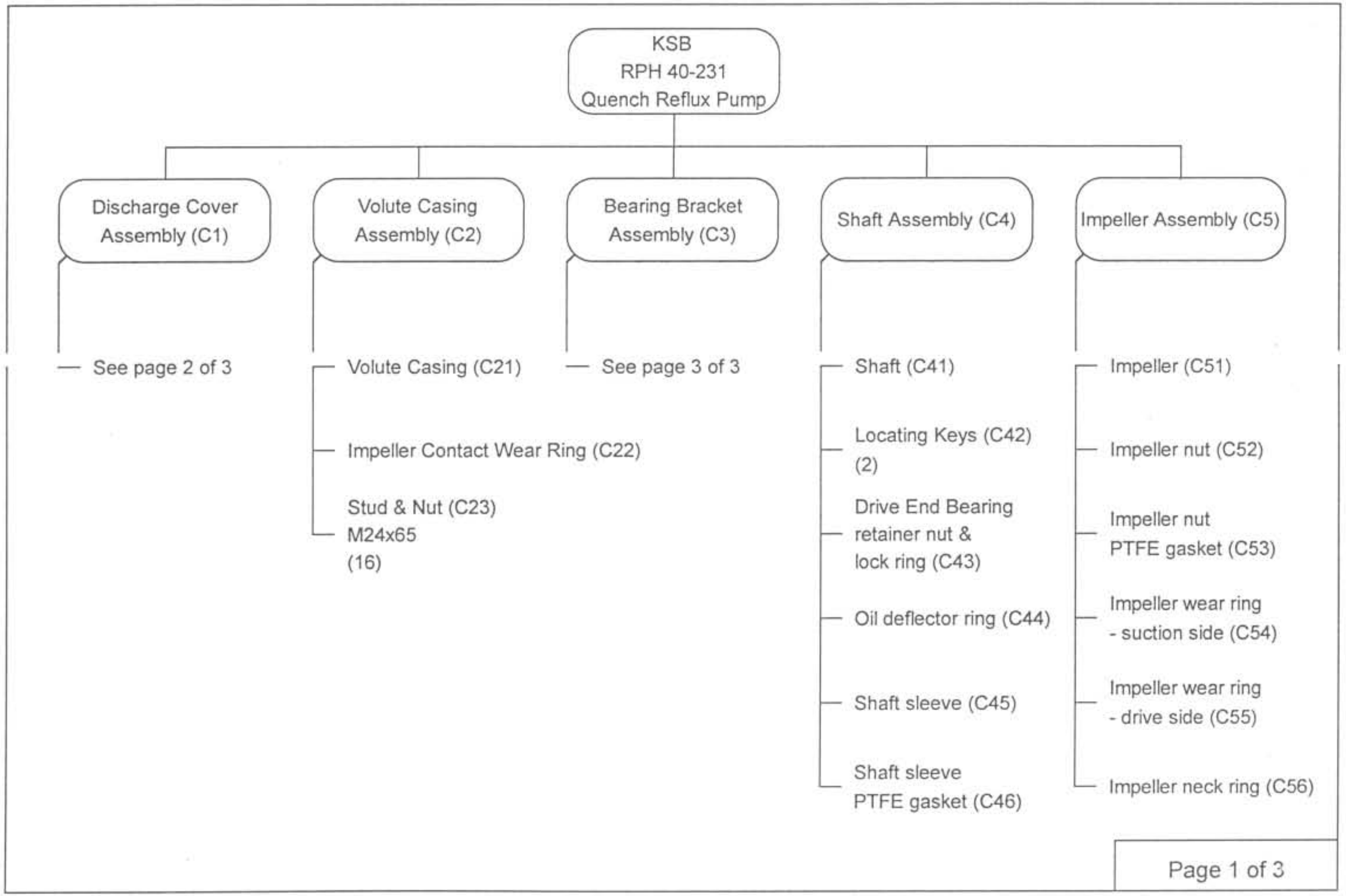

Figure 5-6: Pump breakdown structure

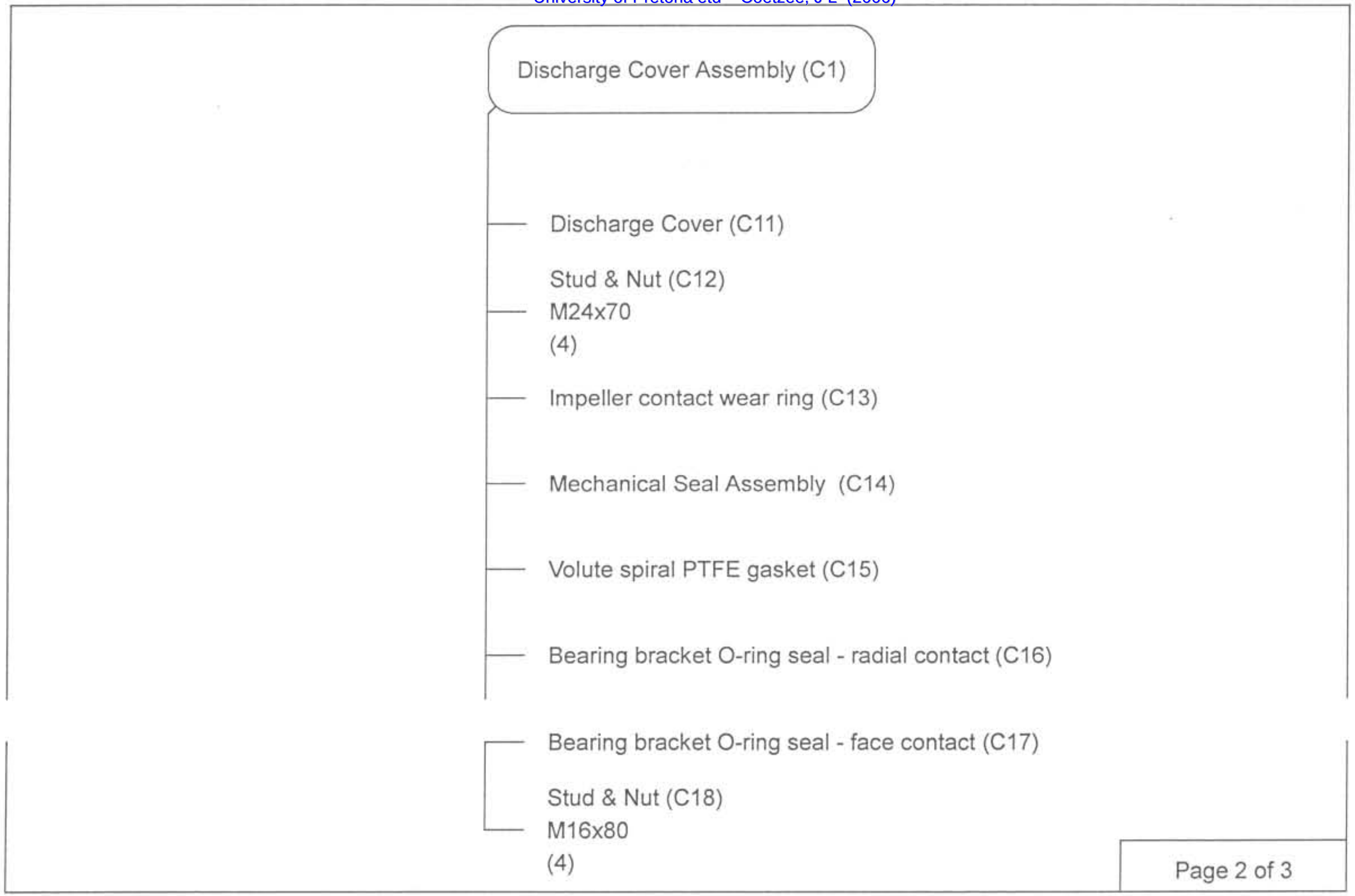

Figure 5-7: Pump breakdown structure

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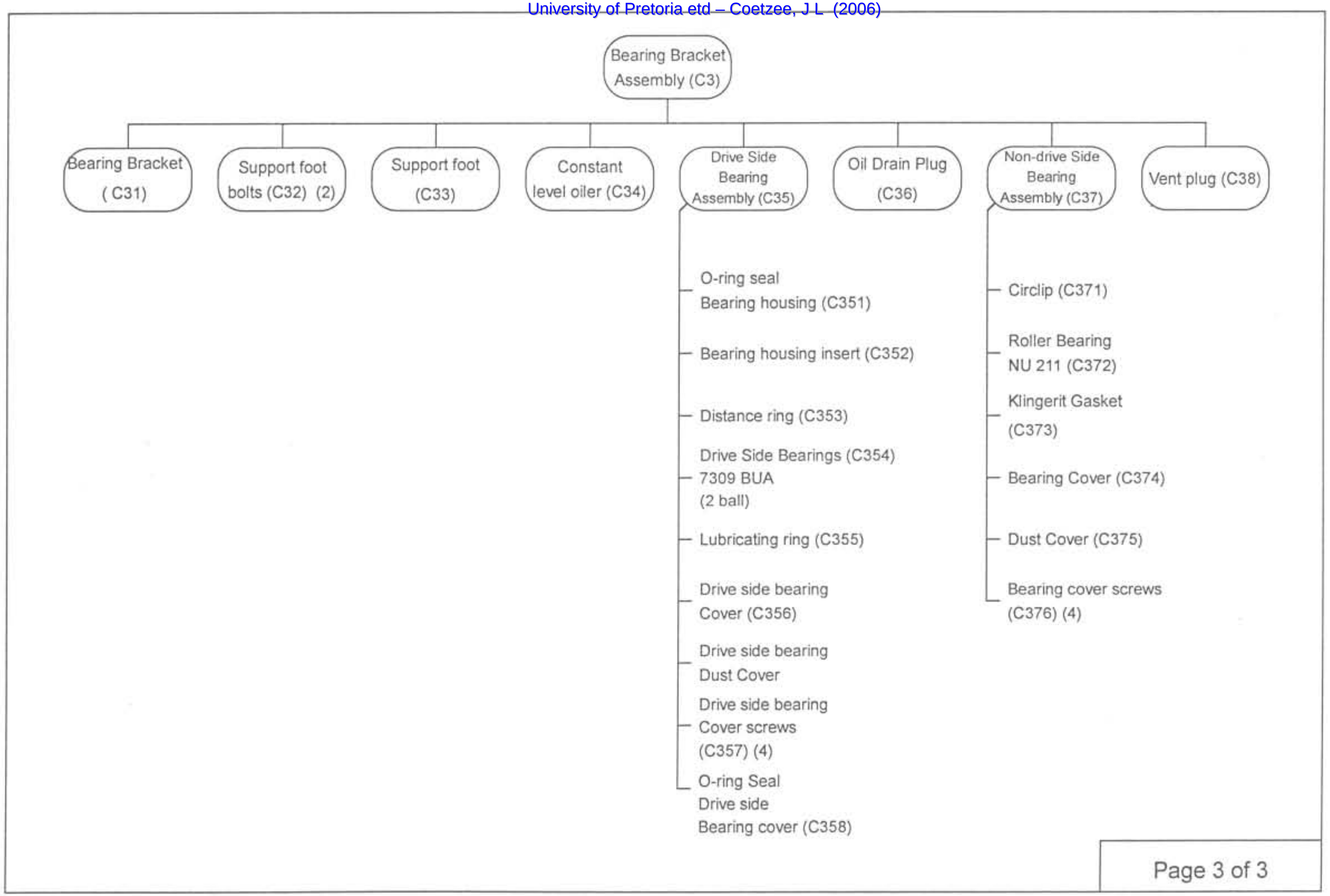

Figure 5-8: Pump breakdown structure

Table 5.2: Order of importance for RCM analysis

Year to Date	Life to Date
Heat Exchangers	Heat exchangers
Piping	Piping
Other (workshop)	Pumps
Pumps	Filters

It is clear that the original RCM effort should be expended on the heat exchangers, piping and pumps (in that order). Although the 'other' category plays a significant role in the costs, it consists of a conglomerate of cost items, and will have to be dealt with separately.

If one has the reliability and safety of plant at heart, a more complete risk analysis, based on the combination of cost, production loss and safety will have to be adopted. In this specific case, the plant management's goal was to reduce the cost of maintenance significantly using RCM analysis, as they were convinced that all the other risk factors are adequately dealt with using various other techniques.

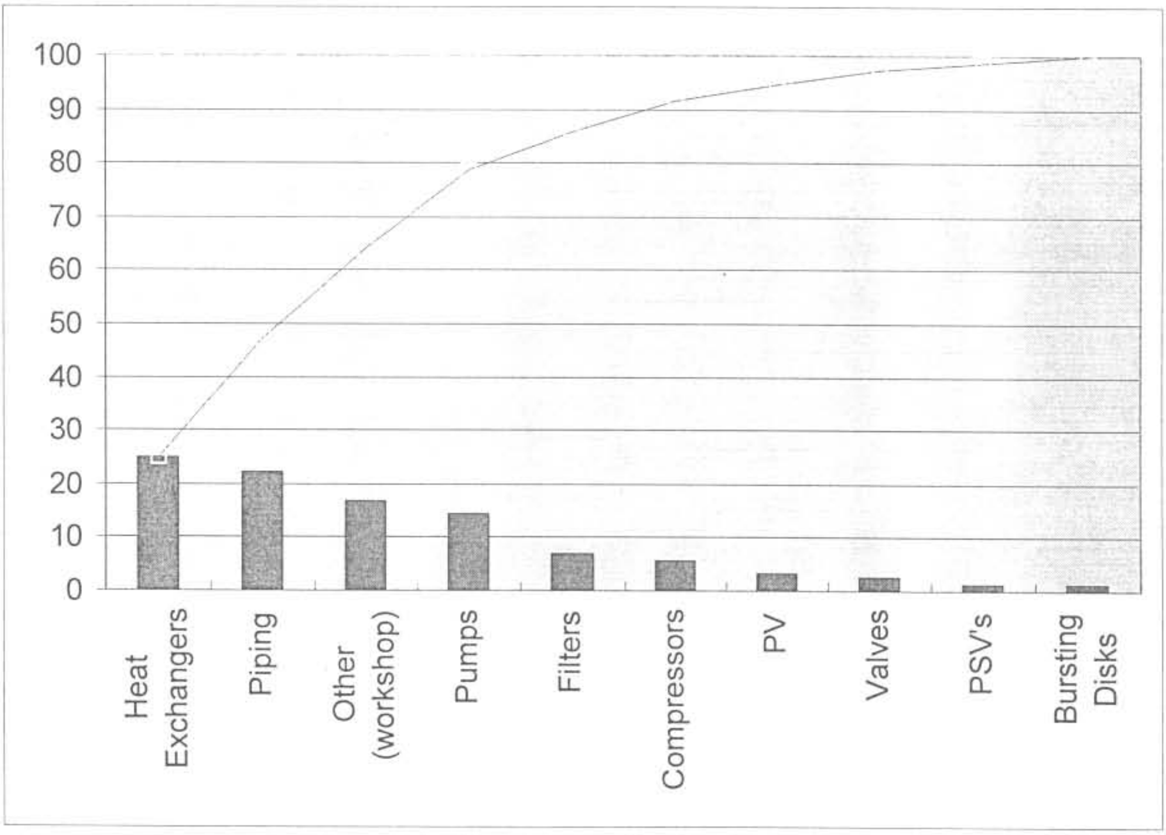

Figure 5-9: Year to date Pareto chart

One of the outstanding contributors to high cost of maintenance was found to be a pair of pumps (one of the categories identified above), the GA-1402 A and B quench reflux pumps described in paragraph 5.1. These pumps have an average MTTF of 1,2 months, compared to the average MTTF of 28 months of all similar mechanical seal equipped pumps.

Figures 5-10 and 5-11 show the monthly and cumulative history of failures for the GA-1402 A and B pumps respectively, while figure 5-12 gives the combined history for both pumps.

In paragraph 5.1 it was stated that most of the work was on pump A, and the comment was made that, this fact could be insignificant, but that it could also point to the real problem. Figures 5-10 and 5-11 seem to reinforce this notion, as it is clear that pump A failed much more than pump B. However, when the two graphs are combined, as in figure 5-12, it becomes clear that this is not the case, as can be deduced from the stable inclination of the cumulative graph. Pump B is only used when pump A is not available, hence the lower number of breakdowns and the long periods of no breakdowns. An enquiry into the matter confirmed this deduction.

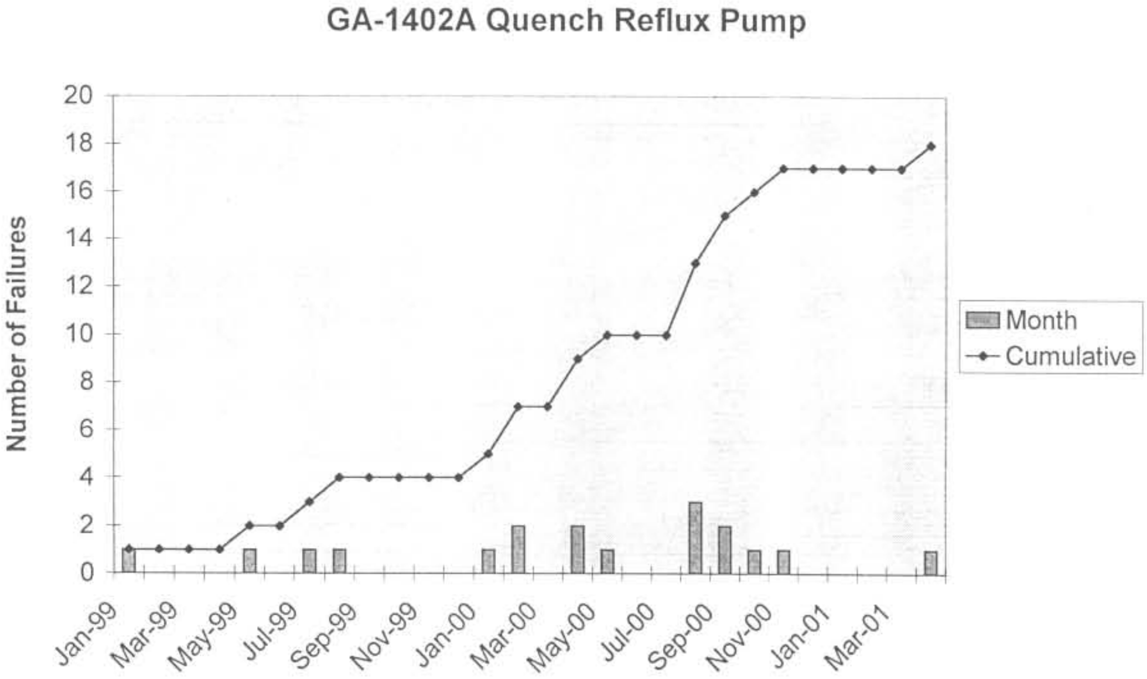

Figure 5-10: GA-1402A Quench Reflux Pump - number of failures

Although the full first stage of the funnelling process was not followed (a jump was made from the top Pareto analyses - figures 5-5 and 5-9 - to the GA-1402 pumps), it was done in enough detail by the plant's management[1] to show the worth of zooming in to the highest risk items. The next step is to identify the MSI's (Maintenance Significant Items) through the partitioning process of

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[1] This was done as part of an RCM analysis under supervision of the author.

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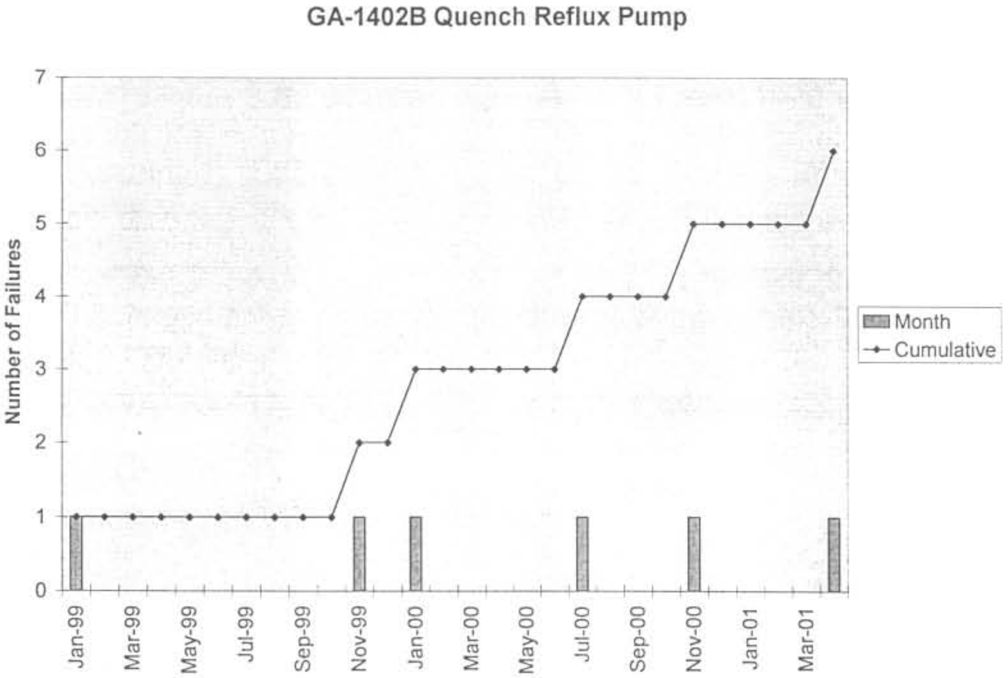

Figure 5-11: GA-1402B Quench Reflux Pump - number of failures

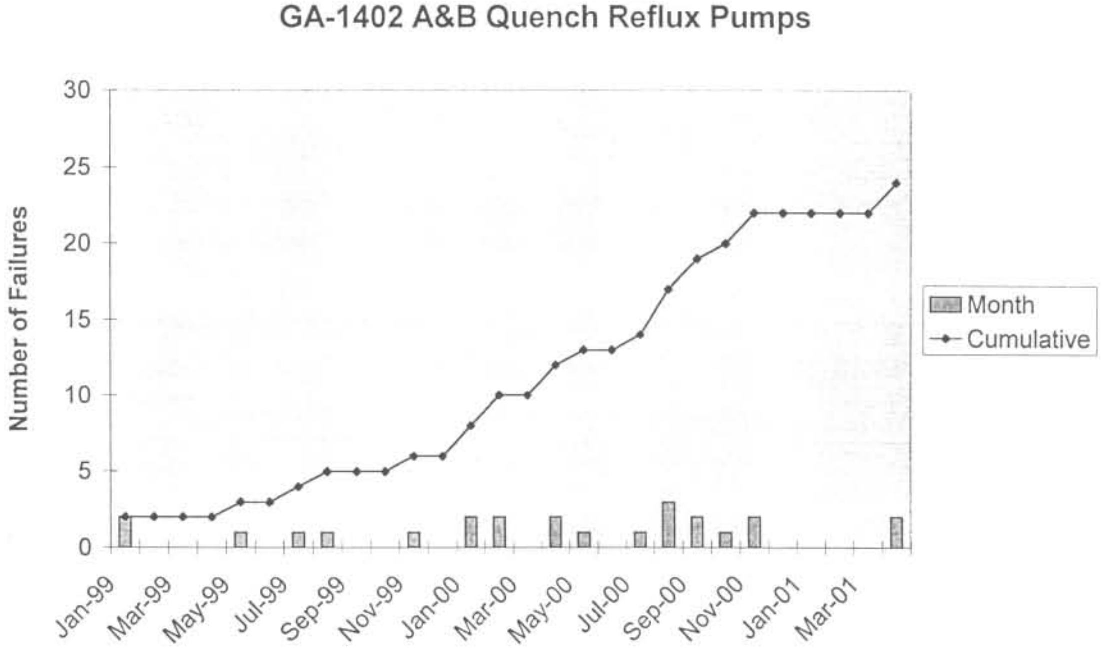

Figure 5-12: GA-1402 A&B Quench Reflux Pumps - number of failures

paragraph 4.3.2.4, using the diagram in figure 4-12. This was done in figures 5-6, 5-7 and 5-8, but in more detail than that envisaged using the *item break-down decision diagram* shown in figure 4-12. The detail is important in this case, to illustrate a few concepts. Instead of interactively deciding on the proper level of analysis, using figure 4-12, the breakdown is done to the lowest level and then the best level(s) for the MSI's is chosen.

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A coding system was used in figures 5-6 to 5-8 to uniquely identify each component as being part of the one above it. The top subassemblies, which make up the pump, was thus identified as being C1, C2, ..., C5 (C standing for 'component') (figure 5-6), while an example of a lowest level component (figure 5-8) is the 'Bearing Housing Insert' (C352), which is part of the 'Drive Side Bearing Assembly' (C35), which is part of the 'Bearing Bracket Assembly' (C3), which is one of the subassemblies making up the pump.

Because of the importance of the preservation of function in the RCM approach, it is expedient to define the function(s) of the pump. These were defined by the plant as:

> *To pump liquid at the rated flow and rated delivery pressure*
>
> **and**
>
> *To contain the liquid being pumped*

The first of these describes the business function for which the pumps was chosen and purchased, while the second reflects the hazardous nature of the liquid being pumped. If any component has a significant bearing on either or both of these functions, then the component should be classified as significant. However, such effect should be verifiable from history or should be reasonably possible (where safety is involved).

It should be noted that no in-situ repair work is carried out on the pump. When a component fails, the pump is replaced by installing the spare unit, while the defective unit is repaired/rebuilt in the service workshops.

The name 'Maintenance Significant Item' implies firstly that the item is significant, that its failure matters at the system level. Remember the requirements for significance as specified by Nowlan and Heap (1978):

The resultant level of MSI's should be low enough that no failure possibilities are overlooked, but high enough for the loss of function to have an impact on the equipment itself. (§ 4.3.2.4)

Secondly, the failure of the item must have 'significant' safety and/or operational effects. To choose the correct MSI's from amongst the list of components, is consequently mostly a heuristic process, using a combination of historic information (table 5.1), the study of all the detailed information that was collected and the ability and experience of the analyst. This is not a process that lends itself to objective description and will also typically differ for each RCM analysis. This is one of the reasons why the organisation must have a well-trained and experienced RCM facilitator. RCM analyses cannot be performed by anyone. This is also the reason behind Nowlan and Heap (1978) and MSG-3 (1993)'s insistence on and accentuation of the importance of the critical evaluation of the resultant analysis result. Refer to paragraph 3.2.10 in this regard.

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A set of reason codes was devised in this specific case to assist in the choice of MSI's and their prioritisation. This was done partly because figure 4-12 was not used (see explanation above) in the partitioning process, partly due to a scarcity of good failure history, and largely because of the need to make a heuristic process visible. These reason codes are as follows:

FE	Significant effect on pumping function (functional effect)
SE	Significant (proven)
PSE	Highly probable effect on containing function (safety)
NFE	No significant functional effect
NSE	No significant (or probable) safety effect
IR[2]	Installation requirement (if installed properly, it remains functional for the life of the pump)
LL	MSI's are defined at lower level

One normally does not use reason codes in this process, but decide on the MSI's during the partitioning process, using the principle as stated by the RCM handbook of the Naval Sea Systems Command (1983):

"*RCM is a methodology intended for use in developing … **the preventive maintenance program for a ship**. If you are involved … in the application of RCM, you should understand that intention. Otherwise, you may focus on some lesser level of assembly rather than **on how it, in concert with other hardware, provides all the function of the ship**.*" (accentuation added).

In the present analysis the reason codes are used in an attempt to make at least part of the thought process accompanying the analysis somewhat visible.

Table 5.3 lists the three levels of components, together with the choice of whether a specific component is significant or not, as well as the explanatory reason code. In this table a combination of the reasoning inherent in figure 4-12 and the prioritisation approach of § 4.3.2.5 is used to identify an item as being significant or not.

Note: If an item is significant, its parent level cannot be significant as well. For any specific item, a restrictive decision has to be made regarding its level of significance.

The last column comprises a type of pre-failure mode criticality allocation. Again, there is not a sufficient source of quantitative data to base the prioritisation on. The criticality allocation is thus not meant to be exact, but is a representation of the facts in the failure history (table 5.1), plus heuristic fuzzy data[3]. It shows that there are six components, for which decisions regarding

---

[2] This type of answer often flows from an RCM analysis. Although this does not add a task to the maintenance plan, it identifies a requirement that should be added to the installation/reconditioning/repair quality requirements for the unit. This is an important positive by-effect of the RCM analysis process.

[3] For this purpose the inputs of plant maintenance personnel was used in line with the methodologies of Moubray (1991) and Smith (1993).

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the maintenance strategy must be taken. These are (in order of importance): Mechanical Seal, Drive End Bearings, Non-drive End Bearings, Impeller, Shaft and Pressure Envelope (Volute Casing and Discharge Cover). The 6th item (Pressure Envelope) is only included because of the safety implications, because the impeller should be worn long before the pressure envelope develops integrity problems). For each of these, the FMEA/FMECA is now completed, figure 4-15, resulting in the failure modes of these seven critical components.

Table 5.3: Prioritisation of MSI's

Component Number	Description	MSI?		Priority
		Y/N	Reason	
C1	Discharge Cover Assy	N	LL	
C11	Discharge Cover	Y	PSE	6
C12	Stud & Nut	N	NFE & NSE	
C13	Impeller wear ring	N	NFE & NSE	
C14	Mechanical Seal Assy	Y	SE	1
C15	Volute PTFE Gasket	N	IR	
C16	O-ring (radial contact)	N	IR	
C17	O-ring (face contact)	N	IR	
C18	Stud & Nut	N	NFE & NSE	
C2	Volute Casing Assy	N	LL	
C21	Volute Casing	Y	PSE	6
C22	Impeller Wear Ring	N	NFE & NSE	
C23	Stud & Nut	N	NFE & NSE	
C3	Bearing Bracket Assy	N	LL	
C31	Bearing Bracket	N	NFE & NSE	
C32	Support Foot Bolts	N	NFE & NSE	
C33	Support Foot	N	NFE & NSE	
C34	Constant Level Oiler	N	NFE & NSE	
C35	Drive Side Brg Assy	N	LL	
C351	O-ring Brg Housing	N	IR	
C352	Brg Housing Insert	N	NFE & NSE	
C353	Distance Ring	N	NFE & NSE	
C354	Drive Side Bearings	Y	FE & PSE	2
C355	Lubricating Ring	N	NFE & NSE	
C356	Drive Side Brg Cover	N	NFE & NSE	
C357	Drv S Brg Dust Cover	N	NFE & NSE	
C358	Drv S Brg Screws	N	NFE & NSE	
C359	O-ring Drv Side Cover	N	IR	

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Table 5.3: Prioritisation of MSI's (continued)

Component Number	Description	MSI?		Priority
		Y/N	Reason	
C36	Oil Drain Plug	N	NFE & NSE	
C37	Non-drive Side Brg Assy	N	LL	
C371	Circlip	N	IR	
C372	Roller Bearing	Y	FE & PSE	3
C373	Klingerit Gasket	N	IR	
C374	Bearing Cover	N	NFE & NSE	
C375	Dust Cover	N	NFE & NSE	
C376	Brg Cover Screws	N	NFE & NSE	
C38	Vent Plug	N	NFE & NSE	
C4	Shaft Assembly	N	LL	
C41	Shaft	Y	FE	5
C42	Locating Keys	N	IR	
C43	Drv End Brg lock	N	IR	
C44	Oil Deflector Ring	N	NFE & NSE	
C45	Shaft Sleeve	N	NFE & NSE	
C46	Sleeve PFTE Gasket	N	IR	
C5	Impeller Assembly	N	LL	
C51	Impeller	Y	FE	4
C52	Impeller Nut	N	IR	
C53	Nut PFTE Gasket	N	IR	
C54	Impeller Wear Ring SS	N	NFE & NSE	
C55	Impeller Wear Ring DS	N	NFE & NSE	
C56	Impeller Neck Ring	N	IR	

The resultant FMEA is based on figure 4-15 and its associated text and is shown in figures 5-13 to 5-16. These analyses result in 13 failure modes, for which functional reference numbers were allocated. In practical RCM situations, these should now be prioritised using the methodology of paragraph 4.3.5. In this case, no such prioritisation is done, given the relatively small sample size. In this case the task analysis will thus be based on all 13 failure modes.

The failure consequence classification is done according to figure 4-23 and is shown in table 5.4. Due to the dangerous product pumped, most of these (critical) failure modes carry a Safety and Environmental Consequence classification.

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Table 5.4: Failure consequence evaluation

FRef	Description	H	HO	S	O	NO
001	Mechanical Seal - barrier fluid pressure too low			X		
002	Mechanical Seal - barrier fluid pressure too high			X		
003	Mechanical Seal - wrong assembly/ installation			X		
004	Mechanical Seal - damage to graphite sealing faces			X		
005	Mechanical Seal - wear			X		
006	Drive Side Ball Bearing - failure			X		
007	Non-drive Side Roller Bearing - failure			X		
008	Impeller - does not rotate				X	
009	Impeller - wear				X	
010	Shaft - snapped				X	
011	Impeller Nut - loose			X		
012	Discharge Cover / Volute - integrity problems			X		

The task analysis is shown in figures 5-17 to 5-19. To illustrate how the methodology is used, the analysis process is described in some detail for a few lines of the analysis table. The first line is used as baseline description:

- Columns 1 and 2 are self-explanatory.
- Column 3 - Relative Risk - this column would carry the relative risk figure for prioritisation purposes (see § 4.3.5) - in this case, we are not using this column as was decided above.
- Column 4 (RC = Risk Check) is checked if the failure mode is to be analysed further due to its high level of relative risk (column 3) - in our case, all our failure modes will be investigated and will thus carry the risk check mark.
- Column 5 shows the Consequence Type, which for our first failure mode was shown to be 'Safety and Environmental' in table 5.4 above.
- Column 6 (Task Type) is completed using an appropriate task analysis tree. In this case the appropriate tree will be Task Decision Tree 1 (figure 4-19 - rigorous tree without truncation - this choice is made by consulting figure 4-23). Because this is an operational issue, lubrication and/or servicing is not applicable but quality improvement is. Refer to tables 4.3 and 4.4 regarding the applicable feasibility characteristics. A quality improvement task is selected, with as content 'Monitor fluid pressure - do a check on barrier fluid pressure (2 700 kPa)' (columns 8 and 9). The technical requirement (table 4.3) is that the task must reduce the risk to a low enough level - the present task will do this in the opinion of the plant personnel.

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Reliability Centred Maintenance Analysis - FMEA

System:	GA-1402 A&B	**Analyst:**	Jasper Coetzee	**Reviewer:**		**Approved:**	
Reference:		**Date:**	2001-09-22	**Rev. No.:**	0	**Page**	1 of 4

System Function: **Quench reflux pump in the VCM (Vinyl Chloride Monomer) plant of Sasol Polymers**

XRef	Item	Function	Functional Failure	Failure Mode	FC	Comments	FRef
C14	Mechanical Seal	To protect people and the environment	Seal leaks	Barrier Fluid pressure too low	☑	Happens when barrier fluid (seal oil) system is not charged to the pre-set pressure of 2700 kPa	001
				Barrier Fluid pressure too high	☑	When barrier fluid is pre-charged to too high pressure	002
				Wrong assembly/ installation	☑		003

FRef	001	002	003	
Local	Product pressure passes O-rings and/or seal faces, damages seal faces, enters seal enclosure.	Damage to both (product side and atmosphere side) seals.	Damage to seals, product enters.	
System	Damage to accumulator	Barrier fluid leak	Damage to accumulator	
Unit	Possibility of venting product to atmosphere.	Possibility of venting product to atmosphere.	Possibility of venting product to atmosphere.	

Figure 5-13: FMEA - GA 1402 A&B Sheet 1

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Reliability Centred Maintenance Analysis - FMEA

System:	GA-1402 A&B	**Analyst:**	Jasper Coetzee	**Reviewer:**		**Approved:**	
Reference:		**Date:**	2001-09-22	**Rev. No.:**	0	**Page**	2 of 4

System Function: Quench reflux pump in the VCM (Vinyl Chloride Monomer) plant of Sasol Polymers

XRef	Item	Function	Functional Failure	Failure Mode	FC	Comments	FRef
C14	Mechanical Seal (continue)	To protect people and the environment	Seal leaks	Damage to graphite sealing faces	☑		004
				Wear	☑	Grooves/marks caused by product entering	005
		To contain the product	Same as above	Same as ref 001 to 005 above, but less critical	☑		
					☑		
					☑		

FRef	**004**	**005**		
Local	Product pushes back face spring mechanism, which 'hangs up'. Product flows through freely.	Product enters		
System	Damage to accumulator	Damage to accumulator		
Unit	Possibility of venting product to atmosphere	Vent product to atmosphere		

Figure 5-14: FMEA - GA 1402 A&B Sheet 2

Reliability Centred Maintenance Analysis - FMEA

System:	GA-1402 A&B	**Analyst:**	Jasper Coetzee	**Reviewer:**		**Approved:**	
Reference:		**Date:**	2001-09-22	**Rev. No.:**	0	**Page**	3 of 4

System Function: Quench reflux pump in the VCM (Vinyl Chloride Monomer) plant of Sasol Polymers

XRef	Item	Function	Functional Failure	Failure Mode	FC	Comments	FRef
C354	Drive Side Bearings	To support pump shaft, faciltate its rotation	Fails to support shaft; fails to facilitate rotation	Wear; seizure*	☑	Both failure modes lead to same effects	006
C372	Non-drive Side Roller Bearing	To support pump shaft, faciltate its rotation	Fails to support shaft; fails to facilitate rotation	Wear; seizure*	☑	Both failure modes lead to same effects	007
C51	Impeller	To pump product	Fails to pump product	Does not rotate	☑	Bearing/external reason related	
				Vane wear	☑		008
				Wear ring wear	☑		009

FRef	**006**	**007**	**008**	**009**
Local	Bearing Failure	Bearing Failure	Does not displace product	Product bypass
System	Shaft failure; product leaks due to mechanical seal failure.	Shaft failure; product leaks due to mechanical seal failure.	No/weak product output	Inefficiency
Unit	Vent product to atmosphere	Vent product to atmosphere	Plant performance degradation	Plant performance degradation

Figure 5-15: FMEA - GA 1402 A&B Sheet 3

Reliability Centred Maintenance Analysis - FMEA

System:	GA-1402 A&B	**Analyst:**	Jasper Coetzee	**Reviewer:**		**Approved:**	
Reference:		**Date:**	2001-09-22	**Rev. No.:**	0	**Page**	4 of 4

System Function: Quench reflux pump in the VCM (Vinyl Chloride Monomer) plant of Sasol Polymers

XRef	Item	Function	Functional Failure	Failure Mode	FC	Comments	FRef
C51	Shaft	To transfer power to impeller	No power transfer	Snapped shaft	☑		010
				Impeller nut loose	☑		011
C11	Discharge Cover	To contain product	Lack of integrity	Wear; Corrosion	☑		012
C21	Volute	To contain product	Lack of integrity	Wear; Corrosion	☑	See FRef 013	

FRef	**010**	**011**	**012**	
Local	No rotation	No effect	Product leak	
System	No product pumped	Gasket between impeller / shaft sleeve fails - leaks between sleeve and shaft - product by-passes mechanical seal.	Product leak	
Unit	Plant production stoppage	Fire hazard	Vent product to atmosphere	

Figure 5-16: FMEA - GA 1402 A&B Sheet 4

The fact that the failure consequences are 'safety and environment' makes financial feasibility of less importance (table 4.4), but the present task fulfils this requirement fully. Because this is a tree without truncation the preventive task types 'On Condition', 'Recondition' and 'Replace' must also be considered, but these are not technically feasible due to the operational nature of the failure mode. The last block in the decision tree then requires that the best task combination be sought, which in this case only consists of this one task.

- Column 7 (Trade-off study number) - no trade-off study is necessary as the financial feasibility is clear.
- Columns 8 and 9 (Task descriptions) - refer to discussion on column 6 above.
- Column 10 (task combination check column) - this task is checked because it is part of the best task combination (see discussion on column 6 above). Following the default analysis (figure 4-23), this is confirmed by a circle around the check block - only tasks with encircled check boxes will be included in the eventual maintenance plan.
- Column 11 (task frequency) - this carries one of the organisation's standard task frequency symbols (in this case 'S') for once per shift. This list of task frequency symbols for the specific organisation is as follows:

Frequency Symbol (F)	Description
S	Once per shift
D	Daily
W	Weekly
M	Monthly
Q	Quarterly
HY	Half Yearly
Y	Yearly
B	Bi-annually
H	Hourly basis (specify period in description)
3Y	Three yearly
6Y	Six yearly

- Column 12 (Trade) is 'O' for 'operator'. The trade list is:

Trade Symbol (T)	Description	Trade Symbol (T)	Description
B	Boilermaker	O	Operator
CM	Condition Monitor	PE	Production Engineer
EN	Engineer	R	Rigger
E	Electrician	W	Welder
F	Fitter		

Reliability Centred Maintenance Analysis - Task Analysis

System:	GA-1402 A&B	**Analyst:**	Jasper Coetzee	**Reviewer:**		**Approved:**	
Reference:		**Date:**	2001-09-22	**Rev. No.:**	0	**Page**	1 of 3

System Function: Quench reflux pump in the VCM (Vinyl Chloride Monomer) plant of Sasol Polymers

FRef	Failure Mode	RR	RC	Cons Type	Task Type	TO	Task	Task Detail	TC	F	T	ST	P	SG
001	Mech Seal - barrier fluid pressure low		☒	S	QI		Monitor fluid pressure	Do a check on barrier fluid pressure (2 700 kPa)	☒	S	O		P	OS
002	Mech Seal - barrier fluid pressure high		☒	S	QI		Repeat of task above	Repeat of task above	☐					
003	Mech Seal - wrong assembly/ installation		☒	S	QI		Improve procedures - see also FRef 011, FRef 012.	Draw up, implement and enforce improved assembly/installation procedures - must solve problem.*	☒		EN			
004	Mech Seal - damage to sealing faces		☒	S	QI		Investigate source of solids	Do a full investigation into the source of light solids in the pumped product - must solve problem.[1]	☒		PE			

* Reinforce this through a quality control plan with checkpoints for critical tolerances and manufacturing quality inspection.

[1] Reinforce this through a quality control plan with checkpoints for achieving success.

Figure 5-17: Task Analysis - GA 1402 A&B Sheet 1

Reliability Centred Maintenance Analysis - Task Analysis

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System: GA-1402 A&B **Analyst:** Jasper Coetzee **Reviewer:** **Approved:**
Reference: **Date:** 2001-09-22 **Rev. No.:** 0 **Page** 2 of 3

System Function: Quench reflux pump in the VCM (Vinyl Chloride Monomer) plant of Sasol Polymers

FRef	Failure Mode	RR	RC	Cons Type	Task Type	TO	Task	Task Detail	TC	F	T	ST	P	SG
005	Mech Seal - Wear		☒	S	OC		Inspect	Do a visual inspection of pump - check for fluid, product leaks.	☒	W	F		P	TW
			☐		Rep		Replace	Replace seal with new unit every 163 days. This brings seal cost down from present R 235,02 / day to R 89,60 /day.	☒	89 days	F		P	
006	Drive Side Bearing Failure		☒	S	LSA		Check	Open vent plug, check oil level, top up, take sample, send for analysis.	☒	M	F		P	TM
			☐		OC		Vibration check	Measure vibration using FFT Analyser	☒	W	CM		P	CW
007	Non-drive Side Bearing Failure		☒	S			Same as for drive side bearing	Same as for drive side bearing	☐					

Figure 5-18: Task Analysis - GA 1402 A&B Sheet 2

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Reliability Centred Maintenance Analysis - Task Analysis

System: GA-1402 A&B **Analyst:** Jasper Coetzee **Reviewer:** **Approved:**

Reference: **Date:** 2001-09-22 **Rev. No.:** 0 **Page** 3 of 3

System Function: Quench reflux pump in the VCM (Vinyl Chloride Monomer) plant of Sasol Polymers

FRef	Failure Mode	RR	RC	Cons Type	Task Type	TO	Task	Task Detail	TC	F	T	ST	P	SG
008	Impeller - Vane wear		☒	O	OC		Check pump performance	Check output pressure, talk to operations personnel.*	☒	W	F		P	TW
009	Impeller - ring wear		☐				Same as 008	Same as 008	☐					
010	Snapped shaft		☒	O			Same as for FRef 006 and 007	Same as for FRef 006 and 007 - otherwise corrective maintenance	☐					
011	Impeller nut loose		☒	S	QI		See FRef 003	See FRef 003 - care should be taken that steps lead to complete elimination of problem.	☐					
012	Wear, corrosion of outer casing		☒	S	QI		See FRef 003	See FRef 003 - inspection standards for inspection of outer casing should be of such high standard that leaks due to wear, corrosion never occurs.	☐					

* If in doubt, switch over to standby pump, check results. If pump performance sub-standard, fit spare unit, send old unit for rebuild.

Figure 5-19: Task Analysis - GA 1402 A&B Sheet 3

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- Column 13 (Set-up type) - see § 4.3.9. In this case, no set-up is required, because of the operational nature of the failure mode, requiring only a visual check.
- Column 14 (Production Indicator) - refer to § 4.3.9 - the present work can be done during production.
- Column 15 (Schedule Group) - This is a unique check, requiring an own schedule group (see the discussion in § 4.3.9). The scheduling groups are:

Schedule Group	Description
CW	Condition Monitor Weekly
CM	Condition Monitor Monthly
OS	Operator once per shift
OW	Operator weekly
TD	Tradesman daily
TW	Tradesman weekly
TM	Tradesman monthly
TQ	Tradesman Quarterly
TY	Tradesman Yearly

Additional comments regarding the task analysis process (figures 5-17 to 5-19) are given in an open tabular format:

FRef	Comment
002	Use RCM Task Decision Tree 2 (figure 4-20) per figure 4-23
003	Use RCM Task Decision Tree 1 (figure 4-19) per figure 4-23 No schedule group as it is a one off project type task
004	Use RCM Task Decision Tree 1 (figure 4-19) per figure 4-23 No schedule group as it is a one off project type task
005	Use RCM Task Decision Tree 1 (figure 4-19) per figure 4-23 Utilise both On Condition and Reconditioning tasks Laplace Test = 1,7321 ≡ Renewal / Moderate Degradation Weibull fit β=1,445; η=40,296 days; Model Accuracy = 90,76% Cost of failure repair, C_f and that of preventive repair, C_p is identical at R 5 500 : thus use based prevention (reconditioning) is not an option. Alternative NHPP fit α_0=-4,662; α_1=0,00303172, Model Accuracy = 88,10%. Cost of repair C_f = R 5 500. Cost of seal replacement C_p=R 9104,50.

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Optimal policy = replace seal every 163 days @ R 89,60 / day
Run to failure policy costs R 235,02 / day.

006 Use RCM Task Decision Tree 1 (figure 4-19) per figure 4-23

007 Repeat of FRef 006

008 Use RCM Task Decision Tree 2 (figure 4-20) per figure 4-23

009 Repeat of FRef 008

010 Use RCM Task Decision Tree 2 (figure 4-20) per figure 4-23
Same as for FRef 006 and 007 - otherwise corrective maintenance

011 Use RCM Task Decision Tree 1 (figure 4-19) per figure 4-23
Extension of FRef 003 - care should be taken that steps lead to complete elimination of problem.

012 Use RCM Task Decision Tree 1 (figure 4-19) per figure 4-23
Extension of FRef 003 - inspection standards for inspection of outer casing should be of such high standard that leaks due to wear, corrosion never occurs.

5.3. Comparison of results

The result of a 'classical' RCM analysis is an array of maintenance tasks, mostly of a preventive nature, grouped together in a logical maintenance plan, which, if rigorously performed, will lead to improved productivity of production machinery. The proposed method widens the scope of RCM somewhat to include repair and non-maintenance quality improvement tasks. This is very compatible with the practices sought by general industry.

Table 5.5 compares the task outputs from RCM 2 (which is really one of the best examples of 'classical' RCM) and the new proposed improved method. For this purpose, use is made of the failure modes identified using the proposed improved technique, as the 'classical' analysis was done using many 'maybe' failure modes. This makes it difficult to compare the two techniques on an even footing - however, the comparison still provides a worthwhile, albeit limited, insight into the relative worth of the two techniques.

A further complication is that it seems as though the RCM 2 analysis was done by a somewhat inexperienced RCM analyst, which makes comparison even more difficult. The various comments should thus not be seen as criticisms of RCM 2, but are primarily aimed at showing the improvement potential of the proposed method above 'classical' RCM and secondarily to show the typical analysis errors made by inexperienced analysts. This again stresses the need for well-trained and experienced analysts.

A full comparison between the proposed technique, 'classical' RCM and the TUE method are left for the closure (chapter 6).

Table 5.5: Comparison between 'Classical' RCM and the Proposed Improved Method

Failure Mode	'Classical' RCM		Proposed Improved Method	
	Task	Comments	Task	Comments
Barrier Fluid pressure too low	Artisan to inspect oil system fittings every morning for leaks.	This is a reactive task.	Operator to do a check on barrier fluid pressure (2 700 kPa) once per shift.	This is a proactive task, which can lead to one of the reactive tasks identified by 'Classical' RCM if necessary.
	Various installation checks, and corrective tasks.	Unfortunately these will have no effect unless transferred to standard installation procedures and training.*		
Barrier Fluid pressure too high	Not identified as failure mode.		Same task as above.	
Wrong assembly / installation of mechanical seal.	Various loosely identified assembly / installation problems. Examples are lines 1A4, 1A8, 1A9, 1A12, 2A3, 2A5, 2B1, 2B2, 3A1 and 3A4 in the seal RCM Decision Worksheet.	Refer to comment marked * above.	Section engineer to draw up, implement and enforce improved assembly / installation procedures - these must be such that they solve the (safety) problems.	Again the approach is very proactive. This approach extends to the assembly / installation of the pump (FRef 011, FRef 012).#

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Table 5.5: Comparison between 'Classical' RCM and the Proposed Improved Method (continued)

Failure Mode	'Classical' RCM		Proposed Improved Method	
	Task	Comments	Task	Comments
Operational damage to the sealing faces of the mechanical seals.	Replace the mechanical seal (reaction).	Refer to lines 1A2 and 1A11 in the seal RCM Information Worksheet (pages 5-38 and 5-39) and the corresponding lines in the RCM Decision Worksheet (page 5-42).	Production engineer to do a full investigation into the source of light solids in the pumped product - must solve problem.	The problem is tackled at its root and the requirement is that it must be solved (proactiveness).
Wear of the mechanical seal faces.	No preventive task identified (line 1A1 on pages 5-38 and 5-42).	Daily visual inspection (line 1A7) should cover this problem. Question is whether daily visual is necessary and practical.	Fitter to do a weekly visual inspection of pump - check for fluid, product leaks	This action does not only cover this failure mode, but is also a very logical act of 'care' for the whole pump installation.
			Replace seal with new unit every 163 days.	This brings seal cost down from present R 235,02 / day to R 89,60 /day.

Table 5.5: Comparison between 'Classical' RCM and the Proposed Improved Method (continued)

Failure Mode	'Classical' RCM		Proposed Improved Method	
	Task	Comments	Task	Comments
Drive Side Bearing Failure	No preventive action apart from 'lubricate as per schedule' (line 1A6, pages 5-35 and 5-37).	Question is: what is schedule? It is certainly something that has to be specified during the RCM analysis?	Fitter to open vent plug monthly, check oil level, top up, take oil sample, send for analysis plus Condition Monitor to measure vibration weekly using FFT Analyser.	Strategy includes two condition based tasks - a weekly vibration analysis and a monthly oil analysis, plus a 'care' check. This should suffice to virtually eliminate bearing caused failures.
Non-drive Side Bearing Failure	Same as above.		Same as above.	
Impeller vane wear.	Corrective Maintenance (line 1A2, pages 5-35 and 5-37).	The failure effect states that this condition can cause serious pump damage - nevertheless, no preventive action is specified.	Fitter to weekly check the pump's output pressure, and talk to operations personnel, and take action based on performance.	This approach will improve the credibility of the maintenance function considerably.
Impeller ring wear.	Same as above.		Same as above.	
Snapped Shaft	Not identified as failure mode, although it has definitely happened before.		Refer to maintenance actions specified for bearing failures. Otherwise Corrective Maintenance	

RCM II - Information Worksheet	**Item** Single Stage Centrifugal Pumps	**No.** 1	**Compiled by:** Owen Meredith	**Date:** 27/11/97	**Sheet** 1
	Component All	**Rev** 0	**Reviewed by:**	**Date:**	**Of** 2

	Function		Functional Failure		Failure Mode (Cause of Failure)	Failure Effect (What happens when it fails)
1	To pump a liquid at a rate Q and at a pressure P	A	Fails to pump at required rate Q and / or pressure P	1	Blocked suction strainer	Dirty liquid blocks strainer, will get low or no discharge and pump will trip on low flow (current).
				2	Worn pump wet parts	Dirty liquid and/or low/high pH will cause wear on pump's internal wetted parts which will adversely affect the pump's Q and P performance and could lead to serious pump damage.
				3	Faulty non-return valve	Dirty liquid (ferric or tars) can cause the valve to stick open, will then get flow through the spare pump, will get poor Q and P performance and can lead to loosening of the spare pump's impeller, OR can cause the valve to stick closed which will trip the motor on low flow.
				4	Pump runs in wrong direction	Caused by incorrect electrical wiring at installation, usually no effect if changed quickly but if left, can lead to serious pump failure as the impeller loosens leading to leak through the sleeve.
				5	Incorrect assembly	Using the incorrect impeller / old, worn or the wrong gaskets / using parts which are of an incorrect material / inaccurate clearances from assembly, these will give the pump poor Q and P performance and will lead to leaks or ultimately serious pump damage.
				6	Bearing failure	Misalignment / lack of lubrication / normal wear and tear / product ingress of bearing / cavitation / assembly errors or wrong bearings installed, all lead to bearing failure; damaged seals; leaks and potentially serious pump failure.
				7	Incorrect electrical settings: high / low / no flow or temperature trips	No protection on the pump can lead to serious pump failure OR overprotection on the pump will stop the pump from reaching it's desired operating condition.

RCM II - Information Worksheet	**Item** Single Stage Centrifugal Pumps	**No.** 1	**Compiled by:** Owen Meredith	**Date:** 27/11/97	**Sheet** 2
	Component All	**Rev** 0	**Reviewed by:**	**Date:**	**Of** 2

	Function		Functional Failure		Failure Mode (Cause of Failure)	Failure Effect (What happens when it fails)
				8	Process instrument failure	If the supply vessel level or pressure instruments fail, the pump will trip on low flow
				9	Worn / corroded / missing orifice in minimum bypass line	Process won't get the desired Q and P and the pump will trip on high flow
				10	Blocked minimum bypass line	Solids blocking the minimum bypass line will cause the pump to trip on low flow.
				11	Isolated bypass	Pump will trip on low flow when main delivery valve is closed.
2	To contain the liquid	A	Fails to contain the liquid	1	Pump leaks due to incorrect assembly	Wrong or worn gaskets used can lead to a leak and potential SHE consequences.
				2	Corroded volute or back plate	If the wrong spares are installed or the process conditions go out of spec (pH), the pump internals could get corroded and lead to a leak, with the aligned SHE consequences.
				3	Failed mechanical seal	Refer to RCM analysis of mechanical seals.

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RCM II - Decision Work-sheet	**Item** Single Stage Centrifugal Pumps	**No.** 1	**Compiled by:** Owen Meredith	**Date:** 27/11/97	**Sheet** 1
	Component All	**Rev** 0	**Reviewed by:**	**Date:**	**Of** 1

Information Reference			Consequence Evaluation				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default Tasks			Proposed Task	Initial Interval	Can be done by
F	FF	FM	H	S	E	O				H4	H5	S4			
1	A	1	Y	N	N	Y	N	N	N				Check strainer for any pump maintenance or if pump trips on low flow	On cond'n	Process
1	A	2	Y	N	N	N	Y						Repair when it breaks	On cond'n	Artisan
1	A	3	Y	N	N	N	Y						Repair when it fails	On cond'n	Artisan
1	A	4	Y	N	N	N	Y						Follow commissioning instructions	Commisioning	Elec/Artisan
1	A	5	Y	N	N	N	Y						Follow assembly procedures	Maintenance	Artisan
1	A	6	Y	N	N	N	Y						Follow installation and assembly procedures, lubricate as per schedule.	As per schedule	Artisan
1	A	7	Y	N	Y		Y						Follow installation procedures else check as per schedule.	Installat'n 6 Monthly	Electrician Artisan
1	A	8	Y	N	Y		Y						Check instruments as per schedule	Schedule	Instrument
1	A	9	Y	N	N	N	Y						Close min. bypass valve in event of low flow, if flow corrects, control min. bypass flow with isolation valve and repair orifice at shutdown.	On cond'n / shut-down	Artisan
1	A	10	N				N	N	N	N	N		Follow low flow trip procedure	On cond'n	Artisan
1	A	11	Y	N	N	N	Y						Follow low flow trip procedure	On cond'n	Artisan
2	A	1	Y	N	N	Y	Y						Follow assembly procedures correctly	Assembly	Artisan
2	A	2	Y	Y			N	N	N				Change wet end materials of construction as required	On cond'n	Artisan
2	A	3	Y	Y			Y						Replace the seal	On cond'n	Artisan

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RCM II - Information Worksheet	**Item** Normal Double Balanced Mechanical Seals	**No.** 1	**Compiled by:** Owen Meredith	**Date:** 12/11/97	**Sheet** 1
	Component All	**Rev** 1	**Reviewed by:**	**Date:**	**Of** 4

	Function		Functional Failure		Failure Mode (Cause of Failure)	Failure Effect (What happens when it fails)
1	To prevent leaks of product to the environment where shaft enters a pump/ agitator casing	A	Fails to seal effectively	1	Normal wear and tear	Lose the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				2	Excessive wear and tear due to dirty product	Lose the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				3	Seal faces jam after pump has stood for a time with dirty product in it's casing	Lose the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				4	Incorrect seal setting	Possible heat generation leading to loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				5	Incorrect 'O' ring used (material)	Lose the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				6	Wrong oil used	Leads to 'O' ring failure and loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak, also results in possible leak of incompatible oil into product stream.
				7	Excessive shaft vibration	Lose the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				8	Seal faces not set square to each other	This is an installation error, you may lose the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.

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RCM II - Information Worksheet	**Item** Normal Double Balanced Mechanical Seals	**No.** 1	**Compiled by:** Owen Meredith	**Date:** 12/11/97	**Sheet** 2
	Component All	**Rev** 1	**Reviewed by:**	**Date:**	**Of** 4

	Function		Functional Failure		Failure Mode (Cause of Failure)	Failure Effect (What happens when it fails)
				9	Incorrect or worn sleeve used	Incorrect seal setting / 'O' ring is ineffective, you then lose the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				10	Incorrect seal face used (material)	Will get excessive wear and tear, heat generation, possible fore risk and will lead to loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				11	Cavitation, pressure fluctuation	Seal faces 'bounce' leading to loss of buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				12	Too much shaft float	Due to the wrong setting on the seal faces, will lose the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				13	Impeller gasket or 'O' ring fails	Seal is in normal, good condition, but product leaks along shaft under sleeve.
2	To maintain a positive pressure (100 kPa higher than pump discharge pressure) on the lubrication system to lubricate the seal faces	A	Fails to maintain a positive pressure	1	Leaking lubrication system fittings	Will get an oil pressure drop leading to loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				2	Worn seal (see 1.A.*)	Lose the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.

Appendix B

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RCM II - Information Worksheet	**Item** Normal Double Balanced Mechanical Seals	**No.** 1	**Compiled by:** Owen Meredith	**Date:** 12/11/97	**Sheet** 3
	Component All	**Rev** 1	**Reviewed by:**	**Date:**	**Of** 4

	Function		Functional Failure		Failure Mode (Cause of Failure)	Failure Effect (What happens when it fails)
				3	Accumulator fails	Bladder fails then the oil system can't fluctuate with temperature or compensate for pressure losses, leading to loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				4	Nitrogen pressure drops	Oil pressure drops, leading to loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				5	Non-return fails on the oil system	Oil pressure drops, leading to loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				6	Compression plate gasket fails	Oil leaks to the environment, oil pressure drops, leading to loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
		B	Fails to provide lubrication to the faces	1	Incorrect oil used	Oil pressure drops, leading to loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				2	Oil pressure drops away, see 2.A.*	Lose the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				3	Air trapped in oil system	Will have no or ineffective oil circulation, temperature increase, pressure increase, excessive leakage of oil into product side, and ultimately loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.

RCM II - Information Worksheet	**Item** Normal Double Balanced Mechanical Seals	**No.** 1	**Compiled by:** Owen Meredith	**Date:** 12/11/97	**Sheet** 4
	Component All	**Rev** 1	**Reviewed by:**	**Date:**	**Of** 4

	Function		Functional Failure		Failure Mode (Cause of Failure)	Failure Effect (What happens when it fails)
3	To cool the seal faces	A	Does not effectively cool the seal faces, allows heat generation on the faces	1	Incorrect pump scroll used	Will have no or ineffective oil circulation, temperature increase, pressure increase, excessive leakage of oil into product side, and ultimately loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				2	Cooling water drops away	Temperature increase, pressure increase, excessive leakage of oil into product side, and ultimately loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				3	Cooling fins blocked or dirty	Temperature increase, pressure increase, excessive leakage of oil into product side, and ultimately loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
				4	Air trapped in the oil system	Will have no or ineffective oil circulation, temperature increase, pressure increase, excessive leakage of oil into product side, and ultimately loss of the buffer liquid pressure leading to product entering the buffer liquid and ultimately to an environmental leak.
4	To provide a pressure and level alarm	A	Fails to alarm when required	1	Instrument failure	This is a hidden failure which could lead to an environmental excursion

RCM II - Decision Work-sheet	**Item** Normal Double Balanced Mechanical Seals	**No.** 1	**Compiled by:** Owen Meredith	**Date:** 12/11/97	**Sheet** 1
	Component All	**Rev** 1	**Reviewed by:**	**Date:**	**Of** 2

Information Reference			Consequence Evaluation				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default Tasks			Proposed Task	Initial Interval	Can be done by
F	FF	FM	H	S	E	O				H4	H5	S4			
1	A	1	Y	N	N	N	Y						When oil pressure drops, replace the mechanical seal	On cond'n	Artisan
1	A	2	Y	N	N	N	Y						When oil pressure drops, replace the mechanical seal	On cond'n	Artisan
1	A	3	Y	N	N	N	Y						Drain the pump when not in use	On cond'n	Process
1	A	4	Y	N	N	N	Y						Make seal setting a hold point during seal installation procedure	Seal install'n	Artisan
1	A	5	Y	N	N	N	Y						When oil pressure drops, replace the mechanical seal	On cond'n	Artisan
1	A	6	Y	N	N	N	Y						'O' ring correctness to be checked	Delivery	Spares Co.
1	A	7	Y	N	N	N	Y						Do visual inspections / Do vibration analyses	Morning / Monthly	Artisan
1	A	8	Y	N	N	N	Y						Make the face 'squareness' a hold point in the assembly procedure	Seal install'n	
1	A	9	Y	N	N	N	Y						Make the sleeve correctness a hold point in the assembly procedure	Seal install'n	
1	A	10	Y	N	N	N	Y						Seal face correctness to be checked	Delivery	Spares Co.
1	A	11	Y	N	N	N	Y						When oil pressure drops, replace the mechanical seal	On cond'n	Artisan
1	A	12	Y	N	N	N	Y						Make shaft float a hold point in the assembly procedure	Seal install'n	Artisan

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Information Reference			Consequence Evaluation				H1 S1 O1 N1	H2 S2 O2 N2	H3 S3 O3 N3	Default Tasks			Proposed Task	Initial Interval	Can be done by
F	FF	FM	H	S	E	O				H4	H5	S4			
1	A	13	Y	N	N	N	Y						Repair the pump by replacing the gaskets / 'O' rings	On cond'n	Artisan
2	A	1	Y	N	N	N	Y						Inspect oil system fittings	Mornings	Artisan
2	A	2	Y	N	N	N	Y						When oil pressure drops, replace the mechanical seal	On cond'n	Artisan
2	A	3	Y	N	N	N	Y						Check accumulator pressure when installing pump	Pump installat'n	Artisan
2	A	4	Y	N	N	N	Y						None		
2	A	5	Y	N	N	N	Y						Check that oil system holds pressure at pump installation	Pump installat'n	Artisan
2	A	6	Y	N	N	N	Y						Replace the gasket	On cond'n	Artisan
2	B	1	Y	N	N	N	Y						Oil correctness to be checked before filling	On cond'n	Artisan
2	B	2	Y	N	N	N	Y						Bleed oil system of air	Pump installat'n	Artisan
2	B	3	Y	N	N	N	Y						Inspect and top up when alarm sounds	At alarm	Artisan
3	A	1	Y	N	N	N	Y						Make scroll correctness a hold point in the assembly procedure	Seal installat'n	Artisan
3	A	2	Y	N	N	N	Y						Check temperature on gauge at pump	Mornings	Artisan
3	A	3	Y	N	N	N	Y						Inspect cleanliness of fins	Mornings	Artisan
3	A	4	Y	N	N	N	Y						Bleed oil system of air	Pump installat'n	Artisan
4	A	1	N				N	N	N	Y			Check trips and alarms	??????	Instrument

Chapter 6: Conclusion

The preceding four chapters were devoted to:

1. Defining the problems in the present definition and application of RCM.
2. Presenting a view of the current state of the methodology and related methodologies from present texts and papers.
3. Developing an improved version of the methodology, using a mixture of reported experience, whatever research exists on the subject, related techniques and own experience.
4. Testing the resultant methodology by application to a physical system and comparing the result with that of an existing RCM analysis for the system.

In conclusion, it now remains to compare the resultant methodology with 'classical' RCM and other methods, to assess whether a better result will be achieved. The comparison of the RCM analysis, performed using the proposed improved methodology, with that of a 'classical' RCM analysis in chapter 5 already indicated the superiority of the new methodology. However, that comparison was hampered by the fact that the 'classical' analysis was not very well executed, as well as that the 'classical' analysis was not done specifically for the GA-1402 system, but rather for a generic high risk pump with double mechanical seal.

In this chapter, the various methodologies are compared for functionality rather than for a specific analysis viewpoint.

6.1. Critical assessment of result

The main objective of any doctoral research is to contribute significantly to the knowledge base in the particular subject area. An assessment of the result of the present research and the resulting thesis will thus have to establish whether a meaningful contribution has in fact been made.

To try to establish the relative worth of the research and development presented in this thesis, it will be compared as a full product[1] to the various avail-

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[1] That is, including all the functionality present in present day versions of 'RCM', including that of Nowlan & Heap [1978], Moubray [1991], Smith [1993], MSG-3 [1993], Coetzee [1997/2] and the SAE Standard [1999].

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able versions of RCM and related techniques. In summary, the comparison is done 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[2].
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]}.

A detailed comparison is given in table 6.1. Although it is clear from this table that the thesis makes contributions in many areas, some of them are very logical developments of the work contained in the various sources, as well as an integration of the various ideas. On the other hand, the thesis does make significant contributions in the following areas:

- The 'funnelling' approach - this is a major contribution of the present research to the knowledge base of the RCM methodology. It ensures that the RCM effort is concentrated on the most important failure modes of the organisation. It thus solves one of the major problem areas in the industrial application of RCM. Refer to the discussion in paragraphs 4.3.2.2, 4.3.2.3, 4.3.2.5 and 4.3.5 in this regard. This solves the problem identified in paragraph 4.1, factor c.

- The principle of progressive application (widening of the 'funnel'). This is a very logical progression from the 'funnelling' approach, as it makes sense to further improve on the initial benefit that is obtained from RCM analyses, following the application of the 'funnel'. Refer to paragraphs 4.3.2.3 and 4.4 in this regard.

- The second major contribution of this thesis lies in the inclusion of the Quality Improvement task in the task selection tree. In the application of the analysis technique in chapter 5, it identified no less than four opportunities for improving procedures of both operations and maintenance work to proactively prevent failure from occurring. This is not an original contribution of this thesis, as Harris (1985) identified the need, but it will certainly increase the effectiveness and relevance of RCM analyses greatly.

- Another contribution of significance is in the area of task packaging, which is an area totally neglected by all authors except Gits (1984). This area has never been properly addressed in any RCM text, and this chore is mostly left to the maintenance planner who has to

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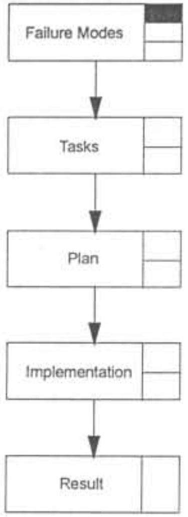
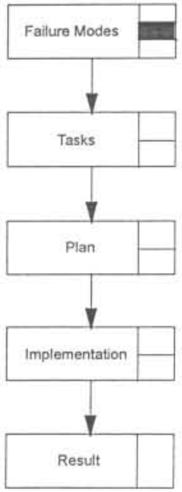
[2] Nowlan & Heap [1978], Moubray [1991], Smith [1993], Coetzee [1997/2].

Table 6.1: Functional comparison between various RCM techniques

Context[1]	Function	Sub-function in new proposed method	Nowlan & Heap (1978)	Moubray (1991)	Smith (1993)	MSG-3 (1993)	Coetzee (1997/2)	SAE JA1011 (1999)	Gits (1984)	Kelly (1997)	Comments
	Selection of application areas (§ 4.3.2)	Identification of major systems (§ 4.3.2.1)			X		X				Nowlan & Heap did not need this, as they did the analysis at the major systems level.
		Choice of units for analysis (§ 4.3.2.2)			X		X			X	
		Progressive application (§ 4.3.2.3)									None of the authors use this principle, primarily because they do not limit the choice of units for analysis (see previous line). Smith and Coetzee limit the number of units for analysis, but do not propose a widening of the choice process later on.
		Partitioning (§ 4.3.2.4)	X	X		X	X		X	X	Moubray uses plant register, Smith only works with functional decompositioning
		Prioritisation of MSI's (§ 4.3.2.5)					X				
	Information assembly (§ 4.3.3)				X	X				X	Most of the other authors most probably assume this step.

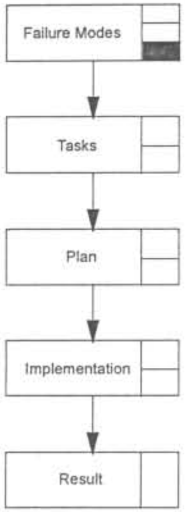
[1] Refers to context in terms of the model presented in figure 4-7

Table 6.1: Functional comparison between various RCM techniques (continued)

Context[1]	Function	Analysis columns	Nowlan & Heap (1978)[2]	Moubray (1991)	Smith (1993)	MSG-3 (1993)	Coetzee (1997/2)	SAE JA1011 (1999)	Gits (1984)	Kelly (1997)[4]	Comments
	Identification of failure modes (§ 4.3.4)	Item cross-reference		X	X				X		
		Item		X	X	X	X		X		
		Function		X	X	X	X				
		Functional Failure		X	X	X	X				
		Failure Mode		X	X	X	X		X		
		Functional Check									Smith does not have an actual functional check, but he implies one in his methodology.
		Failure Mode Cross Reference		X							
		Local Effects		X[3]	X						
		System Effects			X						
		Unit Effects			X						

[1] Refers to context in terms of the model presented in figure 4-7
[2] Nowlan & Heap did not address the FMEA at all - refer to § 3.2.4
[3] Moubray combined the three effects levels in one column
[4] Kelly does not use an FMEA at all - he rather relies on the manufacturer's unit life plan or an engineering study of the item and its known failures.

Table 6.1: Functional comparison between various RCM techniques (continued)

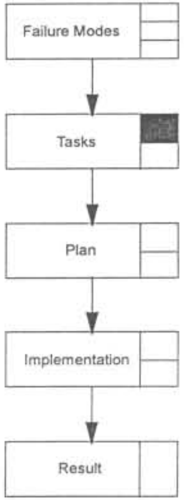
Context[1]	Function	Sub-function in new proposed method	Nowlan & Heap (1978)	Moubray (1991)	Smith (1993)	MSG-3 (1993)	Coetzee (1997/2)	SAE JA1011 (1999)	Gits (1984)	Kelly (1997)[3]	Comments
	Relative criticality of failure modes	Prioritisation of failure modes (§ 4.3.5)							X		This is a facet of RCM which is not addressed by most authors. The only authors who prescribes the use of Criticality Analysis is Anderson and Neri (1990), based on the requirements of MIL-STD-1629A (1980). Jones (1995) proposes the use of quantitative risk techniques for this purpose.
		Classification of failure modes (§ 4.3.6)	X	X	X	X	X		X[2]		This is largely the original basis of RCM (the 'decision tree approach' that Matteson (1989) refers to).

[1] Refers to context in terms of the model presented in figure 4-7

[2] Gits does not have a separate failure classification step, but it is inherent to his task selection process (see figure 3.26).

[3] Kelly does not use failure modes (see second page of table 6.1) or classification.

Table 6.1: Functional comparison between various RCM techniques (continued)

Context[1]	Function	Sub-function in new proposed method	Nowlan & Heap (1978)	Moubray (1991)	Smith (1993)	MSG-3 (1993)	Coetzee (1997/2)	SAE JA1011 (1999)	Gits (1984)	Kelly (1997)	Comments
	Task Selection (§ 4.3.7)	Lubrication/Servicing Task included in tree				X					
		No truncation for failure modes with safety consequences			X	X					
		Inclusion of Quality Improvement task									This task type, after Harris (1985), is a completely new addition to the present RCM task selection structure.
		Failure Finding task at top of tree in hidden consequences case				X					
		Choice of best combination of tasks for failure modes with safety consequences			X	X			X		
		Improvements to technical/economical feasibility measures (§ 4.3.7.2)									These are all changes which includes ideas from previous authors, but are changed/improved to such an extent that no one of the other authors' work conform to this standard
		Improvements to technical selection criteria (§ 4.3.7.3)									
		Improvements to default tasks (§ 4.3.7.4)									
		Improvements to documentation standards (§ 4.3.7.5)									

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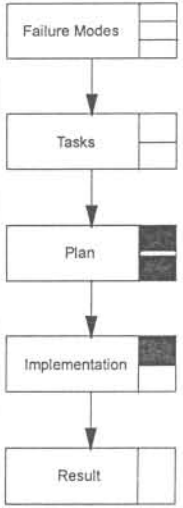
[1] Refers to context in terms of the model presented in figure 4-7

Table 6.1: Functional comparison between various RCM techniques (continued)

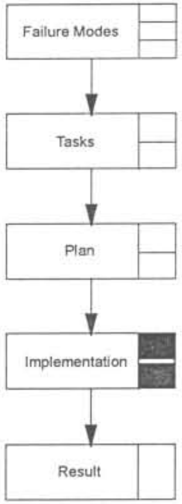
Context[1]	Function	Sub-function in new proposed method	Nowlan & Heap (1978)	Moubray (1991)	Smith (1993)	MSG-3 (1993)	Coetzee (1997/2)	SAE JA1011 (1999)	Gits (1984)	Kelly (1997)	Comments
	Task Frequencies (§ 4.3.8)	Variety of techniques applied in a scientific way	X	X	X		X				Some authors, such as Moubray and Smith are somewhat simplistic in their approach to task frequencies. One gets the impression that they shy away from the analysis involved. Moubray is the only author with a good approach to the calculation of Failure Finding Task frequencies.
	Task Packaging (§ 4.3.9)	Grouped per plant / system / machine		X[2]					X[3]		
		Grouped per set-up type							X[3]		
		Grouped per task frequency class	X	X[2]					X[3]		
		Grouped per trade		X[2]					X[3]		
		Grouped according to production requirements		X[2]					X[3]	X	
	Critical Assessment of resulting program (§ 4.3.10)	Good audit approach based on the work of Nowlan & Heap (1978) - see § 3.2.10	X								Coetzee and Moubray identifies the need for auditing of the resultant program, but does not handle it in any proper depth.

[1] Refers to context in terms of the model presented in figure 4-7

[2] Moubray's handling of task packaging shows that he understands the process, but he does not provide the user with a methodology.

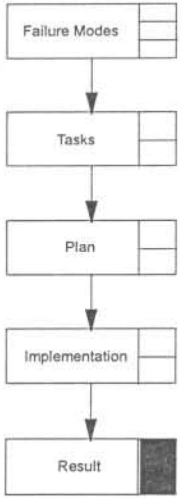
[3] Gits' scheme is quite elaborate, but difficult to understand.

Table 6.1: Functional comparison between various RCM techniques (continued)

Context[1]	Function	Sub-function in new proposed method	Nowlan & Heap (1978)	Moubray (1991)	Smith (1993)	MSG-3 (1993)	Coetzee (1997/2)	SAE JA1011 (1999)	Gits (1984)	Kelly (1997)	Comments
	Application Structure and Methods (§ 4.4)	Using more 'intuitive' traditional ways of establishing a maintenance plan for the '99' % of equipment for which RCM is not applied (fig 4-24)								X	Kelly is the only author that addresses this way of setting up a maintenance plan, but then for 100% of the equipment, thus excluding the optimisation afforded by RCM application.
		Progressive application (progressive increase of the 'funnel' opening)									None of the authors uses this principle, primarily because they do not limit the choice of units for analysis. Smith and Coetzee limit the number of units for analysis, but then do not propose a later widening of the choice process. Also refer to the first page of table 6.1 above.
		Continuous Improvement through closed loop application of RCM based on best experience (RCM living programme)			X						Smith is the only author stressing the importance of continuous improvement of the maintenance plan.

[1] Refers to context in terms of the model presented in figure 4-7

Table 6.1: Functional comparison between various RCM techniques (continued)

Context[1]	Function	Sub-function in new proposed method	Nowlan & Heap (1978)	Moubray (1991)	Smith (1993)	MSG-3 (1993)	Coetzee (1997/2)	SAE JA1011 (1999)	Gits (1984)	Kelly (1997)	Comments
	Organisational issues (§ 4.5)	Application of RCM in the full context of maintenance organisation realities.									There is very much a dearth of understanding of the full complexity of applying RCM in full maintenance organisational context.
		RCM training requirements planning guidelines.									The focus is much more on application than on the training required, although the various texts certainly support and are used in the training effort (but with a very simplistic approach to training).
		Use of a steering committee to steer the RCM effort.	X			X					
		The use of a Management Champion to provide and conserve energy for the process.									
		Use of a well trained RCM facilitator.		X			X				
		Use of an independent reviewer as auditor	X	X							
		Use of failure data as important source of information.	X				X				
		Support of the RCM process through inclusion of RCM related requirements into CMMS databases.									

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[1] Refers to context in terms of the model presented in figure 4-7

try to do the task structuring as well as possible without any particular knowledge regarding task packaging. Gits (1984) has developed an elaborate, but virtually unintelligible, scheme for task packaging. Nevertheless, his thoughts were used very profitably in the development of the task packaging procedure proposed by this thesis. Refer to paragraphs 3.2.9 and 4.3.9 in this regard.

- The combination of the RCM maintenance plan (for '1%' of the failure modes) with the more intuitive conventional plan for the remaining 99% of failure modes to achieve a best maintenance plan for the organisation. This, combined with the progressive application principle depicted above, leads to a maintenance plan that is subject to continuous improvement and will produce an increasing contribution to the profit of the organisation.

- A very important contribution follows from the application of sound management principles in the implementation of RCM. These include understanding the position of RCM in the organisational context (§ 4.2 and 4.5.1), proper structuring of RCM training (§ 4.5.2), use of mechanisms such as a Steering Committee (§ 4.5.3), a management champion (§ 4.5.4), a well trained facilitator (§ 4.5.5) and proper reviewing of the resultant plan (§ 4.5.6). Good failure information support will also be ensured if the requirements of RCM regarding failure data are incorporated into the company's CMMS database (§ 4.5.7 & 4.5.8).

- The most important contribution of the present thesis to the RCM methodology most probably lies in blending concepts from different RCM authors and those of related techniques, together with the innovations listed above into one logical whole. It will certainly assist users in applying the methodology more effectively and obtaining better results for the organisation. This includes the various new diagrams that assist the user in understanding the full scope and use of the methodology. These include:
    - Figure 4-9: Outline of RCM methodology
    - Figure 4-12: Item breakdown decision diagram
    - Figure 4-13: RCM prioritisation processes
    - Figure 4-14: Summarised RCM prioritisation processes
    - Figures 4-19 to 4-22: RCM Task Decision Trees
    - Figure 4-23: RCM Decision Tree
    - Table 4.3: Technical Feasibility characteristics
    - Table 4.4: Economical Feasibility characteristics
    - Figure 4-27: RCM in context
    - Figure 4-28: RCM task selection process summary
    - Figure 4-29: RCM progressive application
    - Table 4.6: Suggested RCM training requirements

RCM is a core methodology in ensuring that the organisation can achieve World Class results from its production equipment. The proposed new RCM approach (methodology), can play a very important part to achieve this goal. It will specifically make a major contribution in ensuring that the organisation's maintenance effort is as proactive as possible.

6.2. Recommendations

In the approach and research of this thesis, the premise was to do a total study of the RCM methodology and, as far as is possible, propose a methodology without any inadequacies. This was largely achieved.

In § 3.2.7.3, it was envisaged to develop a task selection 'decision diagram for dummies'. This goal was not achieved. It is extremely difficult to achieve this, while remaining within the constraints imposed by proper reliability practice. It is nevertheless important to reach this goal, to make RCM more accessible to the average maintenance practitioner.

As was stated in § 4.3.8, it is not within the scope of this thesis to investigate and research better methods for the choice of task frequencies. This is the field of Operations Researchers. Although much work is done in this area, it is often done from a theoretical angle, without any consideration for the maintenance practicalities. One of the greatest concerns is that the maintenance function often has to work with a scarcity of data, while operations researchers tend to assume that there are ample data available for the application of their models. Operations Researchers also tend to think simplistically or try to make as many as possible simplifying assumptions, which does not serve the practical maintenance's purpose. A wide range of decision-making models is needed to ensure optimal RCM task and frequency decisions. Refer to table 4.5 for a listing of the required models.

As was identified in paragraph 4.5.8, it is necessary that Computerised Maintenance Management Systems start adding RCM facilities to their functionality and especially to their databases. There are a number of RCM computer packages, but they are all standalone systems with little or no interfacing facilities with CMMS's. These systems also do not address the full complexity of the RCM process as set forth in this thesis.

The changes proposed and set forth here should be incorporated into the SAE standard [SAE J1011 (1999)]. Furthermore, an ISO standard should be produced as part of an international strategy for proper maintenance standards. The RCM leaders should take the leadership in this action. This will entail burying their differences and developing a single standard for the maintenance community.

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