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 <u>not</u> *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 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.

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.

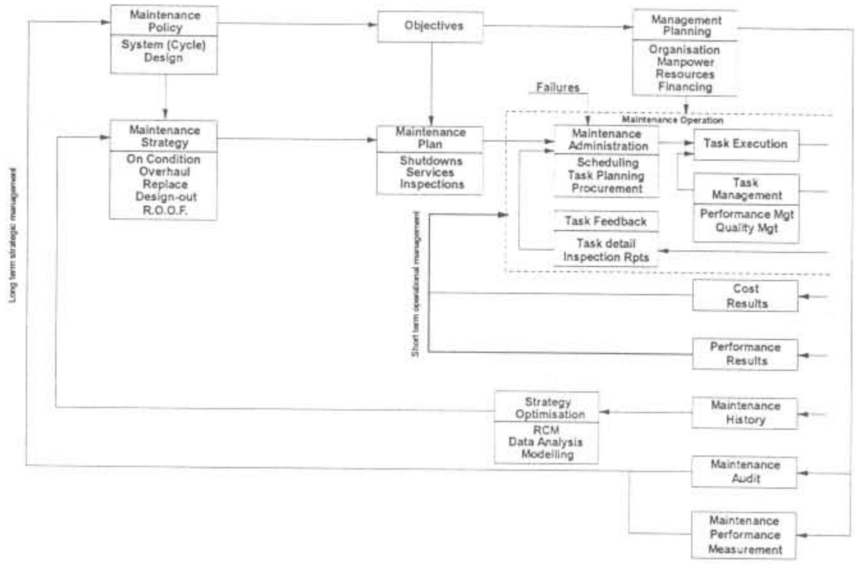

Figure 4-1: The Maintenance Cycle model

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

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

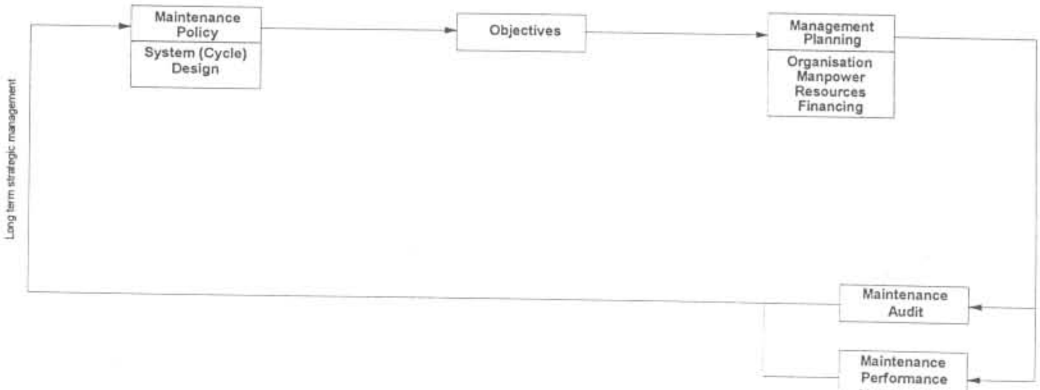

Figure 4-2: The outer (managerial) sub-cycle

- 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).

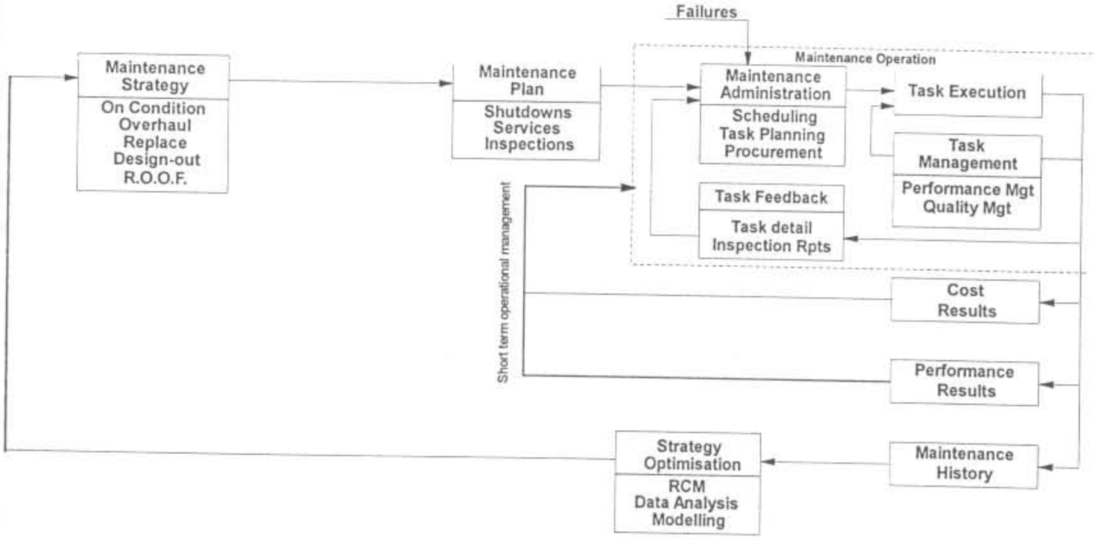

Figure 4-3: The inner (operational) sub-cycle

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:

- 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.

- 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.

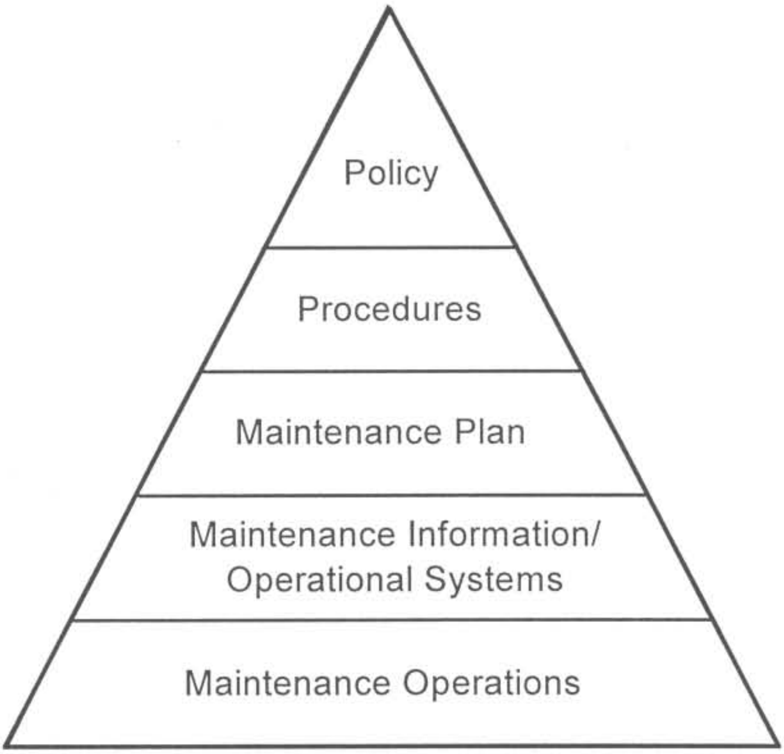

Figure 4-4: Maintenance Functional Hierarchy

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 k^{th}) maintenance situation (such as a single piece of equipment to be maintained) can then be calculated from:

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

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:

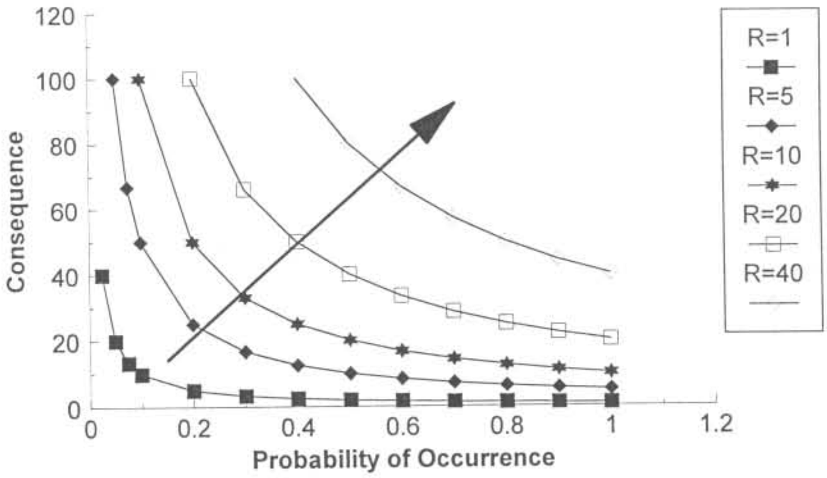

Figure 4-5: Increasing risk

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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.

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)].

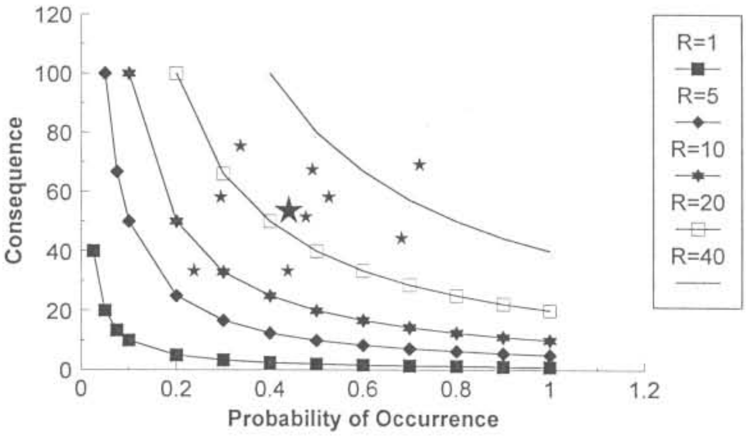

Figure 4-6: Risk plots

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.

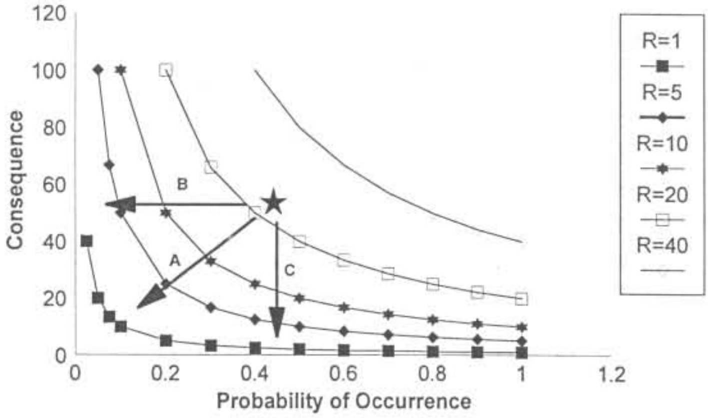

Figure 4-7: Directions of risk reduction

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:

(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.

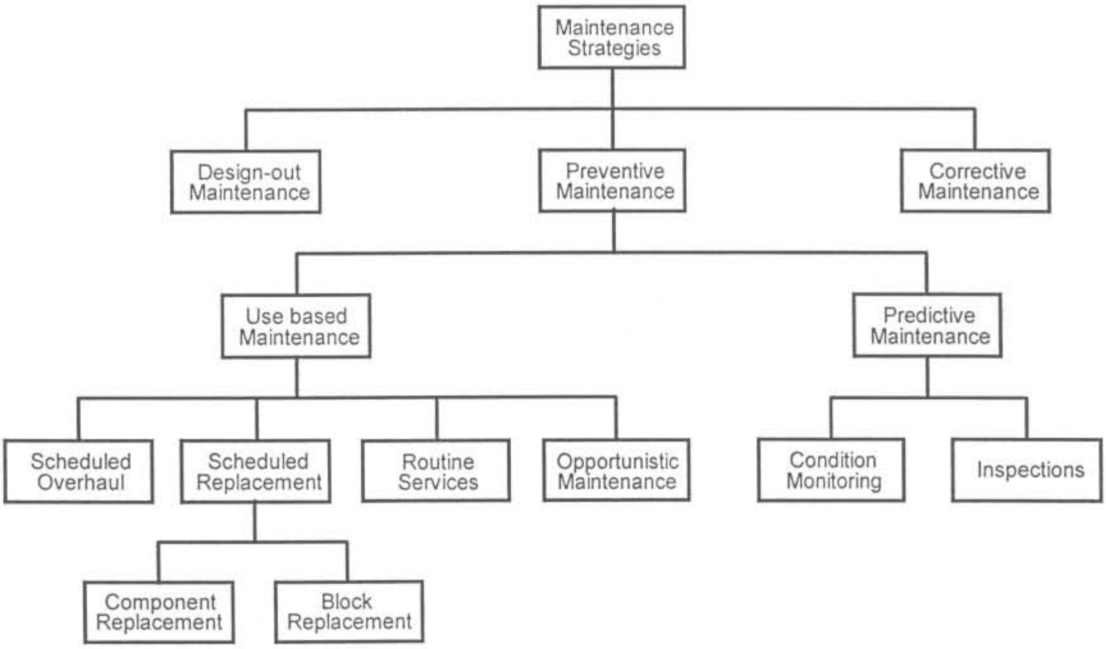

Figure 4-8: Maintenance Strategy Tree

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:

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 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.

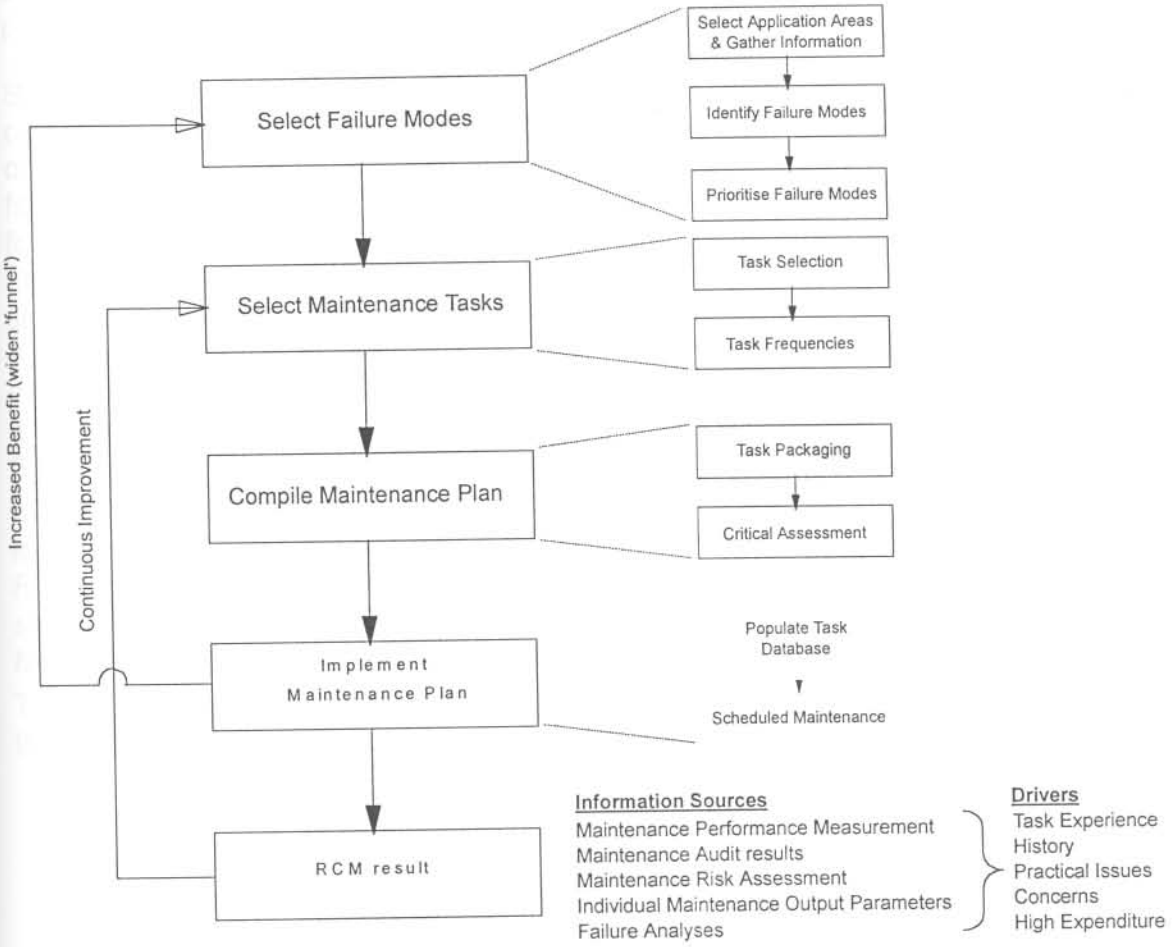


Figure 4-9: Outline of RCM process

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).

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.

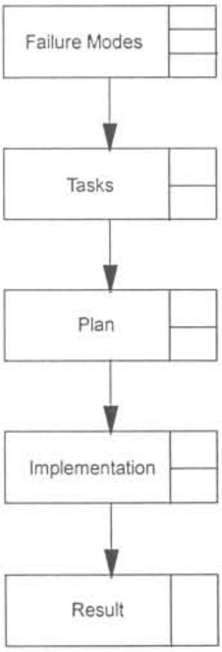
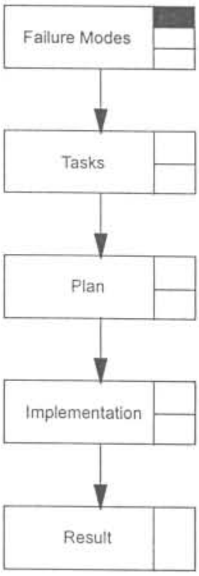


Figure 4-10: Tracking Diagram

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 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.

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.

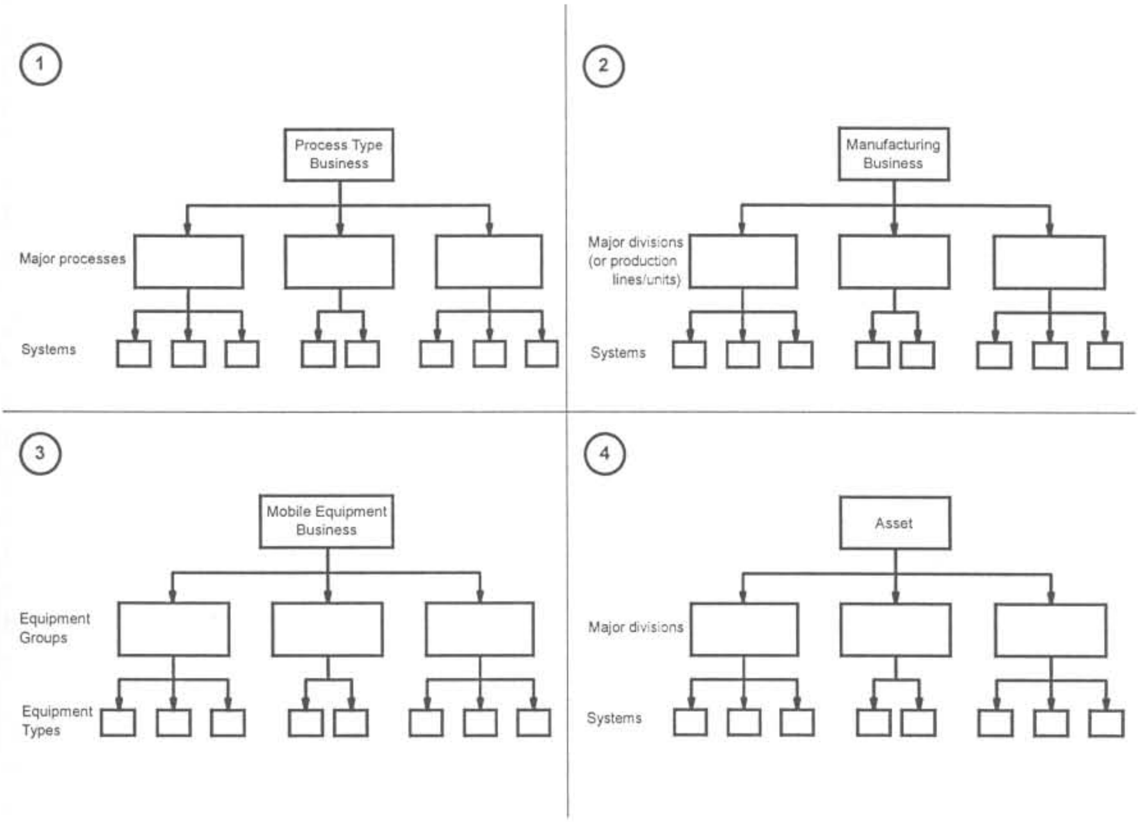


Figure 4-11: Identification of major systems for some business types

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.

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.

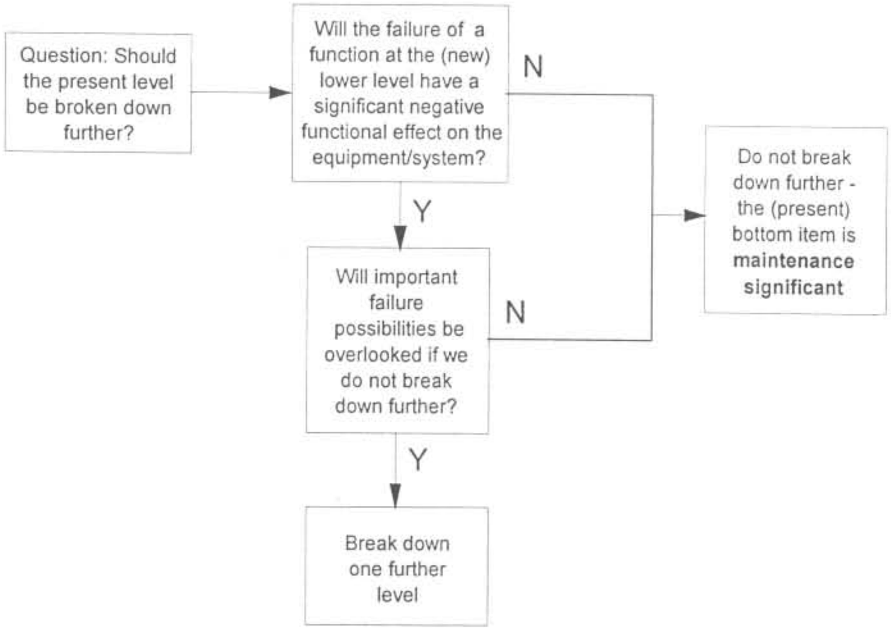

Figure 4-12: Item breakdown decision diagram

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 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.

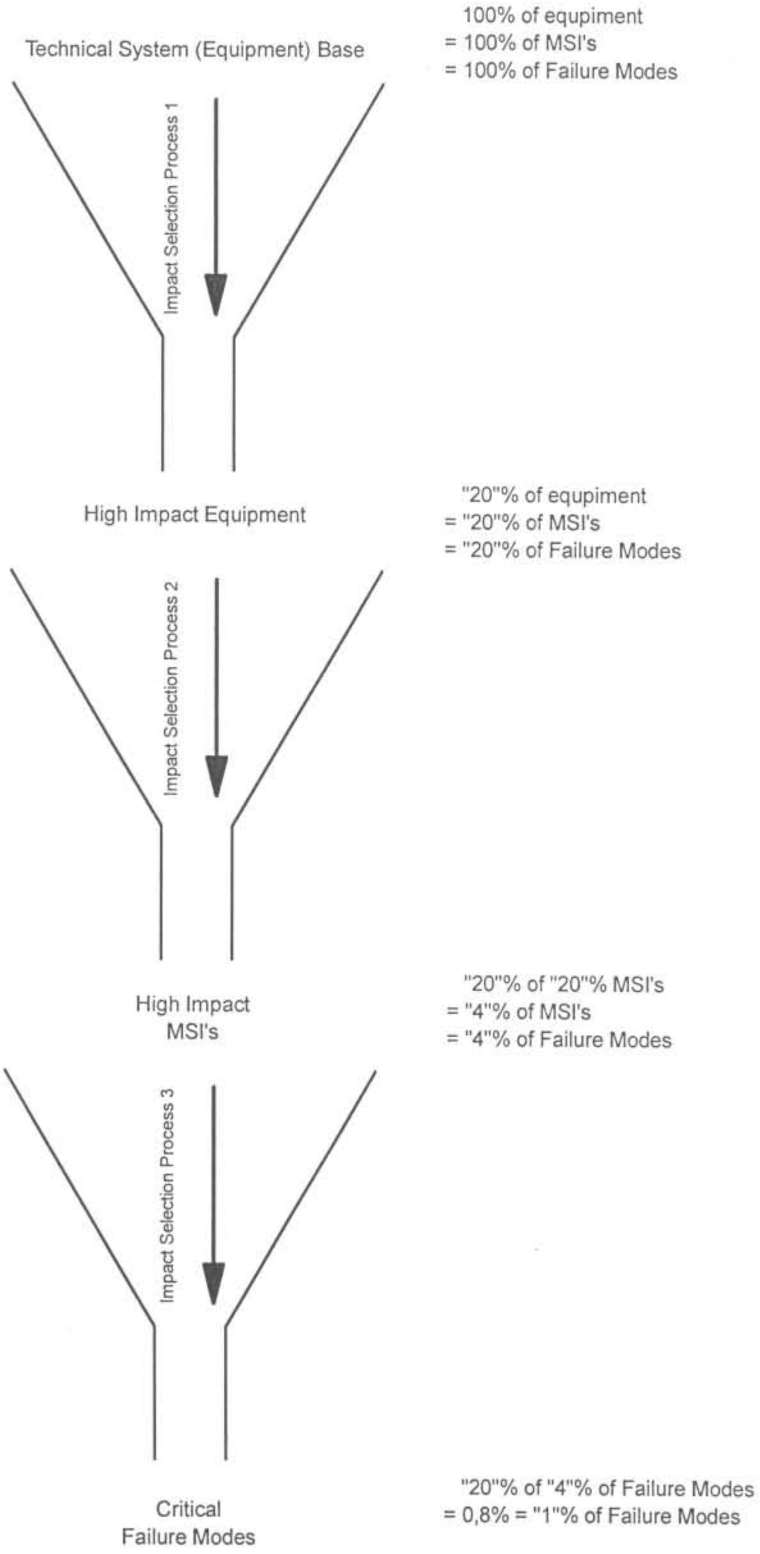


Figure 4-13: RCM prioritisation processes

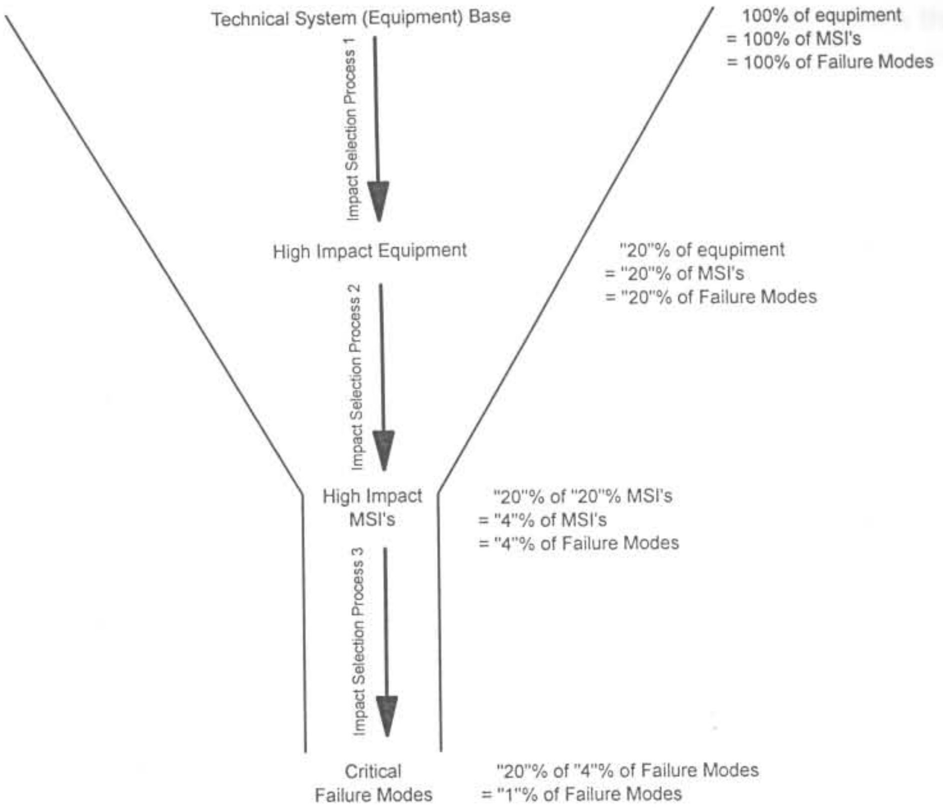
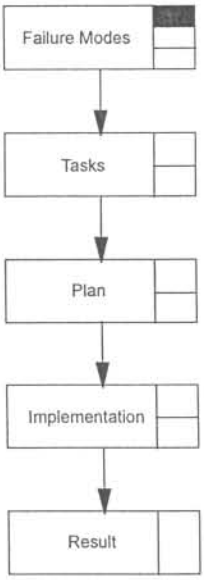


Figure 4-14: Summarised RCM prioritisation processes

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

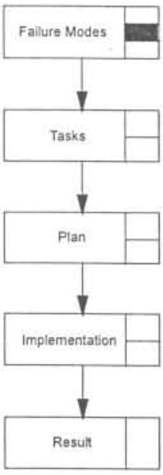
General business operation	Asset-specific information	Maintenance information
Process flow diagrams	Design specifications	Present maintenance plan
Operations manuals	System schematics	Failure data
Operational procedures	Assembly drawings	Maintenance instructions
Asset register	Modification history	Maintenance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



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				

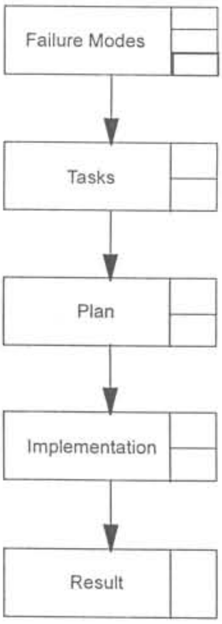
Figure 4-15: RCM FMEA analysis sheet

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).*

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

- % 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:

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

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.

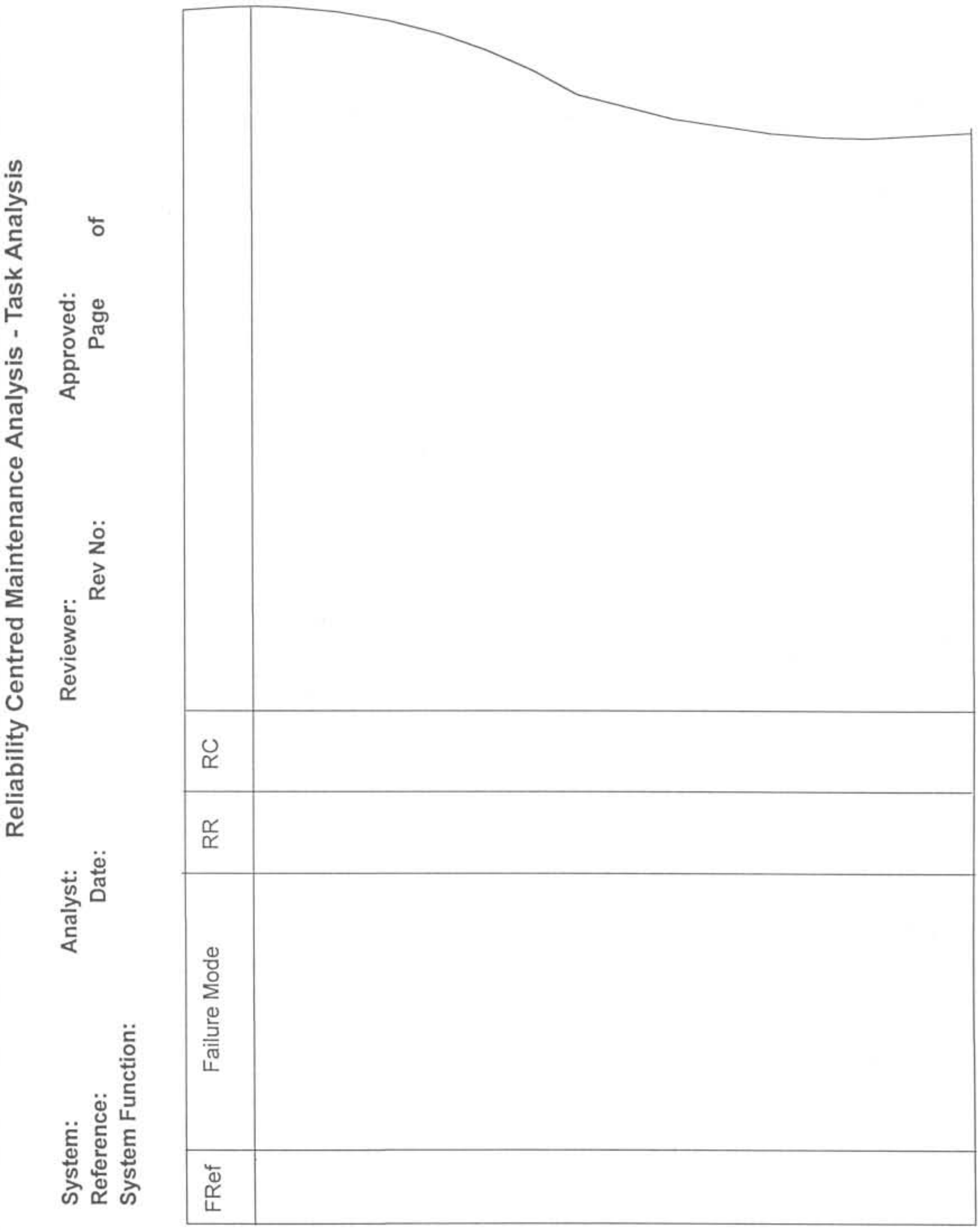
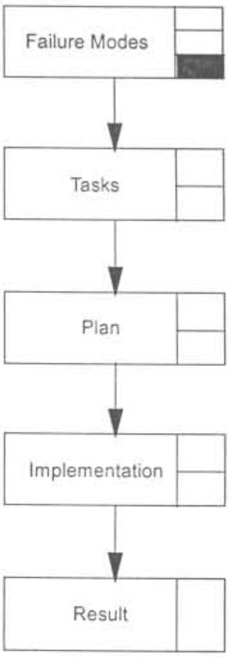


Figure 4-16: RCM Failure Mode Prioritisation

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 substructure. 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.

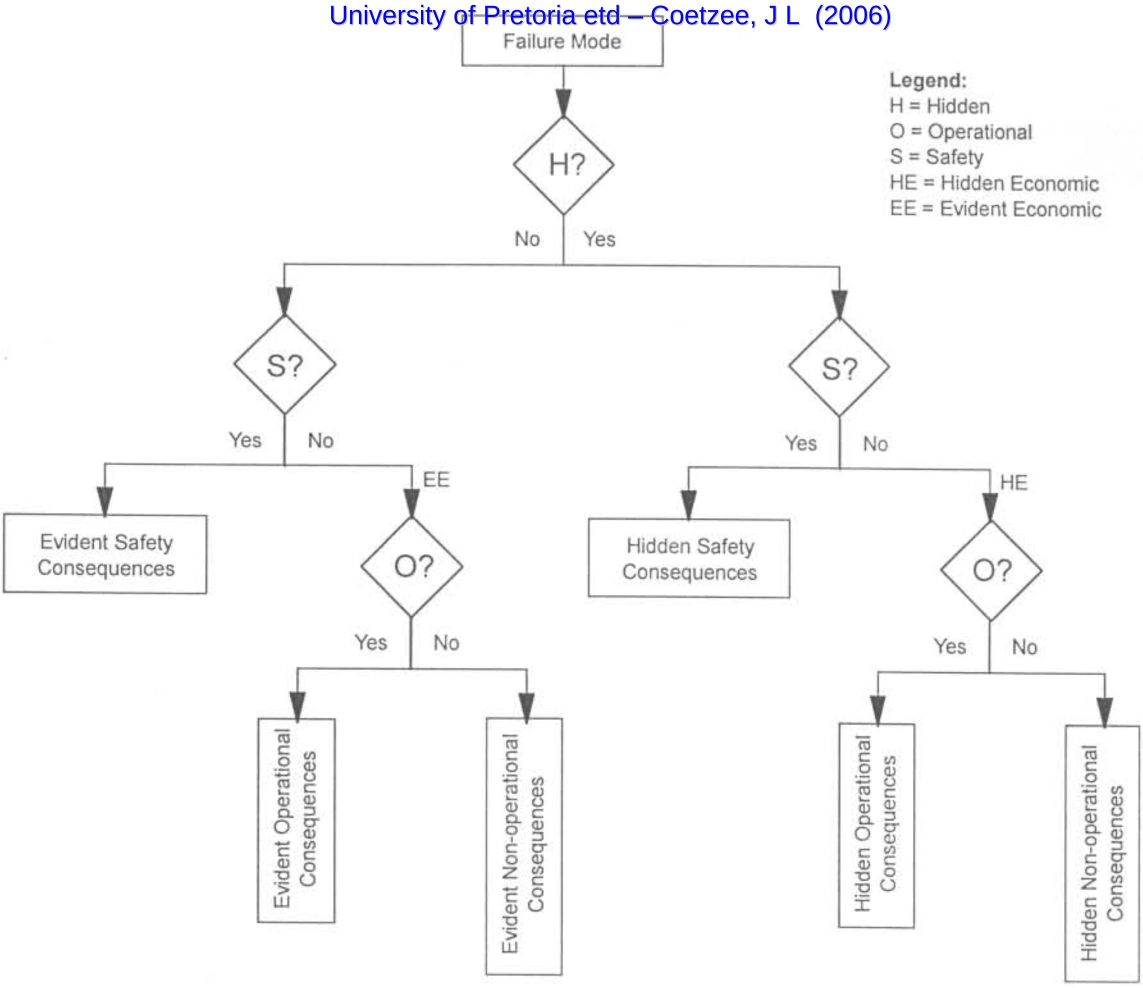


Figure 4-17: RCM inherent Failure Mode Classification structure

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).

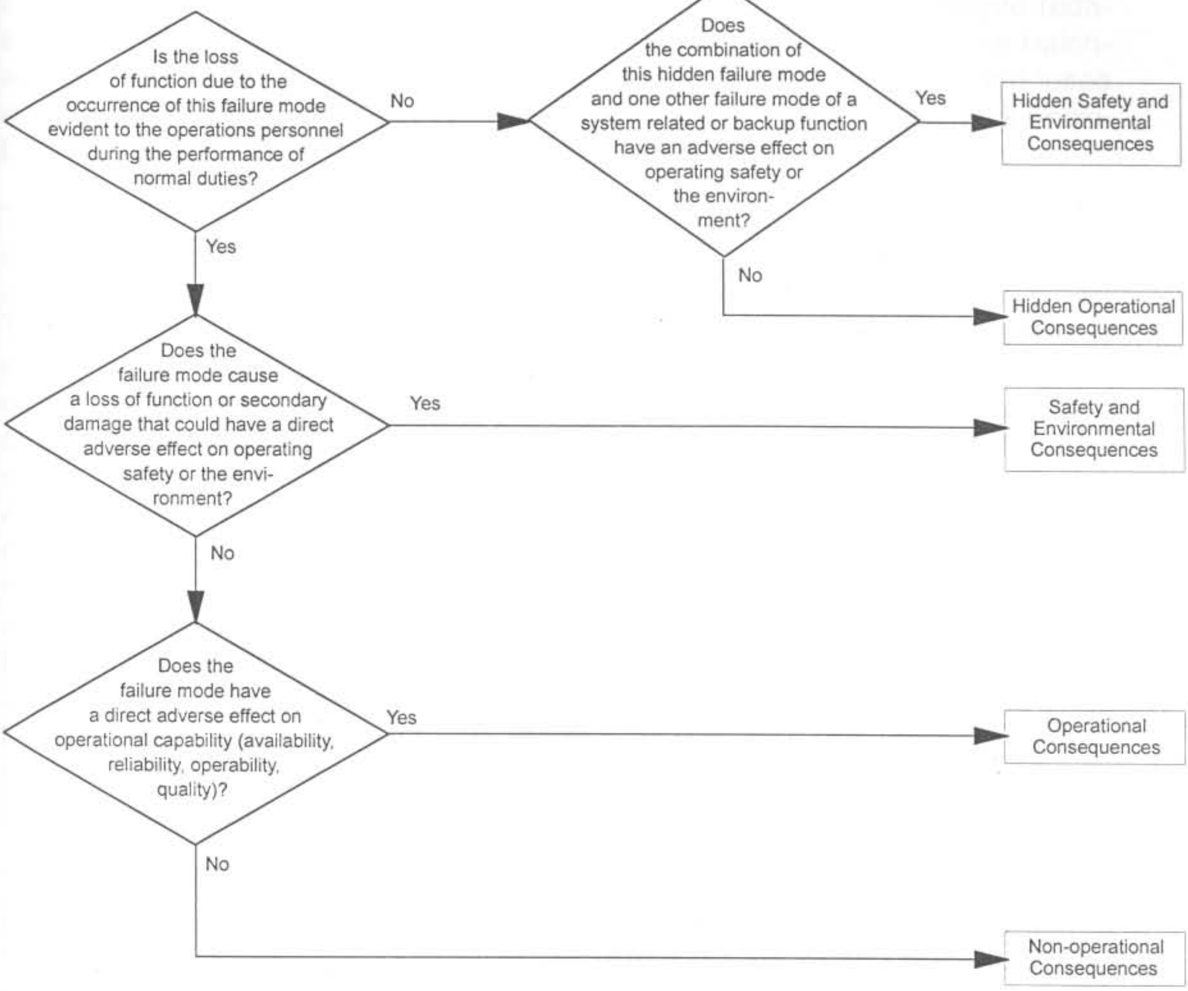
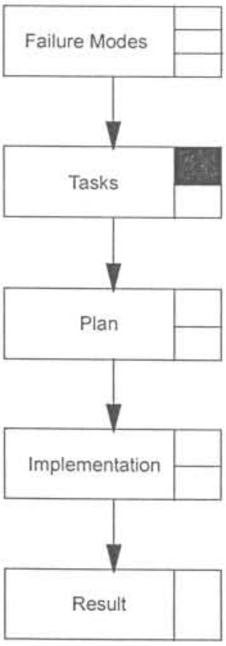


Figure 4-18: RCM Failure Mode Classification

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 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 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.

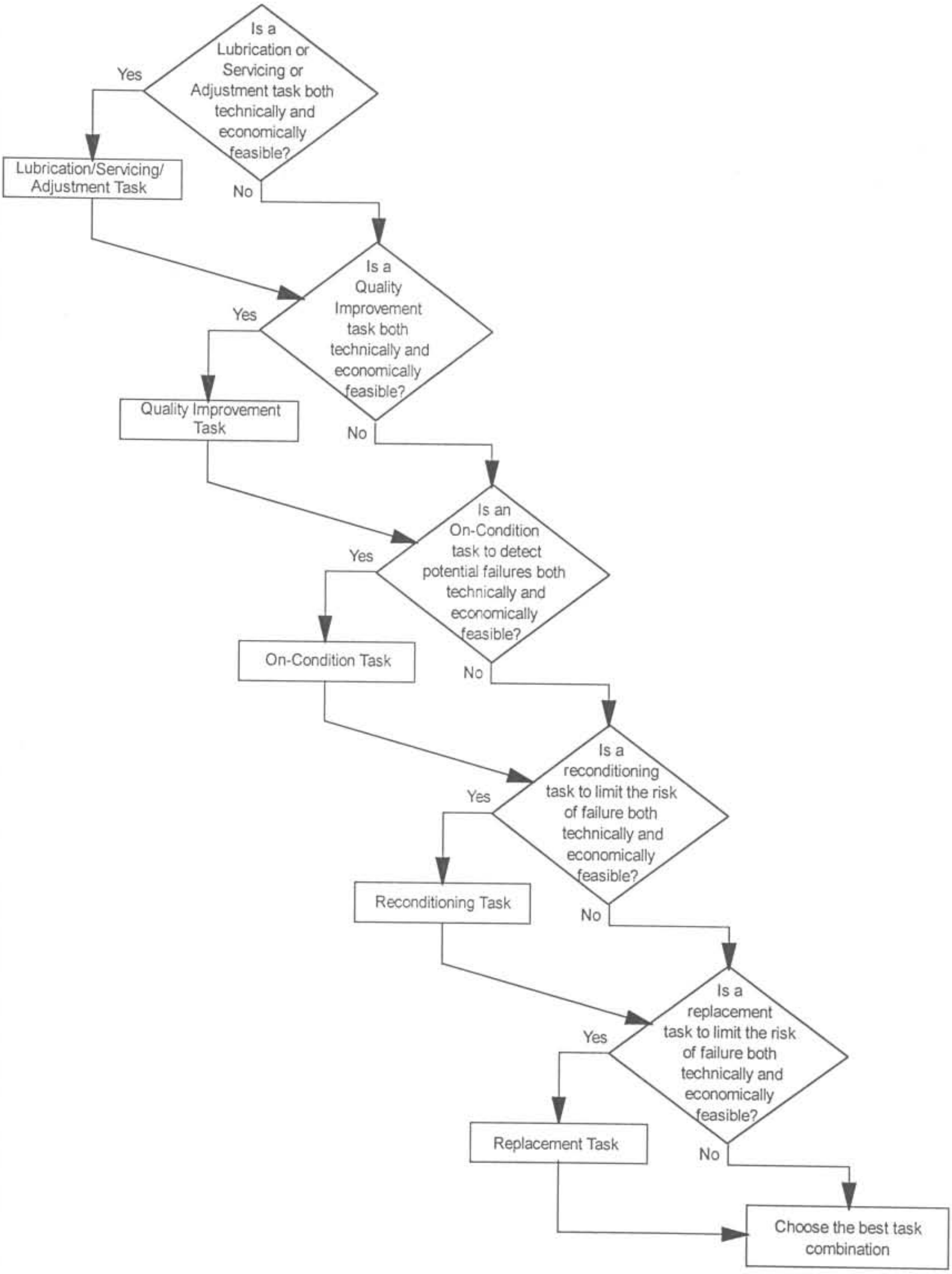


Figure 4-19: RCM Task Decision Tree 1 (without truncation)

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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).

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.

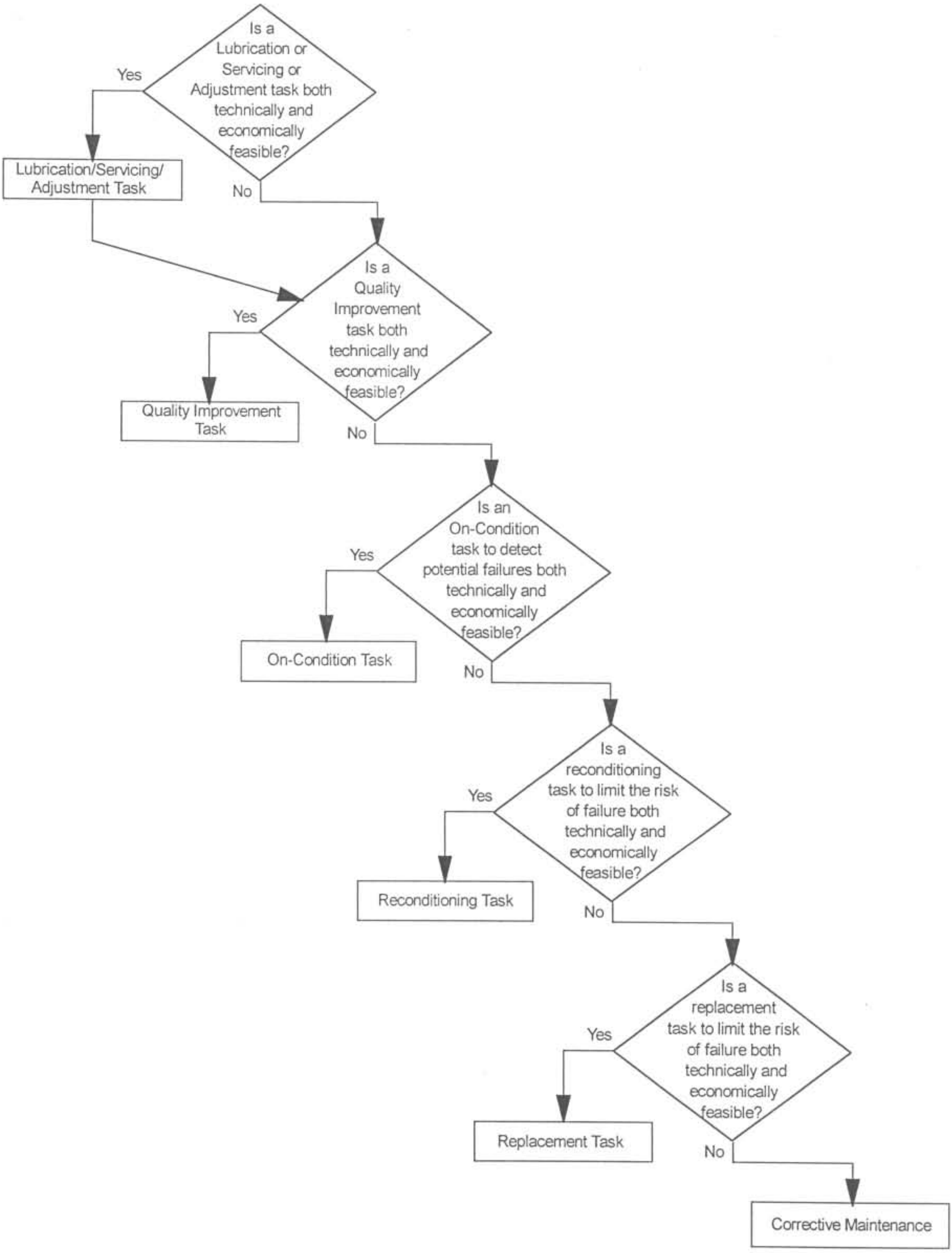

Figure 4-20: RCM Task Decision Tree 2 (with truncation)

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.

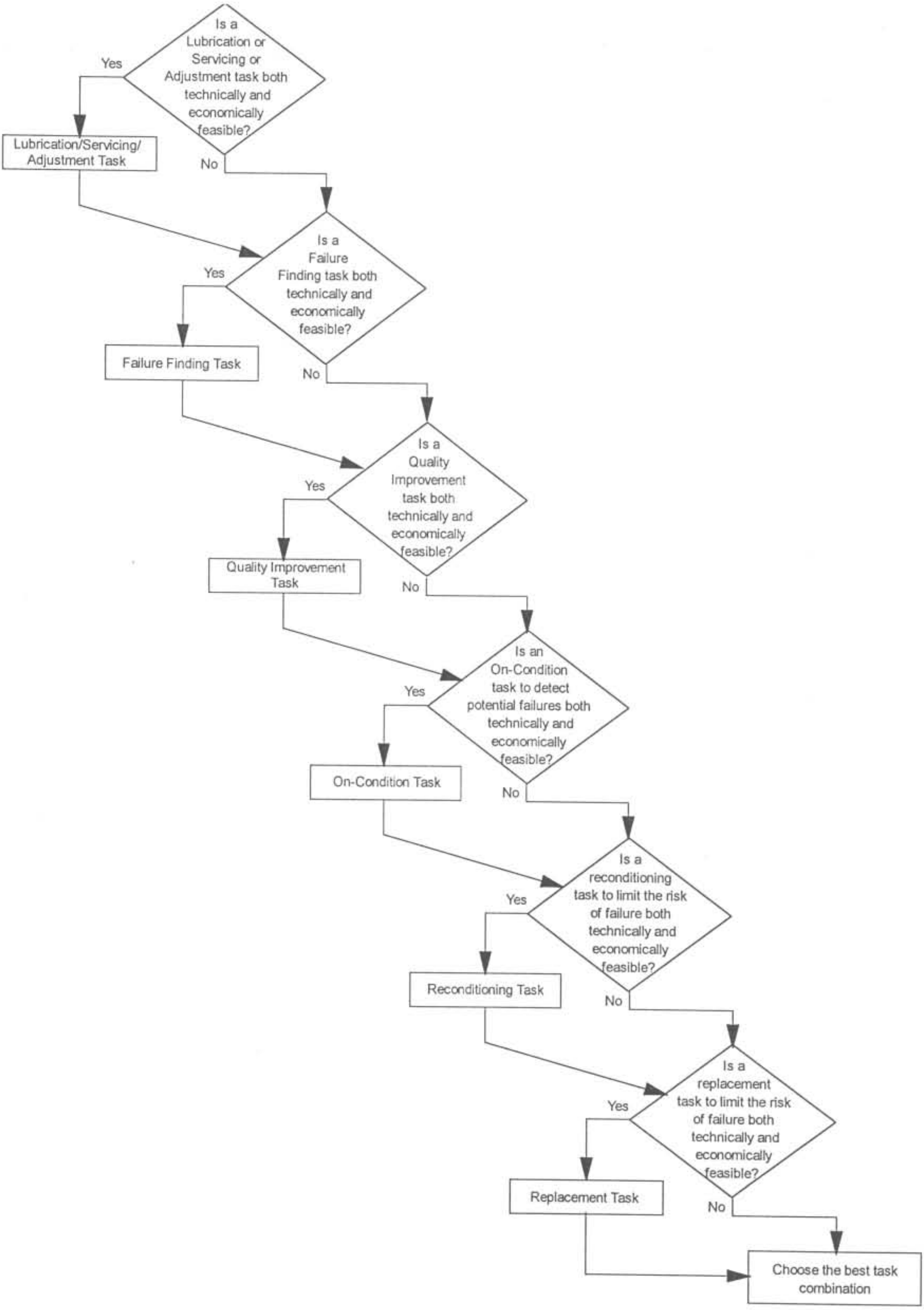

Figure 4-21: RCM Task Decision Tree 1h (without truncation)

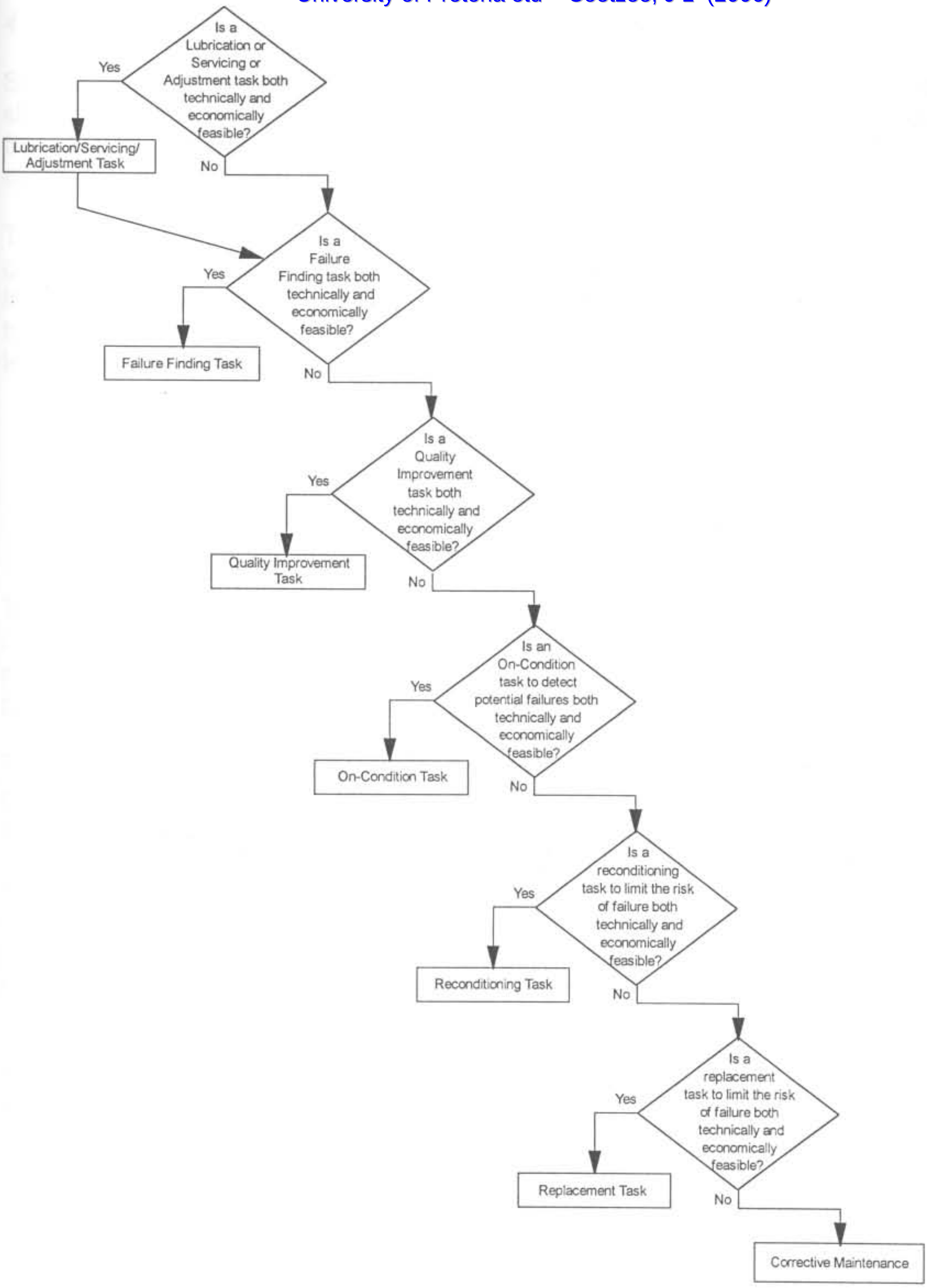

Figure 4-22: RCM Task Decision Tree 2h (with truncation)

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.

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.

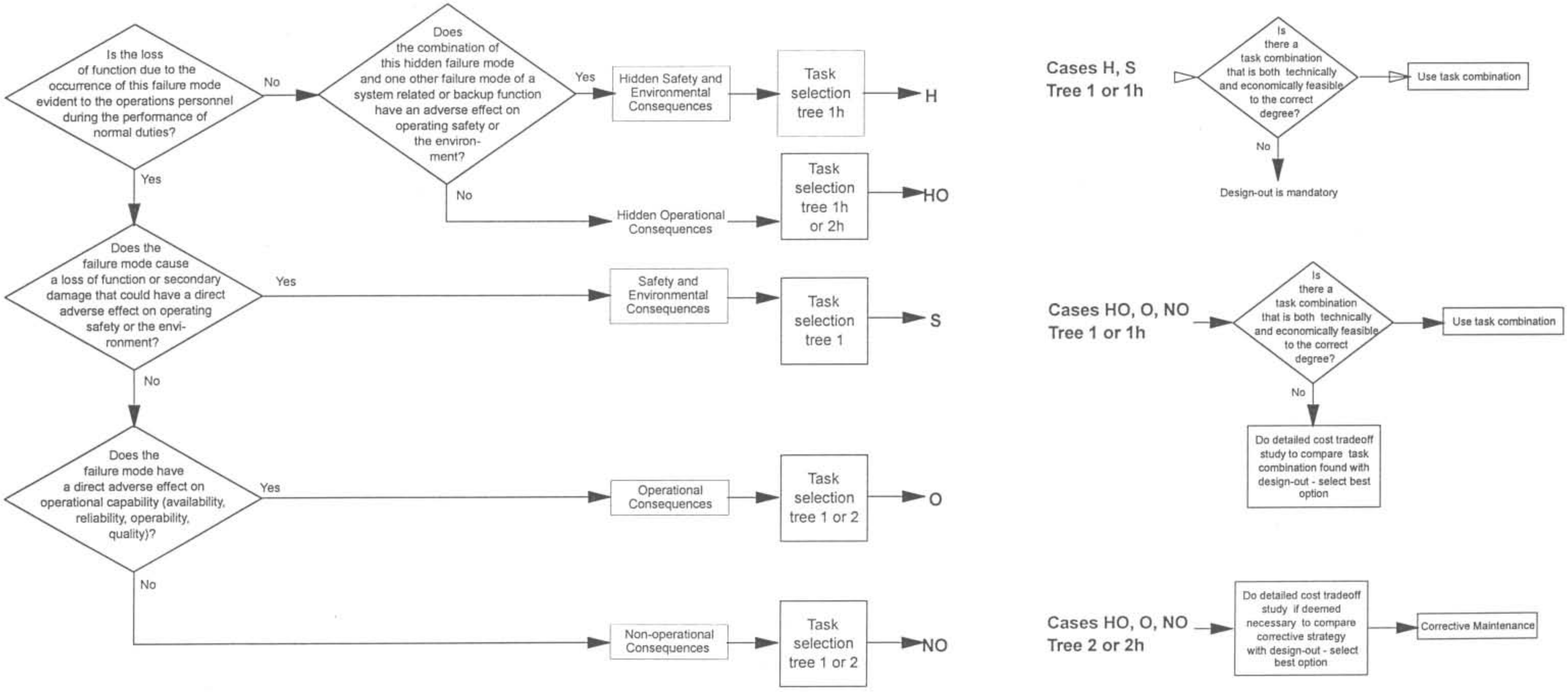

Figure 4-23: RCM Decision Tree

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.

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

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

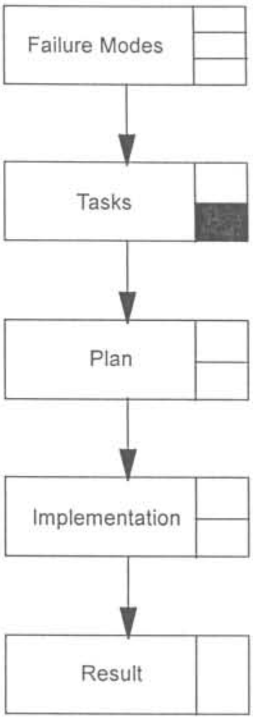
System: Analyst: Reviewer: Approved:
Reference: Date: Rev No: Page of
System Function:

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.

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)]

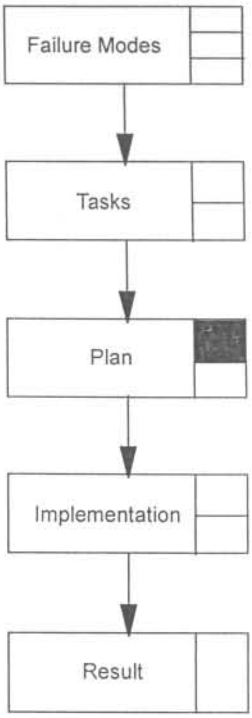
Reliability Centred Maintenance Analysis - Task Analysis

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

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	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)].

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.

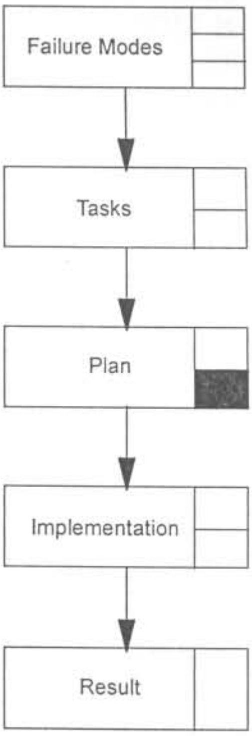
c. Often different parts of the work done on a single unit, but utilising different trades, come from different operating units of the business (workshops typically) or even outside concerns. This does not pose insurmountable difficulties, but has an implication for task packaging in the area of achieving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

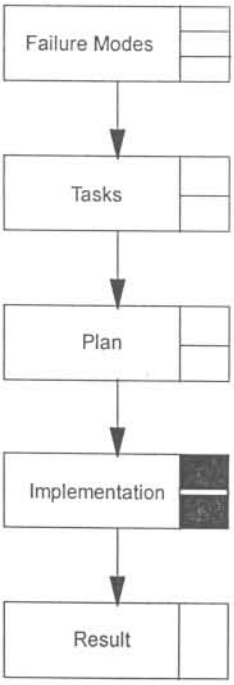
4.3.10. Critical assessment of resulting program



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 users 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.

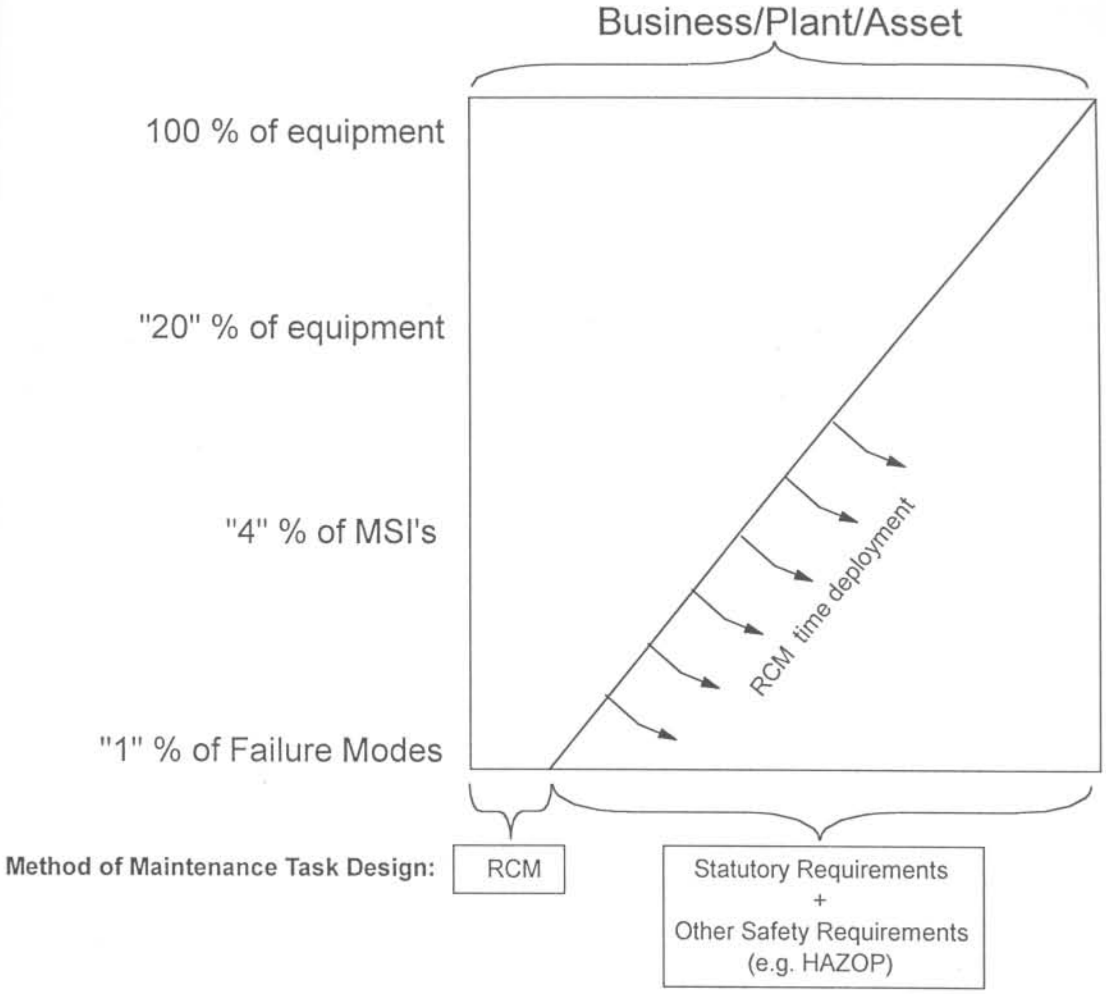


Figure 4-26: RCM versus other techniques

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*.

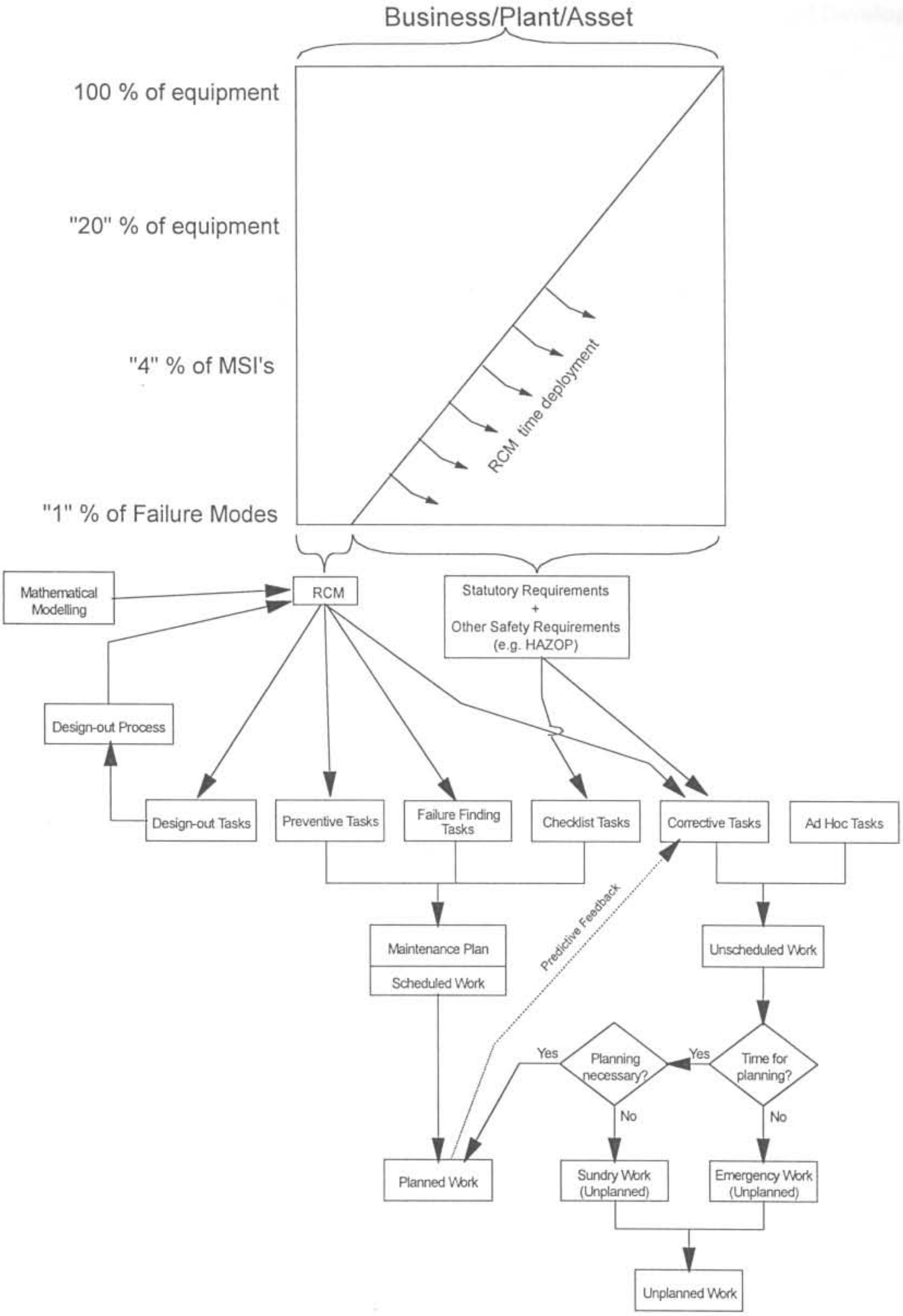


Figure 4-27: RCM in context

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).

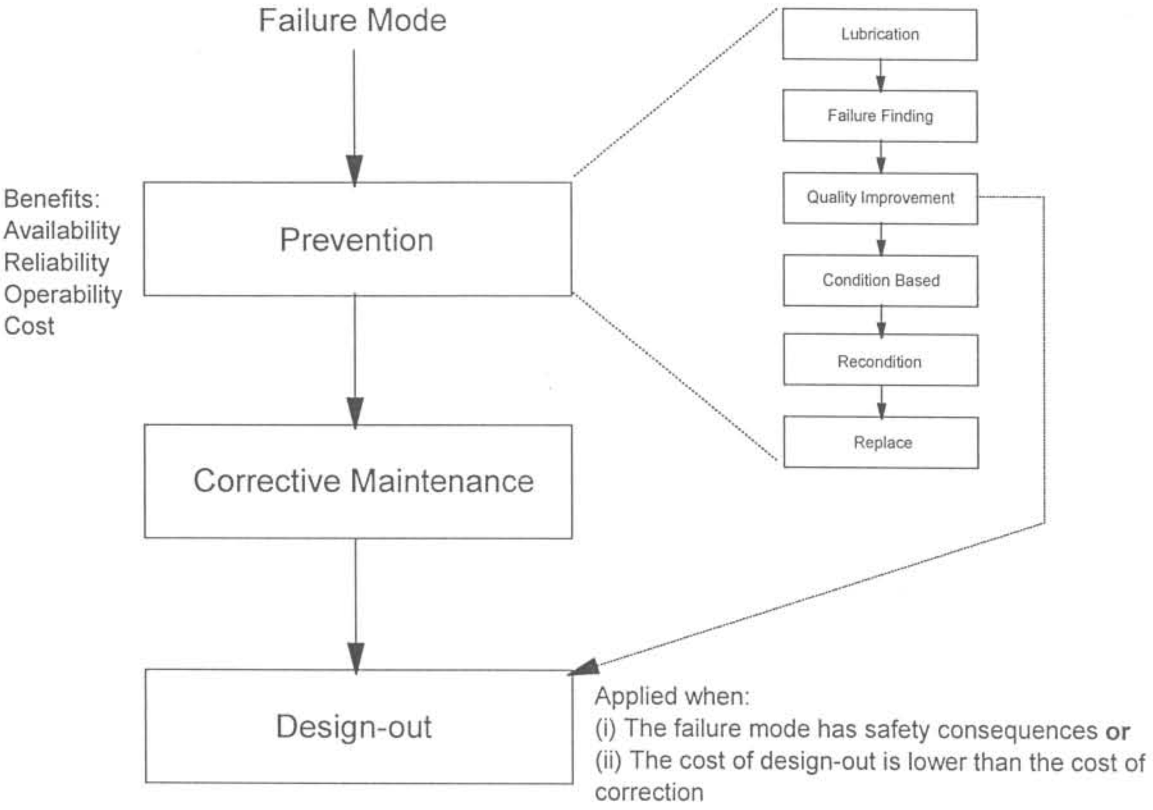


Figure 4-28: RCM task selection process summary

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.

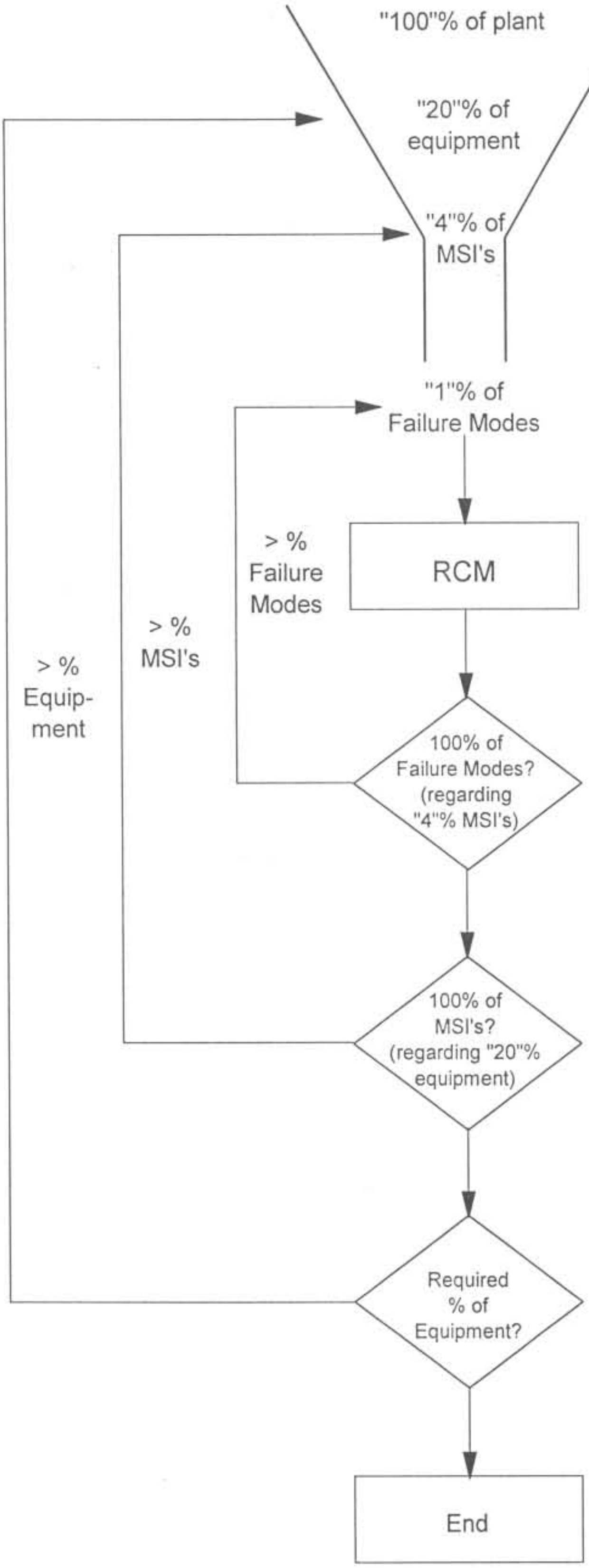


Figure 4-29: RCM progressive application

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.

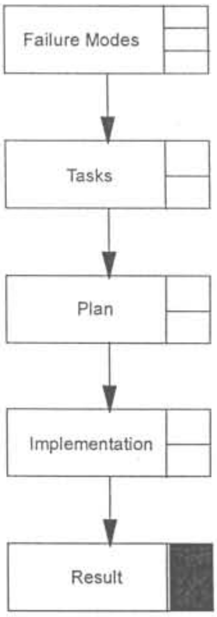
The second feature of importance in figure 4-30 is the feedback loop named 'continuous improvement'. This is what Smith calls the ***living RCM program*** [Smith (1993)]. It indicates that the RCM analysis process can never stop, due to the commitment that was made to continuous improvement of the maintenance 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).

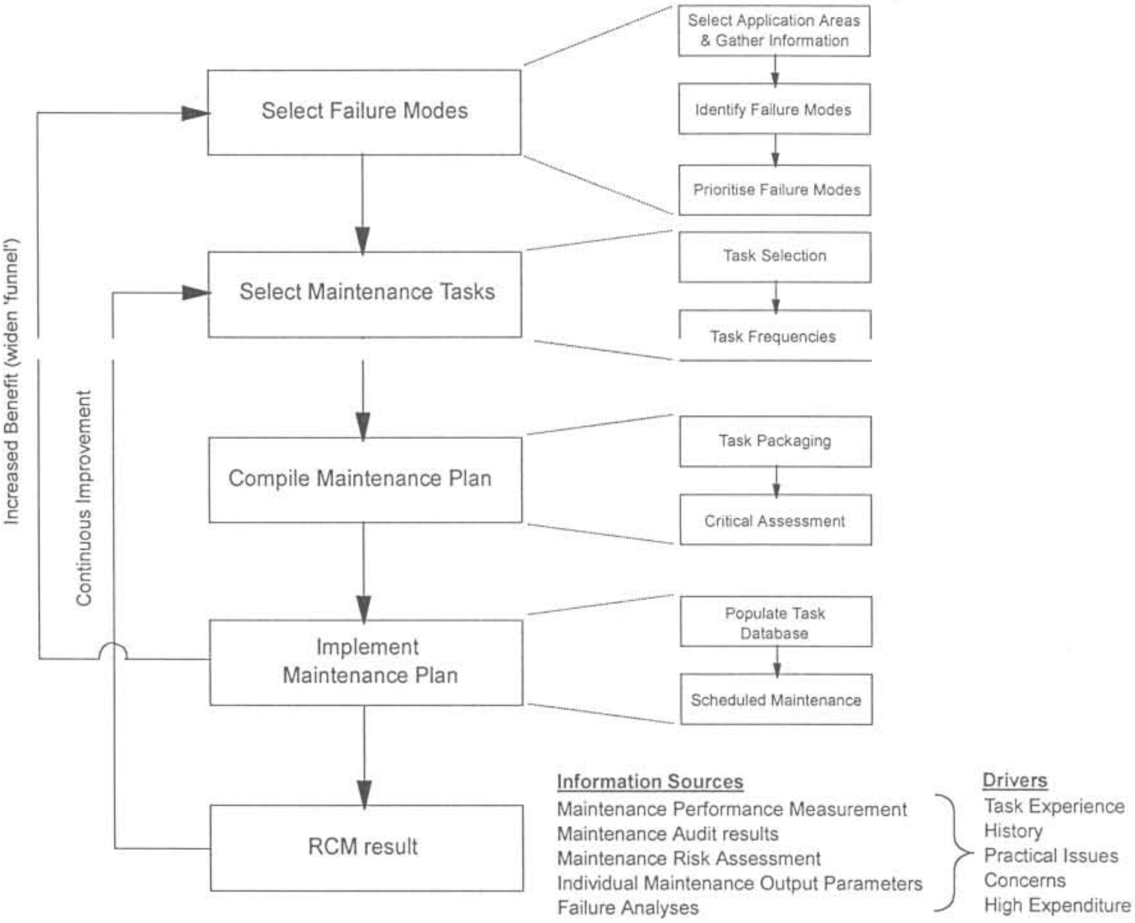


Figure 4-30: RCM Outline

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.

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.

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

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.

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 maintenance 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.

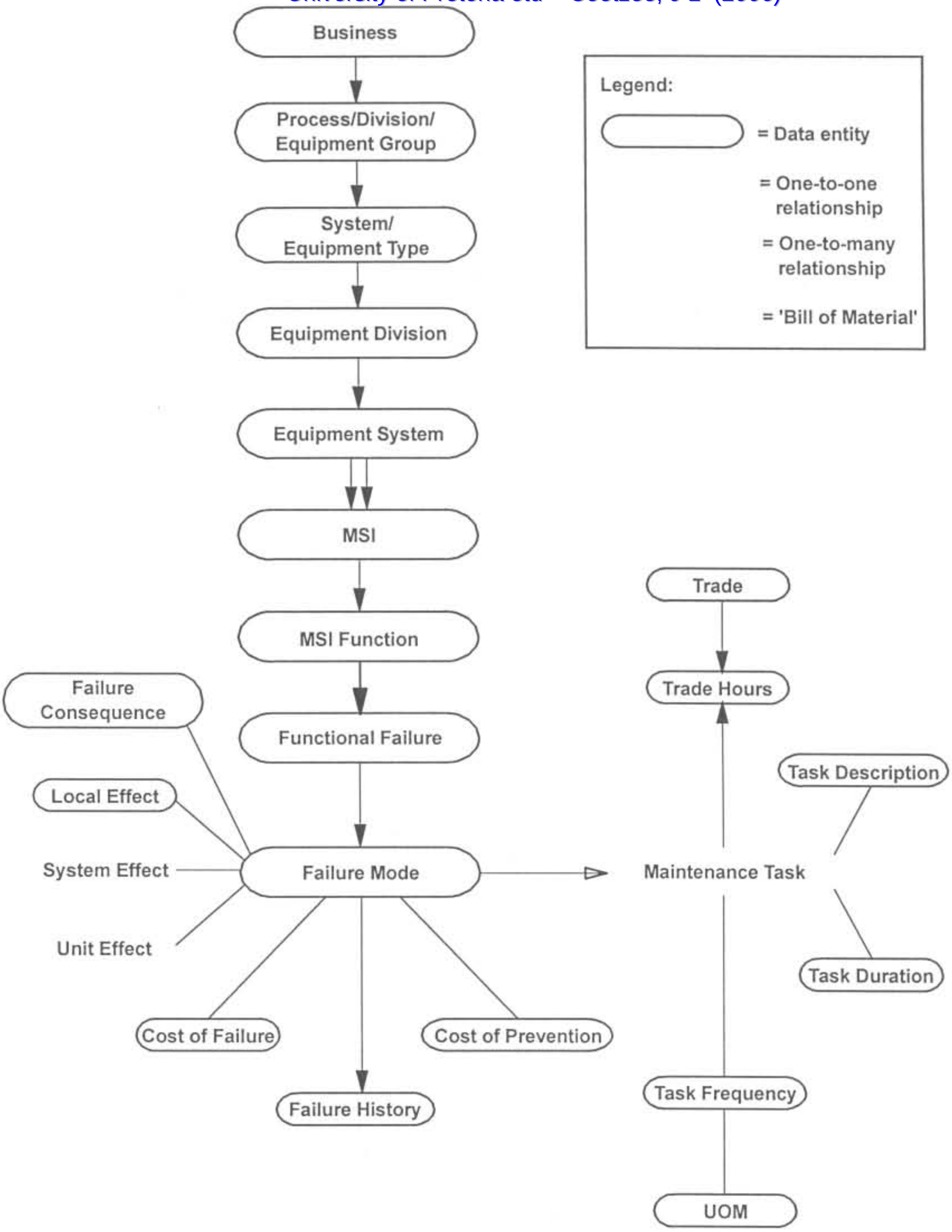

Figure 4-31: Proposed RCM data model

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 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.