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Development of a Life Cycle Management System for Remote Products

In One Volume

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Dedicated to Aoife.............

Declaration

I herby declare that the work presented in this thesis is my own and that it has not been previously used to obtain a degree in this institution or elsewhere

Padraig Hernon

Prologue

The research described in this thesis has been developed as a part of the Reliability and Field Data Management for Multi-Component Products (REFIDAM) Project. This project was funded under the Applied Research Grants Scheme administered by Enterprise Ireland. The project was a partnership between Galway-Mayo Institute of Technology and an industrial company, Thermo King Europe. The project aimed to develop a system to manage the information required for maintenance costing, cost of ownership, reliability assessment and improvement of multi-component products, by establishing information flows between the customer network and across the Thermo King organisation.

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To Aoife, who I dedicate this thesis to. Words cant express your importance to me over the last year. You have been the constant in my life. You made the most difficult times that much easier to endure. I know I made it easier by never being cranky!

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Chapter 1

Introduction

1.1 Thesis Motivation

Today, many companies are competing for market share on the basis of the price of their product. They focus on continuous incorporation of cost saving measures, which concentrate on the design and production stages of the product. In an increasingly more competitive market with tight profit margins, this is becoming progressively more difficult. Due to these demands it is not unexpected that companies are seeking alternative means with which to market their product. Companies are addressing customer value, with a view to replacing the traditional 'brand' as a market share creator, and advertised product differentiator. The relationship a manufacturer has with the customer is now reaching beyond the time of purchase. Customers are being encouraged to look at a life cycle view of product cost, which includes not just it initial purchase price but also all costs arising from its operation and support. The customer portion of this cost, also referred to as cost of ownership, can be used as an extensive marketing tool to induce awareness in the customer with regards to product value.

Value[1] includes all non-price attributes the customer believes the product possesses and is therefore a measure of the products relative desirability, and its ability to create customer satisfaction. Methods for quantification of the monetary aspects of value are found in economic analysis.

[1] To assess the non-monetary value of a product, cognitive socio-psychological methods must be used, such as *sample surveys*, which are now widely accepted as a fundamental means of providing insight into customer value processes [Koh86]. This is not within the scope of this thesis.

In many situations, customers look beyond just the product they buy, and include in value every aspect of their interface with the supplier. This approach to product value is consequently increasing value in other areas. A product with a lower maintenance and support costs that its competitor will generally also have higher quality and a more reliable product. It therefore seems appropriate that a structure should be set in place to continuously support, analyse, calculate and subsequently reduce life cycle cost and ultimately improve customer value.

1.2 Thesis Objectives

This thesis is based on an industrial project entitled Reliability and Field Data Management of Multi Component Products (REFIDAM). The main objective of this project is to develop and prototype a reliability and field data management system. The system should facilitate the frequent retrieval of product failure and maintenance information and provide the means of storing, analysing and managing this information effectively.

The objective of the thesis is to develop an overall model, firstly, to provide a structure to facilitate in the regular or continuous supply of accurate maintenance data from the field, secondly, to provide a tool to retrieve and analyse this data to provide product cost of ownership and reliability information in an efficient manner and finally, to manage and distribute the resulting information to the relevant areas established by the research.

A prototype of the overall infrastructure of the model will be developed and the technical implementation and specification will be presented in the thesis.

1.3 Approach to Work

The research opened with a study into the concept of product customer value, both traditional and modern. During this section of the research it became apparent that there was a trend to move away from traditional value concepts such as company brand and loyalty, to present customer orientated concepts. From this initial research the increasing role of product life cycle cost and cost of ownership in recent value concept became evident. This was followed by research into the area of product life cycle and life cycle cost (LCC). A close examination of LCC components, procedures and existing cost models established the significance of reliability, maintainability and availability as contributors to LCC and a literature review was carried out in those areas.

From the close examination of REFIDAM's industrial partner Thermo King Europe it was evident that accurate reliability, maintainability and availability information was often inaccessible or difficult to obtain. Various means of regularly obtaining field information from the Thermo King's remote products was explored and a system to acquire the information of the product maintenance activities and processes became a clear objective in the pursuit of accurate field data.

Next, the requirement of a maintenance management system to support the established objectives was outlined. The overall system was developed and prototyped in close continuous partnership with Thermo King. The feedback from the company during the development and testing of the system ensured that the system remained a viable solution to the field data acquisition requirements of an industrial company.

1.4 Thesis Structure

Figure 1.1 summarises the thesis structure, which is described as follows.

Chapter One presents the thesis motivation, objectives, approach to work and thesis layout

Chapter Two contains an evaluation of customer value concepts and presents a model to promote modern value requirements. An assessment of product life cycle costing techniques, procedures, activities and models is carried out. This chapter concludes with the selection of elements of a life cycle model to support the value model presented previously in the chapter.

Chapter Three presents a detailed review of product maintenance activities and management with a view to reducing life cycle cost and increasing customer value by supporting the model presented in chapter two. The chapter concludes by presenting the requirements of a maintenance process management model.

Chapter Four describes the Reliability and Field Data Management System (RFDM) that was developed to support the infrastructure for a technical implementation of the Maintenance Process Managements Model (MPMM) in the industrial partner Thermo King Europe. The functional requirements are specified using Data Flow Diagrams (DFD).

Chapter Five describes the Reliability and Field Data Management System using screen shots of the prototyped system.

Chapter Six summarises and draws conclusions from the work carried out in the thesis and presents recommendations for further development.

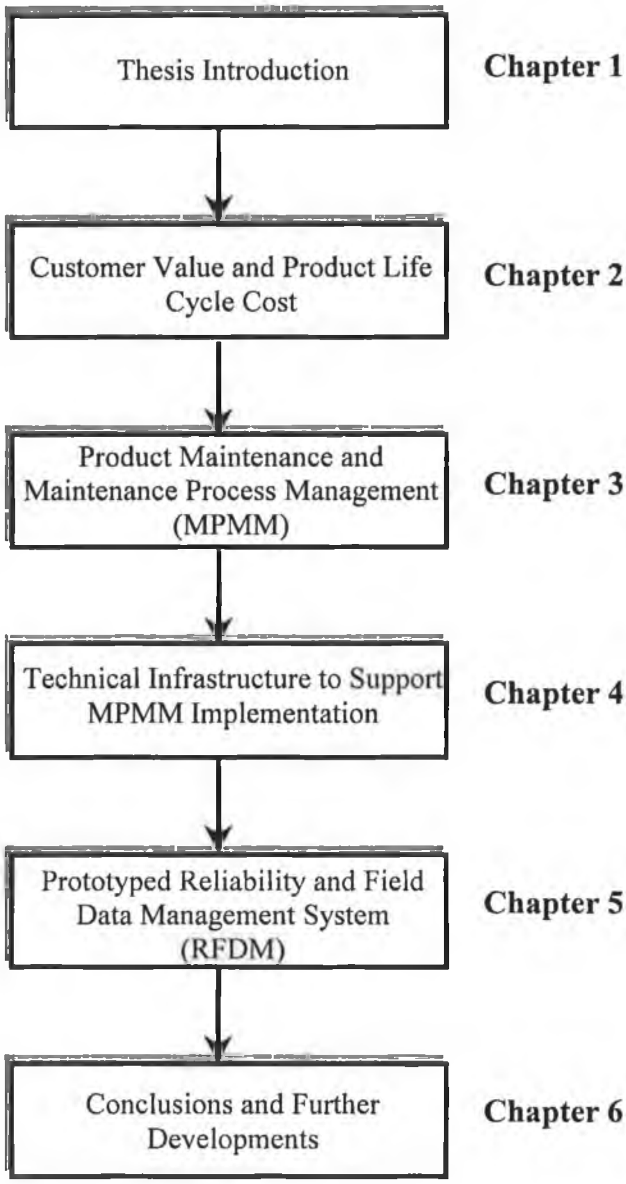


Figure 1.1: Thesis Structure

Chapter 2:

Customer Value and Life Cycle Cost

2.1 Introduction

Traditionally companies have used brand as a market differentiator and for customer assurance of its products reliability and resulting value. However due to increasing market demands and increased competition, the 'brand' is no longer sufficient to maintain or increase market share.

The relationship between producer and customer extends beyond the time of purchase to after-sales service, lasting throughout the period of product ownership. A customer's purchase decision is not only influenced by the traditional concept of value, i.e. perceived quality relative to price, but also to the total cost throughout the products life. Companies are increasingly using *life cycle cost* and *lifetime value* as a market differentiator.

The aim of this chapter is to review the concept of customer value with the purpose of introducing a model to satisfy total product life cycle value. Product life cycle and life cycle cost is then introduced, establishing activities and procedures to carry out cost analysis. The chapter concludes with the development of a life cycle cost model outlining the components of the model that will significantly contribute to life cycle customer value.

2.2 Customer Value

Traditionally, the cornerstone of a company's marketing strategy was to develop loyal customers, willing to pay premium prices for branded goods and services. Throughout the 1980's companies invested heavily in building brands for their products, services and organisations. The brand became the focus for many marketing strategies because it created customer value by recognising customers' purchasing risk: the risk that the product would not perform. The customer value was contained within the information and assurance that the brand provided. The basis of this traditional brand theory can be seen in figure 2.1 [Kno99].

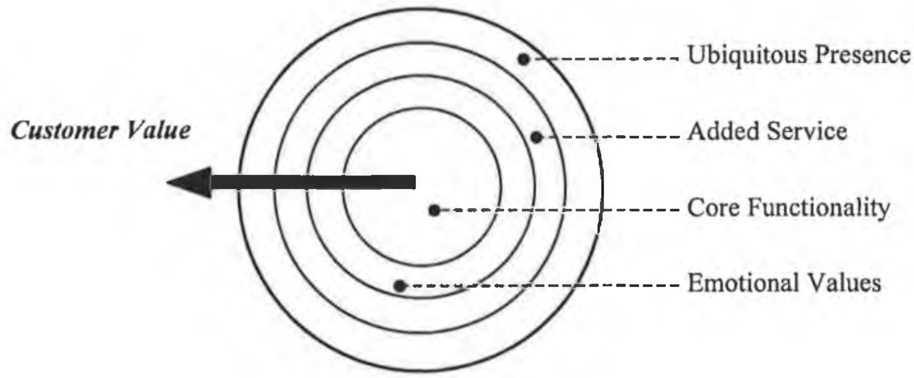


Figure 2.1 Traditional Brand Value [Kno99]

The traditional brand value theory, shown in figure 2.1 illustrates concentric circles emanating from a core product, instructed managers to wrap their undifferentiated products in ever increasing layers of emotional ties and added-value services. Companies focused their efforts on the creation of products that would gain loyal customers bought into the overall brand concept. Customers gave their allegiance to the brands they selected.

However, by the mid 1990's, its had become apparent that the investment in creating a brand was no longer a guarantee of long-term and defendable advantage in the marketplace. Well-known and respected brands found that they could no longer command strong price premiums to their competitors, or did they expect the automatic loyalty of their customers. Today, the traditional brand value has evolved towards what Gale termed *"...a 'customer value management' approach, where emphasis is placed on quality conformance and customer satisfaction"* [Gal94]. The tools of the traditional brand-set and its brand management structure are incapable of delivering today's customer value. Companies cannot create sufficient levels of customer value by relying on traditional tools and methodologies; hence they fail to create a series of activities that add sufficient levels of customer value [Kno97]. The modern environment requires a new framework on which to build customer value. The author proposes a *product lifetime value* approach, which is illustrated in figure 2.2.

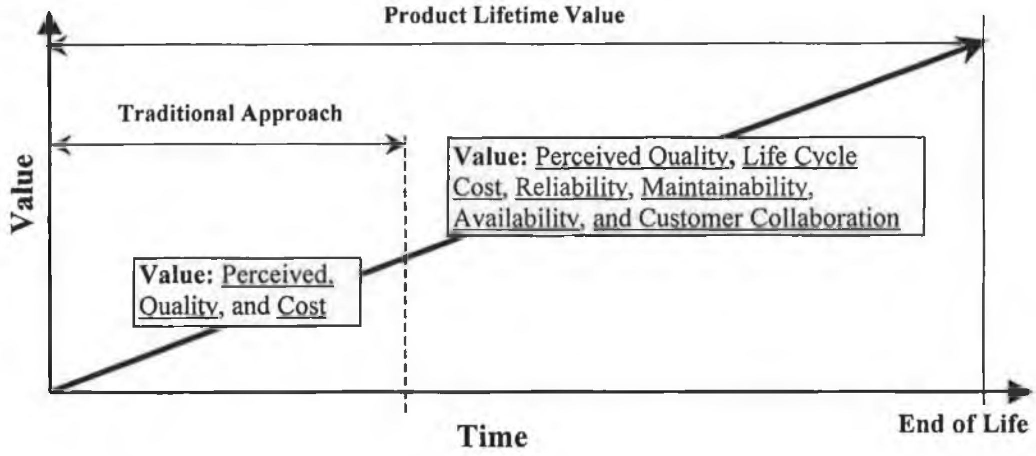


Figure 2.2 Product Lifetime Value

This approach adopts Gale's 'customer value management' concepts and extends them to include product reliability and life cycle cost. Ireson *et al* states "*The wealth of data about customer behaviour, values, and attributes often confirms that reliability is the most important product quality attribute, with the highest impact on value in exchange, expressed by price, and value in use, expressed, for example, in terms of users' return on investment*" [Ire95].

The cost is viewed throughout the total life cycle of the product. The value creation comes from building interactive relationships between the company and its customers. Customers are encouraged to look at value over time and not just at a series of individual transactions. Components of the product's life cycle are evaluated with a view to improve customer value.

2.3 Product Life Cycle

The life cycle of a product describes its entire life, from conception to end-of-life. Figure 2.2 presents a reliability engineering view of a product's life cycle. This four-phase generic structure comprises of the total life cycle of a product or system, i.e. design phase, production phase, operation and support phase, and retirement phase. Each of the four phases is described next

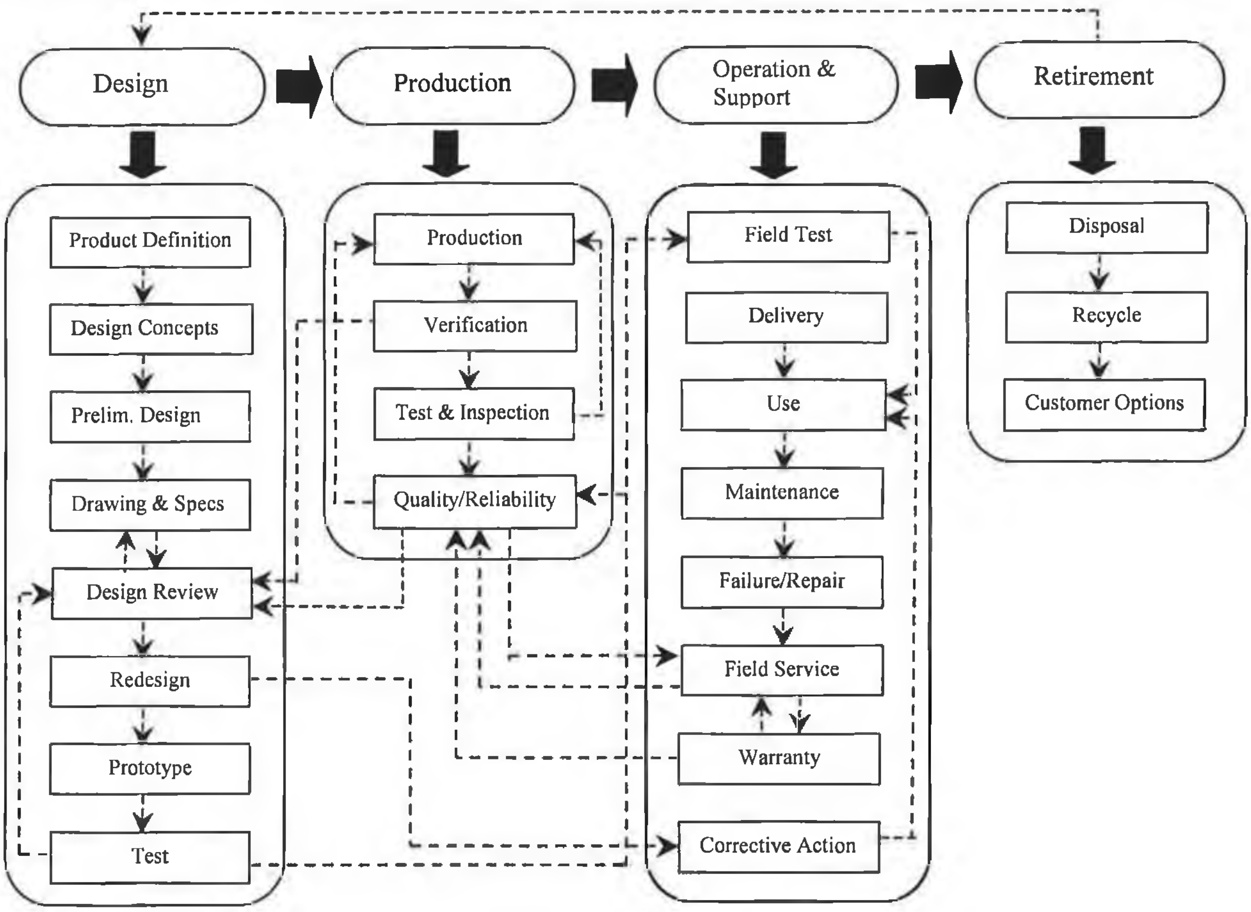


Figure 2.3 Life Cycle of a Manufactured Product (after [Ire95])

During the *Design Phase* design engineers set system definitions. Design concepts are based on prior experiences, results of research and development activities, and marketing research on the need for the proposed new product. Reliability engineering and quality assurance will review historical data and compile records of past reliability and quality experiences when producing similar products. These records will assist the design engineers in identifying previous problems encountered and possible solutions. This will allow the design engineers to set realistic objectives and build intrinsic reliability and quality into the system. During the design phase there is an ongoing review of the design, which the design team and management undertakes. Recommendations are considered and the design altered if necessary. A product prototype is produced and tested in-house and in the field. If the prototype performs satisfactorily within its specified requirements, the design is released for production.

After the *Production Phase* begins, a number of production units are sent back to reliability engineering and quality assurance for verification and full inspection against all design specifications. The test and inspection results are presented to the design review team where changes in specifications or production processes can be proposed. Each design change carried out on the system must be documented in a change and configuration control structure. The serial number and change is recorded, this is necessary throughout the product's life cycle to ensure that spare parts and maintenance procedures are always up to date for each version of the system. Reliability engineering and quality assurance will continue with test and inspection programs during the product life cycle. Results will be recorded and any problems will be brought to the attention of the project manager.

The *Support Phase* begins when the product is released into the field. When a customer uses a product, maintenance as recommended by the manufacturer, will be carried out. These maintenance procedures are documented in maintenance manuals that can be easily accessible by the customer and continuously updated by the manufacturer. However, some unanticipated problems may arise. For example if the field service department of the organisation records any problems, such as failures and underperformance, which occur while the product is in use. The warranty department will process any necessary claims and produce regular reports on consistently failing components. Reliability and quality functions will analyse the data and with the cooperation of the design and production departments propose and implement corrective actions. The problem and solution will be monitored to ensure that the corrective action is effective. All field documentation will be updated if necessary.

The *Retirement Phase* is reached once the product has reached the end of its useful life. The product must be appropriately disposed following any legal or environmental criteria. The manufacturer will have gained vital data, knowledge and experience throughout the phases of the product life cycle; these can be used to improve the process for repeat production of the same product or for the development of new products.

When a product has reached the end of its useful life the customer has a number of options, it may be decided to purchase new equipment from the current manufacturer or decided to procure the equipment elsewhere. There are factors that will affect the choice, e.g. loyalty, satisfaction and performance will play a critical role. However, customer value will be a significant constituent of any acquisition decision. During a products life cycle, both the manufacturer and the customer should pay close attention to any element of the products development, use and disposal that may affect the value of the product.

The concept of *product life cycle,* despite being a subject of continuing debate and even some controversy, form the basis of all current views on product costing. It translates directly into the concept of *life cycle cost*, which combines cost, maintenance and reliability information with the goal of approximating and evaluating economic profiles of product alternatives [Ire95].

2.4 Life Cycle Cost

Brode describes life cycle cost (LCC) as *"the entire cost incurred by a system or product during its useful life, from the initial design stage until the system is phased out and retired"* [Bro75]. LCC is the accumulation of all the costs incurred by a product during all four phases of its life cycle as described previously in figure 2.1. To accurately represent a product's LCC, each element that has an effect on any aspect of cost associated with the product must be included.

2.4.1 Life Cycle Cost Components

The LCC components illustrated in table 2.1 include components anticipated by Blake [Bla92]. In this listing it is assumed that the cost of design and development is recovered in the purchase price and therefore indirectly charged in the acquisition cost.

The components or constituents of a LCC model can be considered to fall into two main categories proposed by Reich, i.e. the costs which are incurred before the system or equipment is operational, called *non-recurring cost* and costs which are incurred subsequently, called *recurring cost* [Rei80]. In this table it is assumed that all non-recurring costs are recovered in the price charged for the product, in some circumstances this may not be the case, for example when a product is being designed, developed and produced for just one customer the design and development cost may be charged separately This is a common occurrence in the military sector. [Bla92].

There are two main perspectives from which the recurring components of LCC can be described, i.e. the manufacturer's perspective and the customer's perspective.

From the manufacturer's perspective, all costs accumulated during the design, production, support and warranty period of a product will comprise the LCC. LCC as a methodology is rarely used in the commercial world, with the military sector being the exception. When LCC is applied it usually focuses on the manufacturer's portion of the LCC. The manufacturers perspective may not have lead to an optimum from a customers' viewpoint, therefore a new approach was required. *Cost of Ownership* (COO) provides a viable alternative to LCC [Ire95].

The customer will bear all costs arising from the acquisition of the product and any costs arising from its use, including maintenance and failure costs that are not covered by the manufacturers warranty.

Components of Life Cycle Cost		
	Components	**Elements**
Non Recurring	Purchase Price	Research and Development Production Profit Margin
	Installation	Installation of equipment.
Recurring Costs	Operation	Initial training of operating and maintenance personnel. Operating costs, including labour, energy, space and services.
	Service	Acquisition of contingency spare equipment. Acquisition of initial float of replacement parts. Acquisition and installation of maintenance support facilities. Acquisition and installation of operating support facilities Scheduled maintenance. Ongoing acquisitions of replacements parts and materials Holding and handling of spares. Loss of net income due to unscheduled maintenance downtime. Overtime loadings because of equipment normal-time unavailability.
	Failure and Warranty	Corrective maintenance. Loss of net income due to scheduled maintenance downtime. Spoiled materials due to equipment failure. Damage to equipment due to failure. Damage to environment due to equipment failure. Legal liabilities due to equipment failure.
	Support	Technical and engineering support and overhead. Service Parts; maintenance and repair.
	Disposal/Miscellaneous	Cost of retirement or disposal. Ongoing personnel training.

Table 2.1 Components of Life Cycle Cost. (After [Bla92])

It is however unlikely that a design optimised from a manufacturers perspective will be optimum from the customer's LCC standpoint. The goal should be to close the gap, that is, to optimise the products design and support systems such that the gap between the manufacturers LCC perspective and the customers COO perspective is minimal. The aim is to create products that have the lowest LCC for both the manufacturer and the customer [Car92].

A balanced approach is required to achieve this, one that trades off all aspects of production costs, quality, reliability, and performance during the developments process, and at the same time considers the long term maintenance and operation aspects of the product once it is fielded [M338]. In summary this thesis interprets LCC to be modelled as follows: LCC equals cost of acquisition plus all operating and disposal costs, therefore LCC equals COO. This thesis focuses on reducing LCC by modifying the elements that directly affect the COO thereby increasing customer value. The technique used to estimate the life cycle cost of a product is termed life cycle costing or LCC analysis.

2.5 Life Cycle Cost Analysis (LCCA)

An important fundamental principle is that the use of LCCA techniques in the decision making process starts from the position that the lowest initial capital cost of a product should not be the sole determinant of an acquisition decision. Most products will have life cycle costs of several times the initial cost, and management requires knowledge of the incidences, causes and the magnitude of the major elements of these costs. Studies conducted by the U.S. Military indicated that the operation and support cost over a products life cycle could be many times the acquisition cost, one such study showed that the acquisition cost to be only 28% of the total life cycle cost [Ear75]. The objective of LCCA is to provide management with the sound appraisal of these costs and other implications relative to a range of alternative proposals.

2.5.1 Life Cycle Cost Analysis Applications

The applications of LCCA and modelling vary from sector to sector and from organisation to organisation, depending on the particular needs, but it can be used effectively in many sectors. Its main purpose is establishing, reducing, and controlling life cycle cost, however it has other useful applications. For example, LCC analysis carried out during the products development phase can be used to evaluate the design alternatives, optimise design, and aid in project decision-making. LCC analysis is applied routinely in the US Department of Defence programmes; however, it is only recently being used routinely in the commercial world [Bla92]. There are factors responsible for this increased awareness of life cycle costing and its benefits in commercial organisations. Some of the factors that are responsible for this trend include [Dhi89]:

- Rising inflation
- Budget limitations

- Increasing cost effectiveness among end users
- Competition
- Costly Products
- Increasing maintenance costs Fuel price increases
- Product discrimination

Manufacturers can use LCC modelling advantageously to evaluate design, manufacturing, and support decisions for costs that they will bear. For example, support costs can be examined for the product that is under a field service contract or within its warranty period, since that cost will be directly passed through to the manufacturer. COO is useful to manufacturers to assist them in establishing the price of maintenance, leasing contracts, and extended warranties accordingly. It is in the manufacturers interest to make the customer recognise the importance of LCC and especially the elements of LCC that constitute COO. The COO can in essence be used as a marketing and sales tool since it relates to costs borne by the customer. The initial investment that the customer makes in terms of purchase price will be important. But also the costs that are incurred by the product on a recurring basis over its useful life are important. Hence, a model of COO for a product is useful as a decision making tool to support the evaluation of competing products.

2.5.2 Life Cycle Cost Analysis Activities and Procedures

There is no set standard in carrying out a costing program. However, as a foundation, the costing should be carried out using some basic procedures. With experience and greater knowledge of the system these procedures can be adapted and developed to suit a specific need. The author proposes a seven-step approach, which amalgamates procedures developed by Blanchard [Bla78] and by Kaufman [Kau69]. The steps are, organisation, information, calculations, evaluation, sensitivity and reporting.

Organise for Life LCCA

This step requires proper organisation and assignment of responsibilities. These responsibilities should be placed with individuals, groups or teams who have direct access to management and have the flexibility and ability to work across the company's functional organisations effectively. This step is also concerned with the preparation of a life cycle costing plan and technical proposal. Two commonly faced difficulties associated with planning is the realisation of the product failure details, specifications and maintenance philosophy so that the detailed costing analysis can be accomplished.

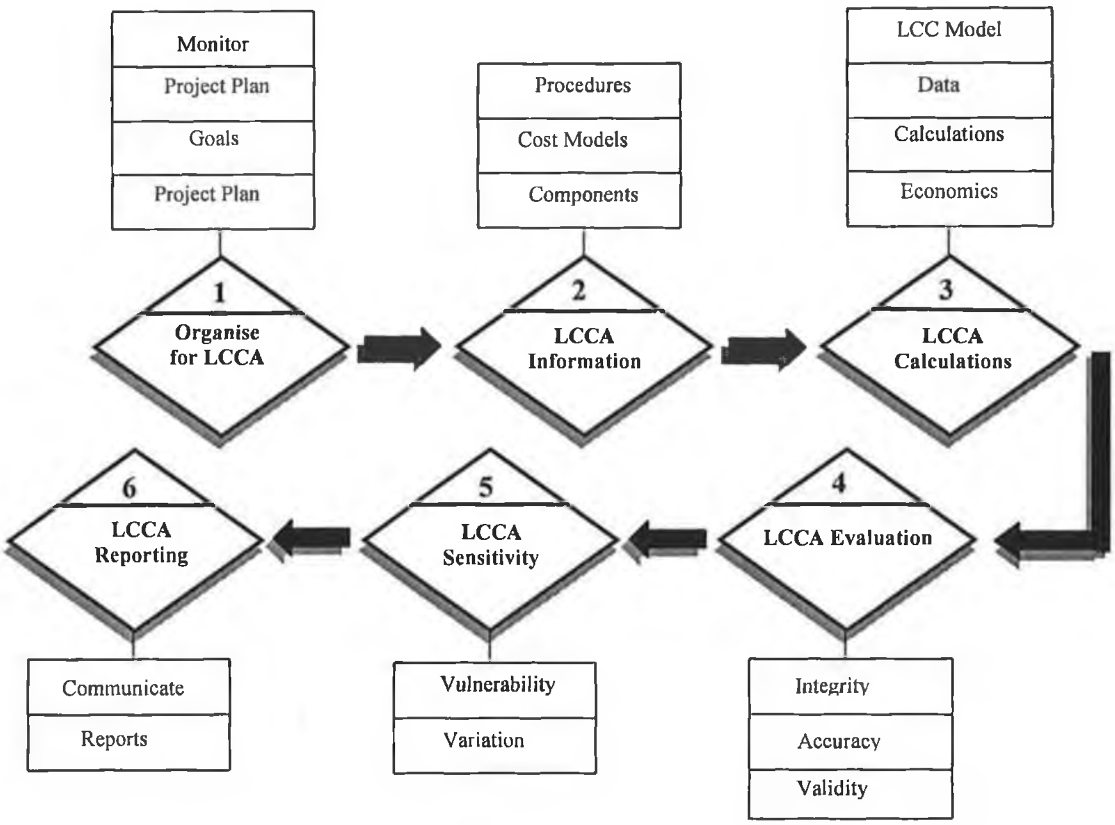


Figure 2.4 Proposed Life Cycle Cost Analysis Procedure.

This step is concerned with establishing a plan for identifying risk areas. It is essential that all areas of associated potential risk from the life cycle cost commitment is made clear to management. This is important when life cycle cost guarantees is part of the proposed acquisition, maintenance costing, leasing contract, or warranty strategy.

This step calls for the development of a plan for setting and achieving life cycle cost goals. The plan should include monitoring of progress toward the set goals. It is important that the goals are set early in the program and in close collaboration with everybody concerned, especially those involved in providing performance and maintenance experience data.

In order to perform effective life cycle costing studies, the team of analysts must possess skills in several disciplines some of which are listed below:

- Reliability and Maintainability engineering
- Statistical analysis and quality control
- Engineering
- Finance and Accounting
- Logistics
- Estimating

It is rare that a single individual or even a team of analysts would possess skills in all of the above disciplines. Therefore, preparation should be made to seek help from other specialists.

LCCA Information

The primary objective in this step is to acquire knowledge of life cycle cost models as well as familiarisation of the life cycle costing process. It is important to be familiar with the product and the components of the life cycle cost that is appropriate to the product.

The information required for the planning depends upon the identification of the equipment design and maintenance philosophy. An analysis of cost models to discover the type of data that is required and the computer resources required with the model. It is essential to have all support that is required for the costing project documented and presented to management to help in the decision-making.

To carry out a life cycle costing analysis, there are costing activities that must be considered. These activities will depend on the organisation's needs and product application. However, most analysis will include a number of the following [Edd81]:

- Identifying cost drivers
- Developing for every component in the life cycle cost breakdown structure the cost estimating relationship
- Developing escalated and discounted life cycle costs
- Defining an item or product's life cycle
- Defining activities that generate product's ownership costs
- Performing sensitivity analysis
- Establishing constant cost profiles
- Determining cause and effect relationships
- Establishing an accounting breakdown structure

When the appropriate cost activities have being explored, there are a number of cost components that must then be evaluated. All elements that affect the cost of the system must be included in the analysis.

LCCA Calculations

Once an agreed and appropriate LCC procedure and strategy has been set in place a generic framework can be used to calculate the LCC. The following five points represent a generic outline for calculating LCC [Coe81]:

- Determine
- Obtain
- Calculate
- Discount
- Compare

The useful operational life of the item or product that is to be analysed is *determined.* It is important to decide which data is representative of the life of the product and which is not. If broad averages are taken it may lead to inaccurate information. It is important that any assumptions made are recorded. Estimates are then *obtained* for all the involved costs of the product. It is important to including accurate costs of operation and maintenance as these costs are often the most difficult to acquire. Inaccurate field information or reliability predictions may lead to inaccurate calculations. Any assumptions and estimations that are made during all aspects of the analysis should be recorded and made available with the final results. In a simple LCC model, the item or products terminal value should be attained and the life cycle cost of ownership *calculated.* A simple mathematical process of subtraction is carried out on the terminal value and the life cycle ownership cost of the product. If future or past worth of a product is being calculated all *discounts* and inflationary factors should be calculated.[1] The process should be repeated for all products being considered. In the case of competing products *comparisons* can then be made.

Using this simple framework the following observations can be made. It is important to have a cost model and set of equations that will ensure that the calculated LCC is a realistic evaluation of the true LCC and that there is no distortion of product characteristics, e.g. of reliability, maintainability or availability. A common problem relates to which cost components to include in the calculation. The allocation of indirect costs and costs of activities and resources that are shared with other products operated or maintained by the same customer is particularly difficult. For comparative assessment it is not necessary to include costs that are shared by all. However, for accurate LCC the allocation of any shared cost must be included in the calculation. Because of the difficulty in getting data, the LCC equations should be kept simple. It may be better to exclude the failure cost of rare but expensive failure modes and instead employ design procedures such as failure mode effect and criticality analysis (FMECA) that will make it extremely unlikely that such a failure will occur or if such a failure is occurring that it is solved accordingly. 'Spread-sheeting'

[1] Life cycle economics is discussed in section 2.5 of this thesis.

should be employed on any LCC worksheets to permit easy analysis of the sensitivity of calculated LCC to variation in the assumed data.

There are two sets of quantative data required for LCC calculation – application data and product data. *Application data* consists of all information on the application of the product. This is usually supplied by the customer and will involve such information as depot labour rates and lost income due to failure. Some failure cost data may be difficult to obtain accurately, e.g. if the damage or lost income depends on the time of day when the failure occurs or the location of the item at the time. It can be difficult to quantify monetarily many of the consequences of failure. This problem is compounded by the fact that working overtime or rescheduling can recoup losses. *Product data* involves information on the products failure modes, and the Mean Time Between Failure (MTBF) and the Mean Time To Repair (MTTR), or the parameters of the failure-time and repair time distributions. This data can only be predicted or calculated with reasonable accuracy by correspondence with previously fielded items or from known behaviour of subsystems from which the item was or will be assembled.

Evaluating the Costing Program

To keep the LCC analysis program in good order, the product's manufacturer should appraise it periodically. The evaluation should be a test to establish the integrity of the programs and its results. It should be used to ascertain if the program's procedures and rules have being followed and also to ensure that each estimation and assumption used in the costing is clearly publicised. There are areas on which questions should be asked to establish the competence of the program. Some of these areas are listed below [Coe81].

- Customer supplied data
- Sufficient consideration of inflation and other costing factors
- Consistent reliability, maintainability, and system safety design to the life cycle cost requirements
- Identification of cost drivers
- Vendors cost performance review
- Accuracy of cost estimating methods used
- Construction of the cost model and equations used
- Management review

The completeness and correctness of any customer-supplied data should be checked. Checking the reasonable accuracy of the claimed reliability and maintainability characteristics of the product that affect failure and logistic support cost costs should validate the product data. The validity of data sources used for reliability and maintainability calculation or prediction, e.g. component failure rates, should be examined. Checking MTBF and MTTR should in the first instance consist of checking that a recognised standard method of calculation has been correctly applied. Where possible field MTTR should be used as they are normally longer than demonstrated MTTR.

Sensitivity Analysis

When evaluating a costing program, it should be undertaken to analyse the vulnerability or sensitivity of the calculated LCC, inaccuracies and variability of input data and invalid assumptions. For carrying out such a sensitivity analysis, a 'baseline' system configuration and data set should be assumed and computed. Followed by reruns with various departures from the baseline. The sensitivity to variation in any input data may be examined, e.g. variation in labour rates, assumed or calculated MTBFs and MTTRs, and damage per failure The following is a list of areas where sensitivity analysis may be desirable. It should be remembered that this list refers to failure and maintenance in an operating and support (O&S) cost mode [Bla78]:

- Sensitivity of the O&S costs and LCC to variation of system utilisation
- Sensitivity of the operating and support (O&S) cost and LCC to disparity in the frequency of maintenance
- Sensitivity of cost to the variation in system failure diagnostics capability. The depth and accuracy of the included diagnostic influences MTTR and also the extent which faults can be traced and made good and therefore the functional level at which repair will be made and spare parts have to be stocked
- Sensitivity of costs to variation of mean corrective maintenance hours per operating hour (MMH/OH). Involving both component failure rates and repair times, MMH/OH is generally inaccurately known.

Life Cycle Cost Reporting

Life cycle cost reporting is an important factor in the costing program. It is therefore important to examine carefully in their writing what they should include. The contents of the report will vary from organisation to organisation depending on requirements. A life cycle costing report should include information such as:

- The cost model and its details

- The total life cycle cost estimate and the essential total cost breakdown
- Relationships used
- Assumptions and ground rules
- Data used, its source and validity
- The significance of the estimate and conclusion
- Sensitivity analyses performed
- Recommendations
- The life cycle cost estimate's comparison calculated by other means (if possible)

There are a number of ways in which to communicate the value of the LCC of a product. However, it is often useful to express the LCC on an annual basis than as the total cost of the product during its life cycle. It can give a clearer insight into the cost of ownership of a product or system than just the lump sum total LCC. There are four ways of considering annualised LCC:

- Simple average
- Cash flow
- Annual costs
- Annuity.

Simple average is the total LCC divided by the number of years of service life. This is applicable when the ongoing O&S cost is fairly constant. Average LCC per unit time, e.g. per year, per running hour.

Cash flow is the representation of the actual costs as they occur. Therefore, the acquisition cost will be shown when it occurred (usually at the beginning) and the cost of failures can be seen when they occurred. Other unexpected costs such as cost due to downtime should not be represented here but can be shown on an accompanying expression of returns.

Annual costs represent the cost by annual depreciation. The amount of depreciation may be based on the expected drop in salvage value during the year. A complete calculation of the annual cost of the acquisition investment, recognising the either the money was tied was borrowed and interest needs to be paid or the money used in the acquisition could be earning interest if it were to be realised at its remaining value capital value. All operating, support and failure costs should be included in the annual costs.

An *annuity* is the constant nominal amount whose payment each year during the period analysed would have the same present value as the LCC.

2.5.3 Advantages and Disadvantages of Life Cycle Cost Analysis

Some of the advantages of life cycle costing are: useful control programs, an excellent tool for making a selection among the competing contractors, beneficial in comparing the cost of competing projects, useful in reducing total cost, and making decisions associated with equipment replacement, planning and budgeting. On the other hand some of the drawbacks are: costly, time-consuming, accuracy of data is doubtful, and obtaining data for analysis is a difficult task.

There are a number of important points associated with life cycle costing. Some of these are given below:

- Management plays an important role in making the costing effort worthwhile
- Both the manufacturer and the user are required to organise effectively to control life cycle cost.
- Life cycle costing is gaining importance as a technique for strategic decisions, design optimisation and detailed trade-off studied [Dhi89].
- The objective of life cycle costing is to obtain the maximum benefit from limited resources.
- Accurate data is essential for good life cycle cost estimates.
- A cost analyst with excellent knowledge and experience may compensate for various data base difficulties.
- The life cycle cost model must include all concerned costs associated with the program.
- Risk management is essential is the essence of life cycle costing.
- Throughout the life of the program, trade-offs between life cycle cost, performance, and design to cost must be performed.

2.5.4 Life Cycle Cost Data

Whenever a costing system is in force it is essential to have reliable historical data of the same or similar items available in order to perform effective life cycle cost estimates. The accuracy of the costing process is often sacrificed in the event of inadequate historical data, or if the data is incompatible with the estimating process. This failing in life cycle costing is only overcome by having sufficient historical data [Bar75].

A life cycle costing database is a useful tool in performing costing estimates. An organisation involved in the estimation of life cycle cost should have access to a life cycle cost database. If a new database is being developed attention should be paid to factors in Table 2.2 [Bow75].

Life Cycle Cost Database Requirements	
Flexibility	The database should have adequate flexibility to handle local conditions effectively
Accessibility	It should be readily accessible for the data retrieval and analysis and database maintenance without the help of the computer support department.
Comprehensiveness	The data base should have sufficient scope to include all the life cycle costing estimates and needs
Responsiveness	The database should have the capability to accommodate and respond to various types of information
Size	The size of the database should be adequate for the task
Uniformity	The database should contain data, which is uniform to allow adequate samples with similar characteristics for performing reasonable analysis.

Table 2.2 Database Requirements

To effectively carry out an appropriate analysis the database should include, at minimum, the following:

- Cost Records
- Failure History: part numbers, hours, etc.
- Procedural records: operation and maintenance history
- Descriptive records, cause of failure, etc.
- Customer comments (if possible)

Because data is essential to any life cycle costing analysis, it is important to question the integrity of the data used. Before a costing program is commenced the integrity of a number of areas associated with data should be checked. The main areas are as follows [Dhi89]:

- Data availability
- Data bias
- Data obsolescence
- Data orientation towards the problem
- Data applicability
- Data comparability to existing other data
- Data coordination with other information

2.5.5 Life Cycle Cost Economics

The discipline of economics plays an important role in life cycle costing. To calculate the LCC of a product various types of economics related information is required. Life cycle costing often requires that the future costs have to be calculated by taking into consideration the value of money over time. This is due to the fact that that same sum of money spent or received at various different points in time will have different values. Money can increase in value due to interest or decrease in value due to inflation. In life cycle cost analysis, the future costs such as operation and maintenance have to be converted to their appropriate value before it is included in toe cost model. A good model should consider these factors in its calculations. There are a number of formulas developed in economics that are vital in life cycle costing [Dhi89]. This section presents a number of aspects of economics that are useful for life cycle costing. The mathematical formulas are given in Appendix B.

Future Worth (FW) is used to calculate the value of a sum of money at a point in the future. FW is the principle sum of money plus the interest due and also considering monetary inflation. FW is important when long term costing is carried out.

Present Worth (PW) is used if it is necessary to calculate the present value of a future sum of money.

Depreciation The meaning of the term depreciation is a decline in value. In engineering terms it is true that a product or system will loose value with age. There are several causes responsible for a product to loose value, these include [BDhi89]:

- Functional depreciation
- Technological depreciation
- Physical depreciation
- Monetary depreciation

In the case of functional depreciation, a change in demand or service expected from a product during it useful life renders it less worthy to its owner even though it can carry out its function effectively. A technological depreciation will result when the development of a better approach to carry out a product's function. When the normal wear and tear of operation reduces the products capability to carry out its specified function, it is called physical depreciation. Monetary depreciation is the result of the value and buying power of money changing. In order to take into consideration the change in value of a product, the depreciation charges are made during the useful life of the product. In life cycle costing depreciation charges can be included in the operational costs of a product and therefore are considered as a recurring cost

Cost Escalation. In general, costs are expected to rise each year. This must be taken into consideration in all relevant economic analysis, including, life cycle cost analysis.

Terotechnology

Terotechnology is defined as "*a combination of management, financial, engineering and other practices, applied to physical assets in pursuit of economic life cycle cost*" [Tay80]. It is a concept in which all the disciplines anyway involved in the life of a product, are given the opportunity to consider jointly the cost consequences of their decision at various points in its life, and bring their professional expertise to bear in seeking economic cost solutions.
Terotechnology embraces more than just the costing aspect, because it places emphasis on technical and user considerations with the aim of producing the best economic solutions. It is innovative as well as cost conscious.
The application of terotechnology concepts should result in:

- Lower life cycle cost
- Planned efficiency and reliability
- Better communication
- Better information for decision-making

Activity-Based Costing

Activity-based costing (ABC) and cost management reveals links between activities and company resources. Its emphasis on the distinction between value-adding and non-value-adding activities allows easier identification of cost reduction opportunities [Ire95]. ABC cost management is allowing managers and teams from areas causing the most significant problems to identify the product characteristics that drive the associated losses, and to suggest improvement actions. In general, ABC supports the achievement of cost and reliability leadership and contributes to providing superior value to customers.

2.6 Life Cycle Cost Model

Dhillon states, "*There are several life cycle cost models available in published literature. They include both general and specific models. There is no single model which has been accepted as standard model and is being used widely*" [Dhi80].
There is often a widespread difference of opinion between the various models, for example Blanchard *et al* presents a model, which gives a breakdown of costs under the main headings of research and development cost, production and construction cost, operation and maintenance support cost, and retirement and disposal cost. This model includes scheduled maintenance, however failure-induced costs are excluded [Bla82]. It has been argued by the Swedish National Committee to International Electrotechnical Commission that if a cost

analysis is made the losses due to downtime caused by failure should be included with the LCC [IEC89]. Mathematical representations of the models discussed here and additional models by Reich [Rei80], Earles [Ear81], Dickinson *et al* [Dic76] are presented in Appendix A.

There are several factors for not having a standard model, these include: nature of the problem, existence of many different cost data collection systems, many different types of equipment, devices or systems and the inclination of the user [Dhi89].

This thesis interprets LCC to include all cost elements associated with each stage of the product life cycle. In figure 2.5 the author presents a LCC model, which illustrates the cost components and their relationship with manufacturer and customer throughout the product's life cycle. It is necessary to recognise, when LCC is to be considered as a value driver, that some elements can add value to the product. This model presents each cost element with a view to establishing it as a value driver. The model presents output costs and gains for both the manufacturer and the customer.

The author has selected the costs associated with service, failure and warranty as significant contributors to LCC. Warranty can be considered to be a result of failure and therefore will be considered a failure cost. For the purpose of this thesis the elements of service and failure will be considered under the single heading of *maintenance.*

The author proposes evaluation of these elements with an aim to reduce LCC. Due to the nature of these elements, i.e. their fundamental dependence on the factors of product reliability, maintainability and availability, any modification to reduce LCC by influencing these factors will directly support the concept of *Product Lifetime Value* proposed at the beginning of this chapter.

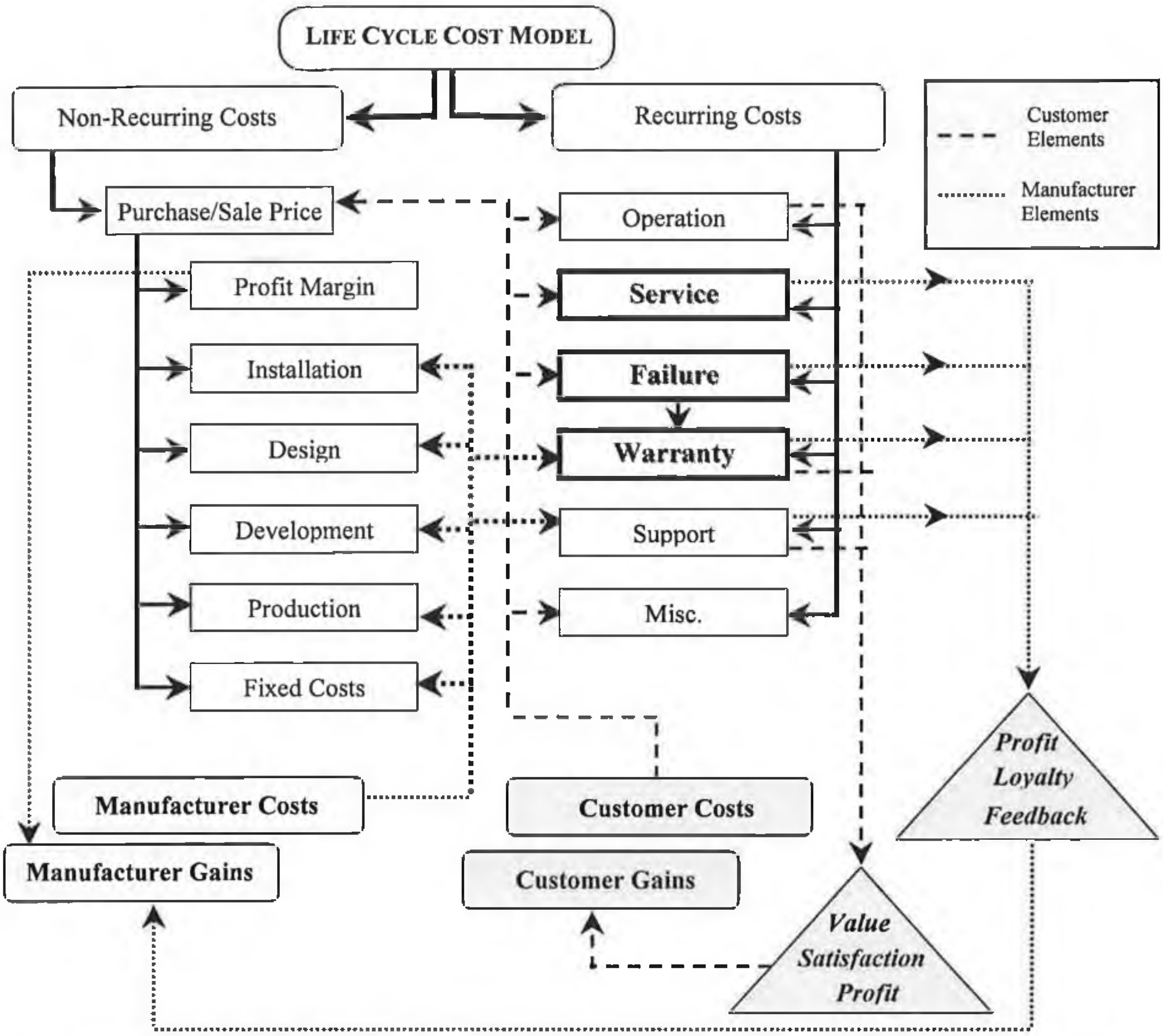


Figure 2.5: Life Cycle Cost Model

2.7 Summary

This chapter has reviewed the concept of customer value from its traditional role, whereby companies focused their efforts on the creation of products that would gain loyal customers, bought into the overall 'brand' concept. Customers gave their allegiance to the brands they selected. Due to increased market demands and competition companies could no longer depend on the tools the traditional concepts provided. Product lifetime cost came to the fore as a product differentiator in an ever-increasing competitive market environment. Companies are using this concept to persuade customers to look beyond the traditional concept of perceived quality and initial price to a more modern *product lifetime value* approach proposed by the author, where the manufacturers relationship with the customer goes beyond the product warranty period and the manufacturer encourages the customer to look at the maintenance and support cost of the competing products and not just at initial price.

A detailed life cycle cost model has been presented with a view to supporting *the product lifetime value* approach proposed. The relationship the customer and the manufacturer have with each of the cost elements is presented, describing the value each of these adds to the product. From this work a number primary elements have been selected, in the pursuit of reduced life cycle cost and increased customer value through increased product reliability, availability and maintainability. Chapter three discusses the principles of product maintenance activities, methodologies, and management.

Chapter 3

Product Maintenance Activities

3.1 Introduction

Chapter two has reviewed customer value and life cycle cost concluding with the selection of maintenance as a key life cycle cost driver to aid in the support of *product lifetime value* approach proposed in the chapter.

This chapter begins by establishing the value of product maintenance and its influence as a life cycle cost driver. A maintenance cost model is presented identifying reliability, maintainability and availability as the core cost drivers. A comprehensive evaluation of these drivers is then carried out, reviewing activities and procedures in their analysis, evaluation and subsequent improvement. Next, existing maintenance methodologies and maintenance management systems are discussed. Finally a Maintenance Process Management Model (MPMM) is proposed with a view to provide a 'best-practice' approach to the function of product maintenance in an organisation.

3.2 The Value of Maintenance

Maintenance Management, or more broadly *equipment lifetime optimisation*, is a prime candidate to simultaneously increase product reliability, effectiveness and profitability and to reduce life cycle cost [Bla92].

Technology and practice have developed to a level capable of recognising most equipment defects in time to prevent failures and minimise unscheduled interruptions.

The concepts of avoided costs and savings are frequently cited as measures to justify advanced equipment management technology and practices, but the results are largely intangible. Therefore, what is the value in preventing a failure? Many companies have gained inter-departmental agreement for an average cost of avoided failures and maintenance actions. While this adds some objectivity, it does not answer the basic question.

Overall performance measures that combine product availability, equipment output, and lifetime cost are necessary for prioritising resources and assessing the effectiveness of optimising efforts. Measures must originate from market conditions and business objectives, point to opportunities for increased profitability, and lead to optimised decisions and greatest value. They must be equally applicable for an entire producer unit as well as individual components [Mit99].

It is clear that a change in mindset is needed. *Asset Management* is being loosely used to describe a more global, enterprise view of equipment optimisation. It is directed to increasing the worth, financial return, and value generated by assets or equipment in the field or in a manufacturing facility. This leads to a primary objective of asset management, i.e. managing equipment assets to gain greatest lifetime value. This means increasing availability, increasing yield and quality, producing higher margin products, and reducing costs. This concept can also be called asset utilisation or *equipment lifetime management.*

Mitchell states, "*The best practitioners of equipment management are passionate, often overoptimistic, and may be totally consumed by technical results with little appreciation of, or even interest in, the profit impact of their work. In times past optimistic expectations and subjective benefits were sufficient. This is no longer true. "Show me the money" is now the way the game is scored.*" [Mit99]. There is a requirement for accurate, traceable information, such as mean time between failure (MTBF), or an equivalent parameter, for each individual piece of equipment. The exact reason for a failure, all components involved, and the cost in terms of both operations and restoration are all imperative information that must be capable of categorising by manufacturer, model, component, cause, and other criteria to detect failure patterns. If improvements are made in materials or maintenance practice, there must be a way to match results with expectations. If the two do not agree, information must be available to determine why. An effective model for equipment optimisation must include the ability to prioritise the application of resources by financial return within an environment where opportunities far exceed resources. The model must be capable of comparing results to expectations, especially when changes and results occur over a considerable period of time.

3.3 Maintenance: A Life Cycle Cost Driver

The costs accumulated during the operation and support phase of a products life cycle greatly contribute to the total products LCC [Bla92]. As discussed in the previous chapter and illustrated in the cost model illustrated in figure 2.2, maintenance and repair costs are significant elements of LCC associated with this phase. Figure 3.1 illustrates the factors, which are proposed to directly contribute to these cost elements.

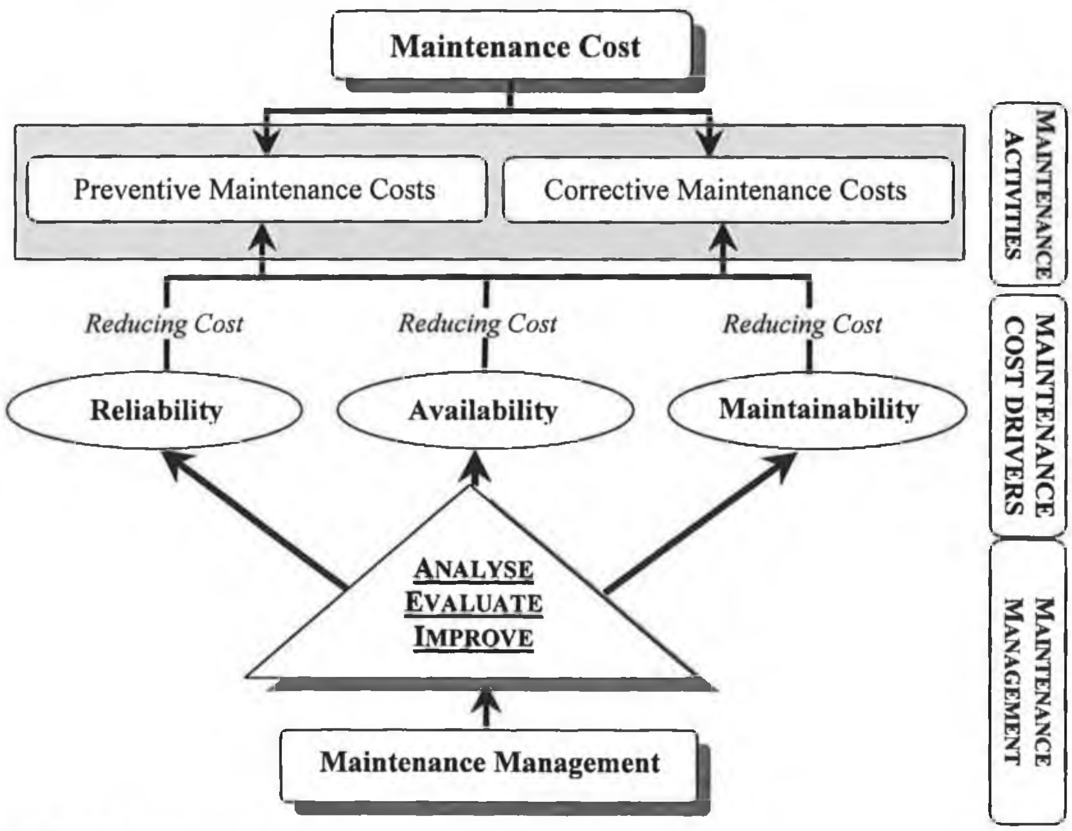


Figure 3.1 Maintenance Cost

For the purpose of this thesis the cost of warranty is assumed to be a failure costs thereby indirectly included in corrective maintenance costs

The costs of preventive maintenance and corrective maintenance presented in figure 3.1 can be attributed to four main factors, i.e. reliability, availability and maintainability. There is a close relationship between reliability and maintainability, one affecting the other and both affecting availability and LCC. The author suggests that by means of *maintenance management,* the *analysis, evaluation* and *improvement* of each of these four factors can play a substantial role in supporting the *Product Lifetime Value* model described in chapter two.

3.4 Product Maintenance

Maintenance is defined as "the combination of all technical and corresponding administrative actions, carried out to retain or restore an item to a state in which it can perform its required function" [Bla92]. Products may be subject to *corrective* and *preventive* maintenance. The relationships that exist between the different types of maintenance concepts and the triggers that causes the maintenance response and the actions carried out can be seen in figure 3.2 [Zwi00].

3.4.1 Corrective Maintenance

Corrective maintenance (CM) also referred to as *unscheduled maintenance* includes all actions carried out to restore a product to an operating or available state, if the item has suffered failure or degradation below a specified performance. The extent of the corrective maintenance carried out is therefore determined by the reliability of the product [Cun72]. Corrective maintenance actions cannot be planned, it happens unexpectedly and it is often measured by *mean time to repair* (MTTR), which is the average corrective maintenance time of an item or population of items. It includes several activities that can be divided into three groups as shows in table 3.3. MTTR data supplied by manufacturers will usually include only active maintenance time and assumes the fault is correctly identified and the spares and personnel are available. The customer should include all maintenance activities in MTTR calculations.

Active maintenance time includes time for studying repair manuals and procedures before the actual repair has started, and the time spent verifying that the repair is satisfactory. It will also include any post-repair documentation if this is required prior to the product being returned to an operating state. Corrective maintenance is also specified as the *mean active maintenance time* (MAMT), since it is only the active time, excluding documentation that a designer can influence.

MTTR Activities	
1. Preparation Time	Locating technicians or dealerships, travel, obtaining tools, etc.
2. Active Maintenance Time	Technicians actually performing the required work
3. Delay or Logistics Time	Once the job has started – waiting for spare parts, etc.

Table 3.1: MTTR Activities

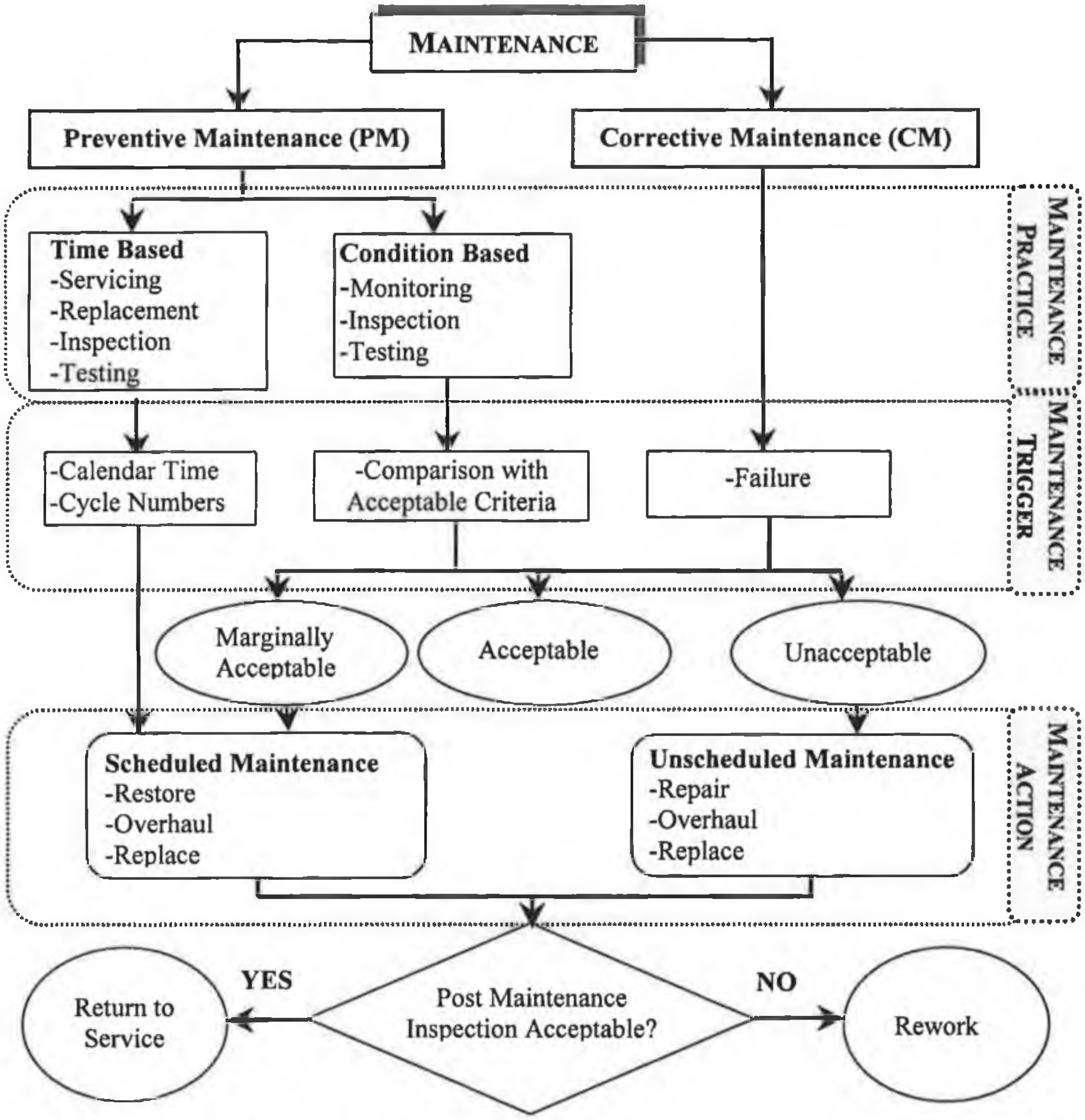


Figure 3.2 Maintenance Flow Diagram [after Zwi00]

CM or on-failure maintenance can be effective if applied correctly, for example, non-critical low cost equipment, or where no other strategy is possible. The advantages of this type of strategy is:

- Low cost if correctly applied
- Requires no advanced planning other than ensuring spares are available

The disadvantages include:

- No warning of failure - safety risk
- Uncontrolled plant outage - production losses
- Requires large standby maintenance team
- Secondary damage - longer repair time
- Large spares stock requirement

In some cases it is more cost effectives to diagnose and restore a product before it fails because failure costs are often significantly higher than preventive costs [Bla92].

3.4.2 Preventive Maintenance Strategy

Maintenance performed in an attempt to retain a product in a specified condition and reduce the probability of failure or degradation occurring is termed *preventive maintenance* (PM) or *scheduled maintenance.* This can be achieved by servicing, such as cleaning or lubrication, or by inspecting. Preventive maintenance affects reliability directly by reducing failure rates. It is planned and should be performed when it is to reduce the risk of failure. PM is measured by the time taken to perform the specified tasks and their specified frequency.

The effectiveness and economy of PM can be maximised by taking into account the reliability distributions of the maintained parts and the failure rate trend of the system. In general, if a part has a decreasing failure rate, any replacement will increase the probability of failure. If the failure rate is constant, replacement will make no difference to the failure probability. If the part has an increasing hazard rate, then replacement at any time will in theory improve the reliability of the system [Oco92]. These are theoretical considerations and they assume that the replacement action does not introduce any other defects and that the reliability distributions are clearly defined. These assumptions must not be made without question but it is necessary to take into account reliability distributions of components in planning a PM strategy. The effects of failures, both in terms of the effect on the system as a whole and of costs of downtime and repair must also be considered.

In order to optimise preventive maintenance, it is necessary to identify the following for each part

- The reliability distribution parameters for the main failure modes:
- The effects of all failure modes
- The total cost of failure
- The cost of scheduled repair or replacement

- The likely effect of maintenance on reliability
- The rate at which defects propagate to cause failure
- The cost of inspection or test

PM can be divided into *condition based maintenance*, carried out by monitoring and inspecting the equipment and *time-based maintenance* which is carried out at specific times or cycles,

Fixed-Time Maintenance

Planned maintenance is the most widely used form of maintenance. It is most effective if implemented as components begin to wear-out and failure probability increases. Planned maintenance tasks are often grouped together into maintenance downtimes or windows to minimise the total number of planned maintenance stoppages per year. This strategy is seriously flawed because the majority of industrial failure modes are random in nature and so maintenance tasks, based on time, will have limited affect in improving equipment performance. The advantages of fixed-time maintenance include:

- Failures reduced
- Labour used cost-effectively
- Maintenance planned well in advance (provision for labour and material)

The disadvantages include:

- Maintenance activity and costs increased
- Unnecessary and invasive maintenance is carried out
- Applicable only to age related deterioration
- Maintenance sometimes induces failures (infant mortality)

Condition Based Maintenance (CBM)

CBM relies on the fact that the majority of failures do not occur instantaneously but develop over a period of time. CBM involves recording some measurement that gives an indication of machine condition, e.g. temperature increase on an insulation surface and vibration increase on a bearing housing. Condition monitoring is not purely a 'high tech' tool to be used by highly skilled engineers. From the early days of steam trains "wheel tappers" used a hammer to strike a wheel to listen for the distinctive "ring" that said the wheel is healthy and without cracks. Operators who work with equipment every day can listen to equipment and identify changes in noise levels and vibrations. Temperature changes can be felt and these give warnings that something is not functioning correctly and investigation can then be carried out to identify the exact problem. The advantages of CBM include the following:

- Maximises equipment availability
- Some forms of inspection utilising human senses can be inexpensive
- Allows shutdown before severe damage occurs
- Production can be modified to extend unit life
- Cause of failure can be analysed
- Maintenance can be planned;
- Labour can be organised
- Spares can be assembled

A disadvantage of CBM is that some of the techniques used, such as, vibration monitoring, thermograph and oil debris analysis require specialised equipment and training.

Design Out

This can prove to be a very effective method of solving a recurring problem, however it can easily be inappropriately utilised e.g. 'over design'. Before considering designing out a problem, it is important to identify exactly what the root cause of the problem is. Having identified the root cause; there are a number of questions than can be asked to help in the decision process. Is it possible to monitor the condition at this problem area? If so, it may be cost effective to monitor the condition and take action as necessary. If this is not the case, can the problem be designed out? If it can; what will this involve and can it have any adverse affects elsewhere? [Bla92]. Once the procedure has been thoroughly developed, it should be possible to proceed with the design-out project. Finally if design out is been considered, is it a symptom that mistakes were made during the original designing of the equipment?

The advantages of this type of strategy include:

- Some minor design out projects can be inexpensive and guaranteed to work
- A recurring problem can be completely resolved

The disadvantages include the following:

- The root cause of the problem may get missed in the exercise
- Larger design out projects can prove to be very expensive.
- Production can be disrupted for a considerable period of time with larger projects
- The expected result may not materialise
- Unexpected problems may occur as a result of a major project

- Solving a problem in one area may overload and cause problems in another.

Opportunity Maintenance

This in not actually a maintenance strategy, it is a combination of maintenance strategies. It can be useful when a forced stoppage gives maintenance unexpected access to machinery to carry out inspections and/or maintenance. Inspections during routine down times can identify unexpected tasks that need to be carried out but time does not allow it to happen. These tasks can be recorded and scheduled into the first available down time.

3.4.3 Maintainability

The ease with which repairs and other maintenance work are performed under stated conditions and using prescribed procedures and resources, is termed *maintainability*. It is important that maintained systems are designed so that maintenance tasks are easily performed. The skill level required for the diagnosis and maintenance should not be too high, considering the likely experience and training of maintenance personnel and users. Features such as ease of access and handling, the use of standard tools and equipment, and the exclusion of the need for delicate adjustment or calibration are desirable in maintained systems. The design function has no direct influence over maintenance personnel; it can directly control the maintainability of a system. Design for maintainability is closely related to design for manufacture in the sense that if a product is easy to assemble is will usually be easily manipulated in maintenance. The following list gives a number of desirable features of products designed for maintainability [Bla92]:

- Ease of checking whether equipment is working correctly
- Ease of fault location through provisions of test points, and fault indicator lights
- Ease of identification of components and subassemblies
- Ability to access equipment safely
- Good visual and manual accessibility
- Ease of removing and replacing components and subassemblies
- Ease of handling items
- Use of standard parts
- Use of standard tools and test equipment
- Minimisation of tuning and adjusting after repair
- Prevention of incorrect insertion of components through non-symmetrical geometries

- Avoiding need for excessive mental or physical skill of maintenance staff
- Minimisation of the need for maintenance

Maintainability affects availability directly. The time taken to repair failures and to carry out PM removes the system from the available state and the cost associated with this 'down-time' adds to products LCC.

Maintenance Manuals

Maintenance manuals help the operation and all aspects of preventive and corrective maintenance and in reducing product MTTR. It is appropriate in other than very simple products to have two manuals. One for giving the user full instructions in the use and care of the product and the recognition of degraded performance. The other manual giving detailed instructions for the correct implementation of the maintenance. Fundamental features for the second manual include:

- Easy identification of the location, situation and configuration of all parts.
- Identification of all part numbers to permit correct replacement.
- Instructions on how to diagnose faults.
- Instructions on disassembly and assembly of the product.
- An index of the tools required.
- Instructions for checking that the maintenance was successful and the product is working correctly.

It is essential that the maintenance manuals are up-to-date and accurate. Incorrect or outdated manuals can lead to inaccurate diagnostic, imprecise maintenance and subsequent failure.

3.4.4 Inspection Frequency Optimisation

Inspection may be performed on almost all items and has three main purposes [Jar73]. The first is to detect equipment deterioration, including incorrect settings and component wear, so that preventive action can be take to reduce the items' probability of failure and the severity of the failure consequences. The second is to detect the failure of equipment that is expected to be in a state of readiness or working order and if failure is detected corrective action is taken. The third is to obtain data on components, where inadequate field data exists, to assist in the specification of the maintenance strategies or design modifications.

The criteria for inspection frequency optimisation consist of finding the best balance between the benefits and costs of inspection. The act of the inspection itself will cost money and if the inspection cannot be carried out during inactive times and the equipment must be shut down; it will contribute to lost revenue due to the unavailability of the equipment. The following list is a citation relevant to determining inspection optimisation [Bla92].

- Maximisation of net economic benefit. This is applicable to equipment whose benefit is financially quantifiable.
- Minimisation of failure cost per unit time of service life. This is applicable if the equipment has no quantifiable benefit.
- Minimisation of total equipment downtime or unavailability. This is applicable if failure costs are not quantifiable or where availability has an adverse effect.
- Maximisation of operational readiness. This is relevant to equipment that will be required to operate at a random time or respond to unpredictable events.

3.4.5 Replacement Policies

The decision to repair or replace a component or product is an important factor in maintenance management. The effect of this decision is often a substantial contributor to maintenance cost and subsequently LCC. The determination of optimum replacement policy and time is therefore of great economic and strategic importance.

The replacement of components or of equipment is normally for one or more of the following reasons. Firstly, the item has deteriorated in quality, output, or reliability to a level where a new item will provide a significantly better service. Secondly, the item has failed and it is not possible, impracticable, or uneconomical to repair. Thirdly, the items risk of failure has grown to an unacceptable level or failure is imminent. Fourthly, the performance specifications of the item are inferior to that of another available design.

The criteria on which to base a decision to overhaul or replace equipment falls into three main categories: optimisation criteria, acceptability criteria and obsolescence criteria.

Optimisation criteria will include the following:

- Minimum cost
- Maximum benefit
- Maximum output
- Maximum availability

Decisions should be based on optimising the future and should not be influenced by factors as how much was recently spent on repair, or how recently it was bought, or how expensive it was.

Acceptability criteria will include the following [Bla92]:

- Maximum acceptable breakdown frequency
- Maximum acceptable maintenance cost
- Maximum acceptable availability
- Maximum acceptable safety risk
- Maximum acceptable unreliability
- Maximum acceptable quality

Obsolescence criteria has two possibilities [Bla92]:

- The demand on the item remains unaltered, but a superior item that would meet it more economically become available.
- The demand on the item increases to a level that it can no longer satisfy it.

Replacement policies may be categorised according to three main considerations; the first is whether the policies refer to repairable or non-repairable items. This may seem like an obvious consideration due to the fact that a non-repairable component must be replaced. However replacement policies are often based on the behaviour of more than one item, some of which may be repairable. The second consideration is whether the policies refer to repairable items and the repair is minimal. In this case the item is replaced according to a predetermined schedule and minimally repaired if failures occur between these scheduled occasions. The replacement schedule can be based either on item operating hours or calendar time, or on the number of minimal repairs since the last replacement. The third consideration; the repair is undertaken only if the cost of a minimally repaired item, estimated at post-failure inspection, does not exceed a predetermined *repair cost limit.*

Under these considerations replacement policies can be divided into a number of categories, as follows [Asc84].

- The item is replaced either at failure or after a planned fixed operating time whichever comes first. Applicable to non-repairable items.
- Pre failure replacement based on *block replacement* where the item is replaced on calendar time and not operating hours. The renewal is therefore independent of when the last failure occurred. Applicable to non-repairable items.
- The item is replaced after a planned number of operating hours, regardless of the number or intervening failures. After each failure the item is minimally repaired. Applicable to repairable items.
- The item is replaced after a number of predetermined failures. The item is minimally repaired for the predetermined number of failures and then replaced.

- The item is replaced after either a planned number of operating hours or a predetermined number of failures whichever occurs first.
- Opportunistic replacement taking the opportunity of system idle time due to failure of another component to undertake a replacement.

The above policies can also be combined or modified to best suit a required function. For example items may be overhauled rather than minimally repaired to avoid replacement if this is what is required.

Replacement Optimisation Models

There are a number of optimisation models in use to help decide the time a component is most economically replaced.

Terbough's model [Ter56] is responsible for the existing rule of thumb that replacement is optimum when the accumulated operating and maintenance costs due to deterioration equals the net acquisition cost. This model is aimed at minimising the average annual cost and assumes a constant inferiority gradient throughout its life. The inferiority arises from both actual deterioration and technological inferiority relative to available replacements. This model suffers from the deficiency of its linear inferiority growth assumptions and also it age dependant salvage value assumptions. *Smith's model* [Smi57] was developed for the replacement of tractors units and aims at maximising the total present value of all future net benefit. It uses continuous discounting equations to include operation, repair and replacement variables. *Alchian's model* [Alc85] provides an extremely complete formulation where the total cost of providing a 'stream of service' consists of the current value of the existing equipment, the net cost of switching from the existing to the new equipment, the total net cost at projected intervals, and the operating cost which includes failure and maintenance costs of the present and all future equipments. Like Smith, Alchian considers technological growth of future replacements, Smith uses linear increase of initial net earning of successive equipment and Alchian modelling technological growth by making the initial cost and income rates of the progressive sequence of equipments negative exponential functions of calendar time, the former decreasing and the latter increasing with time. Within each replacement interval the cost rate increases and the income rate decreases because of the incumbent equipment's deterioration with age. *Jardine's models* [Jar73] deal with thirteen different replacement situations or optimisation criteria. His procedure is to calculate the value of the optimisation criteria for various values of the control variable and by inspecting a graphical representation, determine the optimum replacement time.

Equivalent Annual Cost (EAC) [Bla92] is the average net annual cost of an equipment life cycle, taking into account acquisition cost, annual costs and final salvage value.

3.4.6 Overhaul Policies

As with replacement policies, it is essential to include overhaul policies in the maintenance management function. In contrast to equipment repair, which is localised corrective action in response to equipments failure or degradation, *overhaul* is a restorative maintenance activity applied to the equipment as a whole, normally scheduled to take place preceding failure or significant loss of performance. Overhaul can generally be accepted as the equipment's renewal process, however a complete return to an as-good-as-new (AGAN) state is seldom achieved. The decisions are must be made concerning overhaul are [Jar73]:

- The criteria that determines whether and when overhauls should take place.
- The points in time at which decisions whether to overhaul are to be made, bearing in mind that considerable preparation may be required for the implementation of these decisions.
- The points in time when decisions to overhaul will be implemented.
- The degree to which equipment is to be overhauled.

With concern to the first of these, the criteria on the whole are the same as the criteria that determine replacement policies, particularly minimisation of future costs, maximisation of future benefits, acceptably low failure frequency and acceptably low risk of future failures or catastrophic events due to future failures. The decision is usually based on the likelihood that these can be achieved by equipment overhaul or replacement and will often be based on economic optimisation or on considerations where alternatives provide the most economical way of meeting the acceptability criteria. The effects of obsolescence must be brought into the calculation of economic optimisation. Overhaul, unlike replacement, does not provide a defence against obsolescence. Other considerations are system disruption or availability as well as the level of skills and expertise required for the overhaul.

Overhaul can vary from replacing, refurbishing and adjusting only those components that are suffering from excess wear or under-performance, to a complete renovation of the whole equipment. Different levels of overhaul will cost different amounts, require different downtimes and achieve different levels of post-overhaul performance and reliability levels [Bla92].

The cost of overhaul is likely to vary from occurrence to occurrence, mainly because different sets of parts will be replaced depending on their wear-out life. It may also not be possible to predict the overhaul cost of the equipment until a thorough inspection is carried out and just as there are repair cost limit policies to determine whether to repair or replace, there are overhaul cost limit policies to determine whether to overhaul or replacement.

3.5 Product Reliability

Dhillon defines reliability as "*the probability that an item will carry out its mission satisfactorily for the desired period when used according to the specifications*" [Dhi89]. In percentage terms a product may have a reliability of between zero and one hundred percent for the desired period. Since the concept of reliability is often viewed as a probability, any attempt to quantify it must involve the use of statistical methods. An understanding of statistics as applicable to reliability engineering is therefore necessary. Variability and chance play an important role in determining reliability. Basic parameters like; mass; dimension, strengths and stresses are never absolute but are subject to variations due to materials, processes and human factors. Some parameters may also vary with time. Understanding the laws of chance and the causes and effects of variability is therefore necessary for the creation of reliable products.

There are practical problems in applying statistical knowledge to engineering problems. This is not because the theory is wrong but because engineers have to cope with much greater degrees of uncertainty. Sources of uncertainty are introduced because reliability is often about people who make and people who used the product, and because of the widely varying environments in which products might be used. Reliability is often concerned with the behaviour of unlikely combinations such as load and strength, variations are often hard to quantify. Further difficulties arise in application of statistical theory to reliability engineering owing to the fact that variation is often a function of time or of time related factors such as operating cycles and maintenance periods. Therefore the reliability from any past situation cannot be used to make credible forecasts for the future without taking into account non-statistical factors such as design changes and maintenance strategies.

3.5.1 Reliability and LCC

There are two main purposes for considering reliability-engineering concepts to LCCA. The first is to select, purchase, use, maintain and replace a product in such a manner that dependability, consistent with the products function, is achieved. The second is to do this in an economically optimised fashion, noting that product failure costs money, not only because of repair or replacement costs, but also because of the costs of failure-caused damages and equipment downtime.

The quality of a product can be described as 'fitness for purpose'. For the product user, a very important aspect of this fitness is product dependability, which is comprised of reliability, availability, and maintainability.

Quantifying reliability values, or attempting to put financial or other benefit values to the level of reliability is the subject of debate. The traditional, producer orientated view of reliability is that in which a product is assessed against a set of specifications and attributes, and when passed it is delivered to the customer. The customer accepts the product and allows that it might fail at some time in the future. This simple approach is often accompanied by a warranty. However, this approach provides no measure of quality over a period of the product life cycle, particularly outside the warranty period. Even within the warranty period, the customer usually has no grounds for further action if the product fails once, twice or several times, providing that the manufacturer repairs the product each time as promised [Oco92].

If it fails often the manufacturer will suffer high warranty costs and the customer will suffer inconvenience. Outside the warranty period only the customer will suffer. However, the manufacturer may incur loss of reputation, possibly affecting future business. We therefore come to the need for a time-based concept of reliability. Reliability concerned with the failures during the life of the product.

Reliability Distribution

A statistical distribution is described by its probability density function (p.d.f.) or simply the *distribution* of the plot of measured values. This function is commonly used to describe probability and reliability distributions. A p.d.f. is described by the following the four aspects are considered: The *central tendency,* about which the distribution is grouped. The *spread,* which indicates the extent of the variation about the central tendency. The *skewness*, indicating the lack of symmetry about the central tendency and the *kurtosis,* which indicated the 'peaked-ness' of the p.d.f. These will designate the shape of the p.d.f.

Probability and reliability distribution developed mathematically are used to fit data coming from real world processes or. Once a distribution is associated with a process, predictions and calculations can be made using the statistical model. This is the basis of reliability assessment and reliability predictions. Some of the most common distributions used in engineering problems are the *Binomial, Normal*, the *Lognormal*, the *Exponential*, and the

Weibull, distribution functions. Methodologies have been developed in order to assign the appropriate mathematical distribution to a real life process [Bla92]. The first step generally consists of designing and carrying out tests with a representative sample of population. The results of these tests are then plotted following certain directions, which will depend upon the type of analysis. The remaining task is fitting a curve to these points. This curve represents the process with a certain degree of confidence. Choosing the right curve is a matter of experience and of having sufficient quality data.

Repairable and Non-Repairable Items

In reliability it is important to distinguish between repairable and non-repairable components or products when measuring reliability. For a *non-repairable* item, reliability is the survival probability over the items expected life, when only one failure can occur. During the item's life the instantaneous probability of the first and only failure is called the *hazard rate*. Life values such as the *mean time to failure* (MTTF), or the expected life whereupon a certain percentage may have failed, are other reliability characteristics that can be used. A non-repairable item may comprise of one or more parts or may be comprised of many individual parts. When a part fails in a non-repairable system, the system fails and the system reliability is therefore a function of the time to the first part failure [Ire95].

Items that are repaired when they fail are called *repairable* items in reliability terms. In this case the reliability is the probability that failure will not occur in the period of interest when more than one failure can occur. It can also be expressed as the *failure rate* or the *rate of occurrence of failures* (ROCOF). The term *failure rate* is often incorrectly used for non-repairable items. This is due to the fact that a repairable system may comprise of many parts or subsystems. The subsystems may be repairable or non-repairable. The part being non-repairable cannot have a failure rate, but will contribute to the repairable system's failure rate. The expression ROCOF is often used to stress this point. [Bla92]

Repairable system reliability can also be characterised by the *Mean Time Between Failures* (MTBF), but only under the particular condition of a constant failure rate. *Availability* is also a concern of repairable items, since repair takes time. Availability is affected by the failure rate and by the maintenance time. Maintenance can be corrective or preventive. It is therefore important to understand the relationship between reliability and maintenance, and how both reliability and *maintainability* can affect the availability. Maintainability and availability are further discussed later in this chapter.

Some items can be referred to as both repairable and non-repairable. The cost and ease of repair of a component will determine if the component is to be replaced or repaired on failure, i.e. non-repairable state or repairable state.

Failure Patterns

For a non-repairable system there are three basic ways in which the pattern of failures can change with respect to time. The hazard rate may be constant, increasing and decreasing. By appreciating the way a hazard rate behaves with time a good deal can be understood about the cause of failure. A constant hazard rate is characteristic of failures that are caused by the application of loads in excess of the design strength. For example failure due to maintenance induced failures of mechanical equipment, typically occurring randomly and at a generally constant rate over time. Fatigue brought on by cyclic loading does not occur for a finite time and exhibits an increasing probability of occurrence or hazard rate. Decreasing hazard rates are observed in items that become less likely to fail over time. This is often observed in electronic equipment. 'Burn-in' or screening of electric parts is a good example of the knowledge of decreasing hazard rate used in increasing reliability. During burn-in the products are application tested and stressed, the substandard parts fail and are rejected and the surviving population is more reliable. The combined effect of produces the *bathtub curve* shown in figure 3.3 [Oco92]. The failure pattern of repairable items can also vary with time and important observations can be made from the trends. A constant failure rate can indicate externally induced failures as in the constant hazard rate of non-repairable items. It is also typical of complex systems subject to repair and overhaul, where different parts exhibit different patterns of failure with time and parts have different ages since repair or replacement. Repairable items can demonstrate a decreasing failure rate when reliability is improved by progressive repair, as better 'more reliable' parts replace defective parts that fail.

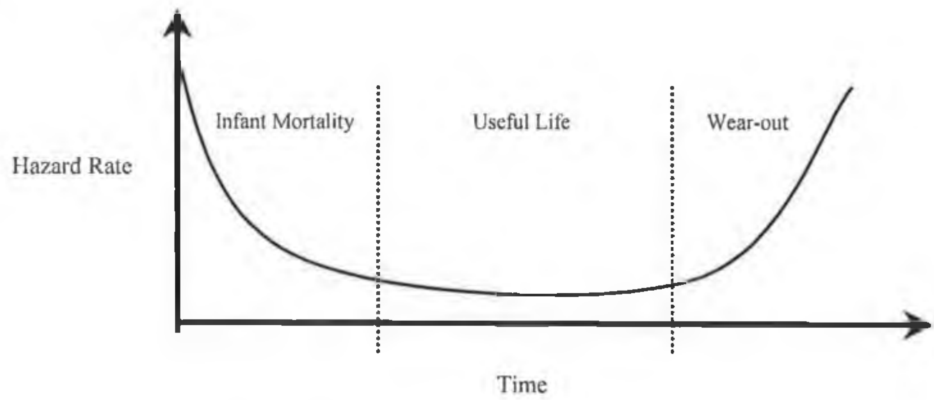


Figure 3.3 Bathtub Curve [Oco92]

Component screening is applied for this purpose. An increasing failure rate may occur when parts begin to deteriorate with age or *wear-out* failures of parts becomes predominant. The pattern of failures with time of repairable systems can also be illustrated by the use of the bathtub curve shown in figure 3.3. However, the failure rate replaces the hazard rate plotted against time.

Reliability Block Diagram (RBD)

Up to now the reliability of individual parts has been discussed. A number of parts will make up a component, which in turn makes up a product. In industry it is necessary to estimate the reliabilities of equipments that interact with each other. Before any form of reliability analysis is attempted, it is necessary to represent the system under consideration, as a block diagram [Ire95]. A block diagram with an individual block for each unit can represent the entire product or system. There are a number of RBD system configurations that can be used:

Series Systems: In a series system, failure of any unit constitutes system failure. The reliability of the system is the product of the reliabilities of the units making up the system Placing units in series increases the failure rate and reduces the overall availability of the system

Full Active Redundancy: In an active redundancy system a number of units sustain the function until one fails; the remaining unit can continue to provide the function.

M-out-of-N In these cases individual units share provision of the function, which can be sustained at a satisfactory level should one or more of the units fail. In active and standby redundancy systems this can be known as m-out-of-n models, at least m units out of a total of n must be in operation for the system to operate.

Failure Modes Effects and (Criticality) Analysis (FME(C)A)

FMEA & FMECA are engineering analysis that, if performed properly, can be of great value in assisting the decision making process of the engineer during the design stage or maintenance review to analyse possible and existing modes of failures of a piece of equipment. The analysis is often called a 'bottom up' analysis as it examines equipment at the spare level, and considers the system failures that result from their different failure modes. In an FMECA analysis a relative criticality is calculated for each failure mode.

The following are some of the benefits of FMECA [Ire95]:

- It provides designers and maintenance engineers with an understanding of the structure of the system, and the factors that influence reliability.
- It helps to identify items that are reliability sensitive or of high risk, and so gives a means of deciding priorities for corrective action.
- It identifies where special effort is needed during manufacture, assembly or maintenance.
- It establishes if there are any operational constraints resulting from the design.
- It gives assurance to management and/or customers that reliability is being or has been properly addressed in the project.

A good FME(C)A will present in tabular form for each failure mode of all the components:

- The effect on sub-assemble, assembly, sub-system etc. to system level;
- Likelihood of occurrence;
- Severity and criticality (for a criticality analysis).

The report may also include further information, such as recommendations for:

- Manufacture and assembly (inspection, test, quality of components etc.);
- Maintenance (inspection, test, replacement periods etc.);
- Detestability (user, maintainer, etc.).

Fault Tree Analysis (FTA)

Fault Tree Analysis can be a very detailed process and is used in the analysis of complex systems. It complements FMECA in that it is a top-down analysis, starting with a system fault or the top event and analysing this fault in terms of sub-system faults. For example in the refrigeration industry the top event could be a leak of refrigerant from a heat exchanger. The heat exchanger is then analysed to identify every possible way it could leak such as a leaking flange or cracked pipe. Each sub event is then analysed to identify how each one could occur, such as incorrect flange packing fitted, incorrect flange pressure, excessive pressure, etc. One of the next levels would then be to identify all possible reasons for a pressure build up inside the heat exchanger pipes. The process is complete when every possible root cause of a leak from the heat exchanger has been identified. Each event can have a probability associated to it. The probability of a leak from the heat exchanger can estimated, i.e. the reliability of the heat exchanger can be calculated

Reliability Management

The concept of reliability in industry goes beyond statistics and probability and is often used in the general sense to include all reliability related activities i.e. reliability, availability, and maintainability. Reliability is too frequently viewed as an activity mainly relevant to design, analysis and production. Application of its concepts by the equipment user is equally important, since these concepts guide production selection, specification and procurement, and the basis for performance monitoring and optimised replacement policies. Furthermore, field failure reporting and analysis is the only way of creating a meaningful reliability and maintainability databank for use in future product procurement, system design and the determination of optimum replacement schedules. [Bla92]

A formal reliability programme is necessary whenever the risk or costs of failure is high. The key elements in implementing a successful reliability program are in the continuous commitment at a managerial level. It is up to the these decisions makers to understand and access the need for reliability, to analyse the economics involved, the direction to take, and to allocate the resources that are needed in order to do so.

3.6 Product Availability

Availability is the ability of an item, under the combined effects of its reliability, maintainability and maintenance support, to perform its required function [Bla92] or the proportion of total time that the item is available for use. The availability of a repairable item is therefore a function of its failure rate and of its repair or replacement rate. The proportion of the total time that the item is available is termed the *steady-state availability.* The probability that an item will be available at a stated instant in time is termed the *instantaneous availability.*

Availability is an important consideration in relatively complex systems, such as refrigeration units. In such a system, high reliability alone is not sufficient to ensure that the system will be available when needed. It is also necessary to ensure that essential preventive maintenance tasks can be performed quickly, if possible without shutting down the system.

3.7 Maintenance Methodologies

The traditional approach to maintenance, based on fixed interval component replacement and overhaul, is rapidly being replaced by a new framework using condition based maintenance approaches, which focuses strongly on the consequences of failure. Maintenance is also responding to changing expectations. These include a rapidly growing awareness of the extent which product failure affects safety and the environment, a growing awareness of the connection between maintenance and product quality, and increasing pressure to achieve high product availability and to contain costs [Mou92]. In the face of this change, managers and engineers are looking for new approaches to maintenance. They seek a strategic framework to implement these approaches, to correctly apply those that are of most value to them and their customers. Two of the main methodologies are *reliability-centred maintenance* and *total productive maintenance.*

3.7.1 Reliability Centred Maintenance (RCM)

RCM evolved during the 1950s in the aircraft industry as a result of a number of major reliability studies concerning complex equipment. In particular, the 1960 FAA/Airline Industry Reliability Program Study was initiated to respond to rapidly increasing maintenance costs, poor availability, and concern over the effectiveness of traditional time-based preventive maintenance strategies [Ken00]. This centred around challenging the traditional approach to scheduled maintenance programs which were based on the concept that every item on a piece of complex equipment has a optimum age at which complete overhaul is necessary to ensure safety and operating reliability.

RCM is a strategic approach for determining the most appropriate maintenance strategy where each component is systematically analysed to identify their failure modes and appropriate maintenance tasks are then assigned. This analysis is carried out by asking seven questions about each component [Mou00].

1. What are the functions and associated performance standards of the asset in its present operating context?

Functions are categorised as follows:

On Line Functions that are in use continuously or at such frequency that personnel will be continuously aware of their state.

Standby Functions that are under the supervision of operations personnel but are used so infrequently that a special check is required to identify (hidden) failures that have occurred.

2. What are the failure modes?

The failure modes to be considered are:

1. Failures that have previously occurred on the equipment or similar machines.
2. Possible failures that have not occurred before but could have serious consequences.

3. Failure modes for which preventive maintenance has already been applied in order to prevent failure.

3. What causes each failure?

Each potential failure must be investigated to identify every possible cause. Maintenance actions are then put in place to tackle the causes and not the symptoms of a failure. This stage of RCM must be controlled as time can be wasted investigating unlikely causes of failure.

4. What happens when each functional failure occurs?

It is necessary to understand the consequences of each functional failure to determine if any preventative maintenance is actually required.

5. In what way does each failure matter?

Once the failure consequences have been identified, they are categorised, which will aid in the determination of an appropriate maintenance task.

6. What can be done to prevent each failure?

The characteristics of the individual failure mode will determine which one of the four maintenance strategies will be chosen

7. What should be done if a suitable preventative task cannot be found? (Default tasks*)*

An obvious maintenance task may not exist for some failure modes. RCM provides a detailed decision tree to ensure the correct type of maintenance task is selected for each failure mode.

Implementing RCM

RCM can be implemented through the setting up of maintenance review groups who work through the above 'seven questions' to develop the maintenance requirements for specified equipment. This approach necessitates a high degree of understanding of the equipment being analysed. If the necessary skills do not exist within the company external specialists may be invited to join the group to discuss specific problem areas. A facilitator should control the flow of information, ensuring it is recorded on specific RCM worksheets and chair each review group. The group works together to answer the first four of the 'seven questions'. The RCM Information Worksheets are used to record the answers to these questions:

- Function of the asset
- Functional failure

- Failure mode
- Failure effect

The next stage of RCM considers the final three of the 'seven questions' to evaluate the consequences of the failures and based on the consequences, identify appropriated maintenance tasks. The RCM Decision Tree is used in this task. The output from the groups will be RCM Decision Worksheets detailing:

- Item or component
- Proposed task
- Periodicity
- Trade

It is then the responsibility of maintenance and production management to introduce these revised tasks to the maintenance employees.

3.7.2 Total Productive Maintenance (TPM)

Unlike RCM that emerged from the American aircraft industry, TPM had its origins in the Japanese car industry in the 1970s. It evolved at Nippon Denso, a major supplier of the Toyota Car Company, as a necessary element of the newly developed Toyota Production System, which was originally thought to only incorporate Total Quality Control (TQC), Just in Time (JIT), and Total Employee Involvement (TEI). It was not until 1988, with the publication in English of the first of two authoritative texts on the subject by Seiichi Nakajima, that the western world recognised and started to understand the importance of TPM [Ken00].

It became obvious that TPM was a critical missing link in successfully achieving not only world class equipment performance to support variation reduction and lead time reduction, but was a powerful new means to improving overall produce performance. TPM is now having a major impact on bottom-line results by revitalising and enhancing the quality management approach to substantially improve capacity while significantly reducing not only maintenance costs but also overall operational costs. Its successful implementation has also resulted in the creation of much safer and more environmentally sound workplaces.

The Evolution of TPM

The traditional view of maintenance was to balance maintenance cost with an acceptable level of availability and reliability often influenced by the level of buffer stocks, which hid the immediate impact of equipment problems. In traditional companies, maintenance is seen as an expense that can easily be reduced in relation to the overall business, particularly in the short term. Maintenance managers have argued that to increase the level of availability and reliability of the equipment, more expenditure needs to be committed to the maintenance budget [PMRC]. With the on set of substantial availability problems caused by new ways of running equipment management soon realised that just giving more resources to the maintenance department was not going to produce a cost effective solution.

This conflict between maintenance cost and availability is similar to the old quality mind-set before the advent of Total Quality Control (TQC): that higher quality required more resources, and hence cost, for final inspection and rework. TQC emphasised 'prevention at source' of the problem rather than by inspection at the end of the process. Instead of enlarging the inspection department, all employees were trained and motivated to be responsible for identifying problems at the earliest possible point in the process so as to minimise rectification costs. This did not mean disbanding the quality control department but having it now concentrate on more specialist quality activities such as variation reduction through process improvement. This new approach to quality demonstrated that getting quality right first time does not cost money but actually reduces the total cost of operating the business.

This new Quality approach of prevention at source was translated to the maintenance environment through the concept of TPM resulting in superior availability, reliability and maintainability of equipment and also significant improvements in capacity with a substantial reduction in both maintenance costs and total operational costs. TPM is based on prevention at source and is focused on identifying and eliminating the source of equipment deterioration rather than the more traditional approach of either letting equipment fail before repairing it, or applying preventive strategies to identify and repair equipment after the deterioration has taken hold and caused the need for expensive repairs.

The Importance of Overall Equipment Effectiveness

Many companies who recognise the important roll equipment and process performance have on bottom-line results are turning to the measure which drives TPM called *Overall Equipment Effectiveness* (OEE) which incorporates not only availability, but also *Performance Rate* and *Quality Rate*. Hence, OEE addresses all losses caused by the equipment: not being available when needed due to breakdowns or set-up and adjustment losses; not running at the optimum rate due to reduced speed or idling and minor stoppage losses; and not producing first pass, high quality output due to defects and rework or start-up losses. A key objective of TPM is to cost effectively maximise Overall Equipment Effectiveness through the elimination or minimisation of all losses

The Cost Impact of Failure

TPM significantly reduces operational and maintenance costs by focusing on the Root Cause of Failure through the creation of a sense of ownership by the plant and equipment operators, maintenance and support staff to encourage prevention at source. To help understand the thinking behind TPM there is a need to investigate what causes failure [PMRC].

The concept of the *Root Cause of Failure* is the tool most commonly used to assist in the search for the root cause. The *5-Whys* is a simple technique of asking *why?* 5 times, recognising that statistically it has been shown that after 5 whys it is most likely to discover the root cause [Ken00].

Operator Equipment Management

Operator Equipment Management is about caring for equipment at the source so as to ensure the basic equipment conditions are established and maintained. This is to allow the successful implementation of planned preventive and predictive maintenance to be successfully administered by the maintenance department. Ultimately operators become responsible for the overall equipment effectiveness of their equipment through a *root cause* approach to defect avoidance [Zwi00].

A systematic approach, supported by a robust process, needs to be adopted to allow the changes to be implemented at a rate proportional to the organisation's evolving culture.

Although implementation of Operator Equipment Management needs to be specific to the situation and plant environment, the final goal of achieving mature equipment-competent area-based teams is for the area-based teams to be responsible for the Overall Equipment Effectiveness (OEE) of their plant & equipment. This does not mean operators carry out all maintenance activities, but that they are responsible for knowing when they need to carry out the simple defect avoidance and maintenance service work themselves and when they should call in maintenance experts to repair problems, which they have clearly identified.

3.7.3 The Relationship between RCM and TPM

The original precepts for RCM were developed for the aircraft industry where 'basic equipment conditions', i.e. no loose components, contamination or lubrication problems, are mandatory, and where operators skill level, behaviour and training is of a high standard. Unfortunately in most operations these basic equipment conditions and operator skill and behaviour levels do not exist thus undermining the basis of any RCM application.

For this reason, the application of TPM as a company wide improvement strategy is highly advisable to ensure that basic equipment conditions are established; and equipment-competent operators are developed.

Before attempting a full RCM analysis or a partial RCM approach following the basic RCM process. Failure to do this in an environment where basic equipment conditions and operator error are causing significant variation in the life of equipment parts will block the ability to cost effectively optimise maintenance tactics and spares holding strategies.

The other key difference between RCM and TPM is that RCM is promoted as a maintenance improvement strategy whereas TPM recognises that the maintenance function alone cannot improve reliability. Factors such as operator lack of care and poor operational practices, poor basic equipment conditions, and adverse equipment loading due to changes in processing requirements such as introduction of different products, raw materials and process variables, all impact on equipment reliability. Unless all employees become actively involved in recognising the need to eliminate or reduce all losses and to focus on 'defect avoidance' or early defect identification and elimination failures will never be cost effectively eliminated in an industrial environment.

3.8 Computerised Maintenance Management System (CMMS)

Computerised Maintenance Management Systems are increasingly being used to manage and control equipment maintenance in modern industries. In recent years commercial companies have come to recognise the value of these systems as a maintenance performance and cost improvement tool. Companies are also investing in CMMS's because they are a key part of the RCM and TPM philosophy [Wei00].

3.8.1 Manual Systems

Computerised systems are now being installed in preference to the paper based manual preventive maintenance systems that have been around for many years. Commonly, these paper systems are little more than a record of scheduled maintenance. These have had limited success because of:

- The problems associated with training people to be disciplined enough to uphold the maintenance system, that is, to input the data to the system

- The effort required, by supervisors and managers, in the organisation and documentation of the system
- Service group's reluctance to become involved in paper work
- The effort associated with the acquisition and compilation of meaningful data and statistics from the system.

In a typical paper system, each piece of equipment or asset will have a history card or file. This file will contain the asset's detailed description, along with information on maintenance procedures to be used, periodicities, trades required and last maintenance dates. To determine what maintenance is due requires someone to look through every card, check each of the last maintenance dates against the periodicities and select those, which are due. Next, the appropriate maintenance *procedures* must be selected from the file before work instructions are raised and issued to the relevant trade's persons. Upon completion of the work, the relevant asset's file must be selected, details updated and the file replaced in its slot. Whether one or several persons complete these tasks, many man-hours are involved and to properly support any reasonable sized system of this type can become virtually a full time occupation.

3.8.2 What does a CMMS do?

CMMS's often fail soon after implementation because they have been badly specified. Often it is not until after the installation is complete, that users realise their new system does not meet their requirements. Some of the basic functions available from a CMMS are [Fer00]:

- Control the company's list of maintainable assets through an asset register
- Control accounting of assets, purchase price, depreciation rates, etc.
- Schedule planned preventive maintenance routines
- Control preventive maintenance procedures and documentation
- Control the issue and documentation of planned and unplanned maintenance work.
- Organise the maintenance personnel database including shift work schedules
- Assist in maintenance project management
- Provide maintenance budgeting and costing statistics
- Control maintenance inventory (store's management, requisition and purchasing)
- Provide analysis tools for maintenance performance.

The above listing illustrates most of the functions, which may be available in a CMMS. It is extremely important however to be clear on the following [Wor99]:

- Are the resources and the commitment to implement the system? Even a medium sized company a significant amount of time will be required to collect and input data. Someone will be required to create a library of maintenance procedures where this does not already exist.
- Is there a willingness to provide support and administer the system on an on-going basis? The extent of this support will clearly be dependent on the size of the system.
- Is there a requirement that the system controls stores and or purchasing? Is there a willingness to commit the people power to input the data for this?
- Is there a need to use the system for accounting purposes or just maintenance control?
- Is there a need for a multi-user system, and if so, how many people are likely to use it?
- On multi-user systems, is there a willingness to commit personnel to the training, which is likely to be required?

In conclusion, much thought and discussion must take place before any decision can be made on the system's requirements.

3.8.3 Expected CMMS Returns

The transition to CMMS will require a substantial investment. The return on this investment will be dependent on the suitability of the selected CMMS package, the effectiveness of its implementation and the commitment of all personnel to the new system. Many systems are developed with the following goals:

- Increased product availability - by reducing down time
- Lower operating costs - by reducing overtime, spares inventory and
- Prolonged asset life - by more effective maintenance
- Reductions in spare part inventory - by identifying parts through links to equipment
- Much improved control over preventive maintenance schedule and documentation
- Simplified access to maintenance data and statistics - through report generator

One of the main benefits to be gained from a CMMS is that it helps and encourages the user to focus on good maintenance practice. Procedures become formalised and organised through having to conform to the requirements of the new system. Table 3.1 illustrates a few of the common differences in an organised versus a disorganised maintenance department.

Badly Managed Maintenance	Well Managed Maintenance
• Maintenance is heavily dependent on skilled and specialised trades persons • No records are kept and much of the equipment history is inside people's heads • It is impossible to estimate maintenance costs • High levels of maintenance related overtime are being worked • Maintenance is a perceived by management as a necessary evil • The greater amount of maintenance man hours is spent on unplanned work	• Maintenance is recognised by management as an integrated, essential part of production • The Maintenance section focus is upon making equipment available through increased reliability • There is an emphasis on analysis of the reasons for down time • There is a commitment to planned work • There is an emphasis on training • Continuous improvement programs are in place • Operators are involved in the maintenance of their equipment

Table 3.1 Factors in Good and Bad Maintenance [Fer00]

3.8.4 Implementation Strategy

With the impact any CMMS will have on a service department it is important that a proper implementation strategy is developed. Apart from decisions on the functions required from a system, it will be necessary to properly manage its installation. Production and service group training requirements will have to be considered. The initial data input, which in itself can be a huge task, will have to be planned. If a good company asset register is available this will help, but drawing from experience, it is unlikely that even if it does exist, this will have been properly maintained.

The commitment of all involved should be assured before proceeding with the project since lack of commitment from any one group could cause it to fail. The commitment of service groups should be sought at an early stage since it is likely that, at least initially, they will view any changes with suspicion.

Many people see the introduction of the CMMS as a means of closely monitoring the amount of work, which they are doing. While it is likely that there will be an element of this, the positive aspects should be selected and used to 'sell' the system. For example, stress the ease with which users will be able to get information and the access they will have to formal work procedures. If stock control is being introduced stress the advantages of this. When the system has been implemented and accepted it is likely that it will improve accountability due to jobs being linked to personnel. Also, if service groups are to be involved in the input of data to the system, it is crucial that they are fully trained and aware of the importance of accurate input [Wor99].

3.9 Maintenance Process Management Model

As discussed previously, many companies increasingly search for competitive advantage; maintenance and reliability of products have evolved as major contributors. Organisations are being challenged to improve efficiency. Various processes, such as RCM, FME(C)A are being implemented as part of improvement initiatives with varying degrees of success [Fer00]. Many of these initiatives result in some progress toward enhanced reliability of a product, but to achieve world-class performance, a fundamental shift in the mindset of workers and the nature of work is needed. A new approach to maintenance management can provide the capability to change the nature of work and drive a reliability-orientated culture.

The author proposes a new model called Maintenance Process Management Model (MPMM)[1]. This model integrates processes to create a world-class approach to maintenance management. It is divided into separate processes and sub-processes describing the high-level flow between each. Criticality ranking, failure analysis, equipment reliability strategy development, equipment reliability strategy implementation, work management, reliability analysis, and external processes comprise the model (See figure 3.4). MPMM provides the elements necessary to support a world-class management program. Many organisations are defining and executing standard business processes for maintenance work management. This is most often driven by a computerised maintenance management system (CMMS). The majority of new processes implemented by world-class performers have been proactive, reliability-focused processes and post-execution reliability analysis. Some organisations may find improvement by focusing on traditional work management, but to see long-term improvements, companies must implement other processes.

A reliability-centred model for maintenance management seeks to better understand components before failure, put in place proactive equipment reliability strategies to cost-effectively eliminate the likelihood and consequence of failures, and move toward an environment where the only equipment failures will be pre-determined and due to wear-out.

[1] MPMM is developed using the available information, structure and requirements of Thermo King Europe.

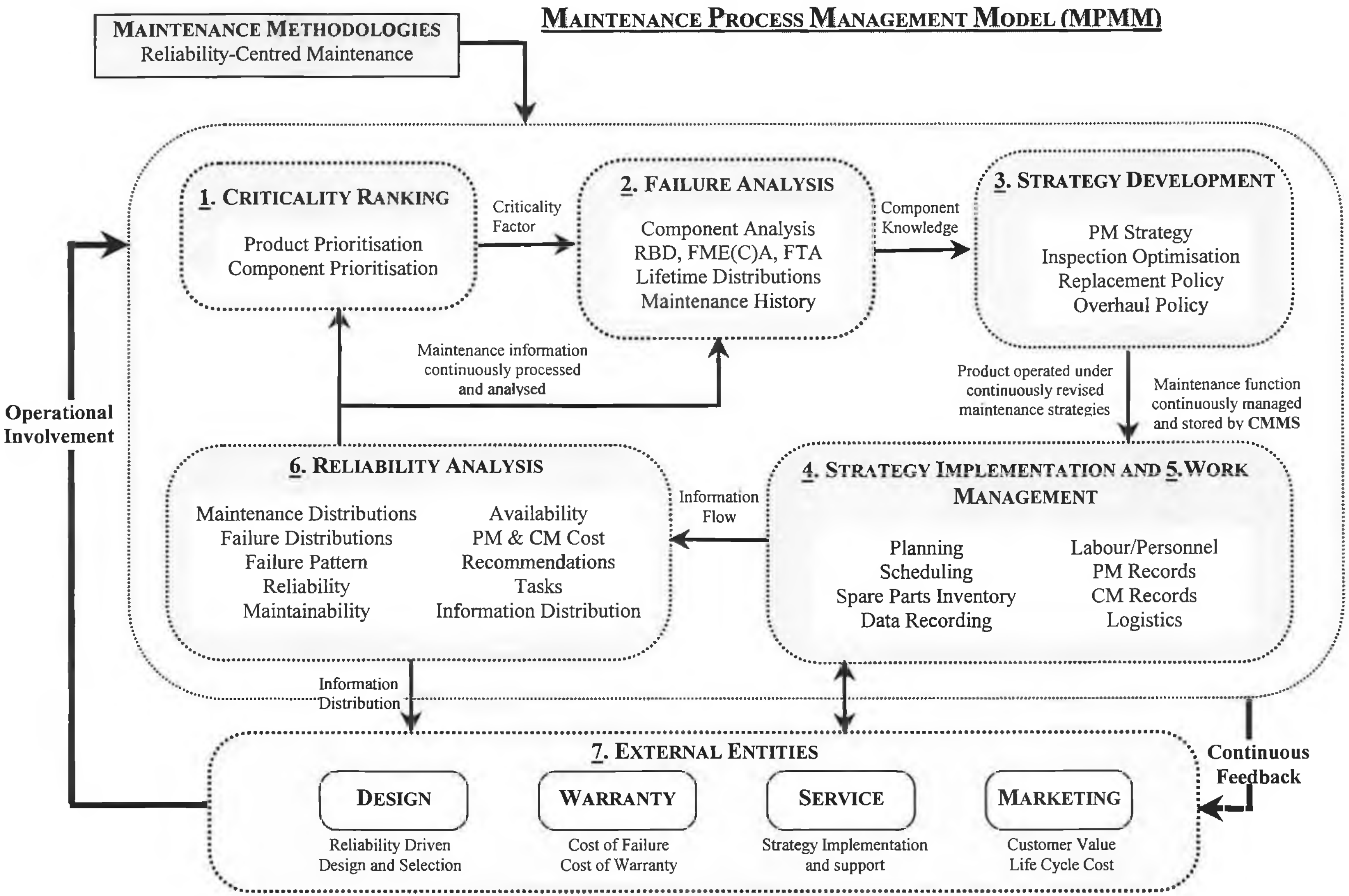


Figure 3.4 Maintenance Process Management Model

3.9.1 Elements of the Model

The Maintenance Management Process Model can be divided into a seven-process approach. Each process is described next.

Process 1: Criticality Ranking Process

The *Criticality Ranking Process* is used to better understand and identify products that are truly critical to the business. This process is essential to a cost-effective approach to implementing the model. It provides the basis for focusing personnel and other resources on the equipment that has the most direct impact on the business. This process guides the organisation to the product where efforts should be focused, along with the specific components within that product that deserve the most attention.

Process 2: Failure Analysis

Equipment identified as *critical* then enters into the *Failure Analysis* (FA) process. The FA process includes common RCM elements including identifying functional definitions for equipment, functional failures, failure modes and causes, and the expected functional life. The FA process is not dependent on equipment history, although comprehensive performance history and experience will allow for better analysis and results[2].

Process 3: Strategy Development

This is the natural extension of the Failure Analysis process. Equipment Reliability Strategies (e.g., inspection optimisation, preventive maintenance (PM), etc.) are developed for *critical* products and focus on the detection, alleviation, and/or elimination of the expected failure modes. The strategy's intent is to ensure the equipment continues to perform its intended functions for the expected functional life, within its current operating context.

Existing PM tasks, original equipment manufacturer (OEM) maintenance recommendations, and regulatory constraints will provide the basis for the strategies, but they often are improved based on a better understanding of the equipment gained through the analysis.

[2] Appendix C provides a sample of the maintenance and failure data used in the models developed by this thesis and calculations carried out in this thesis.

Process 4: Strategy Implementation

A key element of this model is the *Strategy Implementation* process. A considerable amount of work is required to perform the failure analysis and to develop equipment reliability strategies. Depending on the scope of products involved and how well technology is used, there also can be a sizable amount of work involved with implementation of the strategies' tasks. Once a strategy's tasks have been determined, the best implementation approach must be selected.

For instance, if the strategy calls for a recurring type of condition or process monitoring, a decision must be made whether it can be automated or not, whether it could or should be performed as part of an operator's round, or whether it should be part of a PM or other mode of implementation. There also will be opportunities to bundle tasks with consistent scheduling intervals so they can be handled more efficiently as one work effort.

Process 5: Work Management

The *Work Management* process in this model is extremely critical. Many organisations have focused on work management excellence, but in a *reactive* environment. The philosophy in a reactive environment is to 'fix it when it breaks'. This philosophy usually demands personnel to make quick repairs at the sake of preserving evidence, understanding the cause, and updating the strategy to prevent the occurrence of that failure in the future. Elements of a traditional maintenance organisation such as high percentage of reactive work, constant breaking of the schedule, little if any root cause investigation, minimal amounts of PM tasks, etc., are undeviating and perpetual. The prospect for breaking this reactive cycle is poor until an integrated process, focusing on proactive work, is established.

There is and always will be a place for fast and efficient repairs. However, the work management process in this model places the focus on other elements. Better work order prioritisation methods based on criticality can be deployed. Proper analysis of the situation using non-intrusive condition monitoring can eliminate or delay unnecessary work. Inventory and spare parts can be forecast better through the understanding of equipment criticality. Forward-looking schedules can be planned and met. More PM tasks will be performed replacing reactive work. Better equipment history can be documented, providing valuable information necessary for failure and reliability analysis.

Process 6: Reliability Analysis

The *Reliability Analysis* process utilises observed equipment behaviour (See Appendix C) and compares it against the expected failure effects and modes identified as part of the FA, thus creating a continual improvement process. This results in continual reliability strategies that are continually customised to ensure optimal performance for equipment.

The ultimate result of this process is to move toward an equipment-specific reliability strategy for each equipment item based on its actual performance. It is not likely that anyone would ever get to that point nor would it necessarily be practical or cost effective, but the process provides a path to continually evaluate the actual observed conditions and create the optimal equipment reliability strategy for each product.

This process enables the equipment reliability strategies to continually move away from a theoretical model to a realistic one based on actual performance. As observations are recorded, whether good performance, failures, degradation, or any other relevant information, the process provides a path to further customise the equipment-group being studied. There are various types of reliability analyses that can be utilised, some of which were discussed previously in this chapter. The process most often is triggered by a failure or other event. However, another aspect is to perform continual unplanned reliability analyses. These can include the basic types of reporting such as Pareto or frequent failing charts. As observed history becomes more accessible and accurate, advanced statistical modelling, such as distribution analysis, can be used.

Process 7: External Processes.

The *Maintenance Process Management Model* also identifies a number of important *External Processes*. These processes can operate regardless of the status of this model. However, each is considered important to the reliability of products. The more integration with the external supporting processes, the better the overall enterprise maintenance management program.

Throughout the life of a product, there are various environmental and operational factors that impact the Maintenance Process Management Model. The model must be flexible to respond to these factors, which include changes to business strategy, feedstock/raw material, regulatory and environmental compliance, etc. The entire model, its processes, and resulting data should be evaluated for validity upon the introduction of these factors.

For example, Ferguson states "*it is not uncommon for petroleum refiners to change their crude slate over time. In most cases, the plant was built originally to refine a "sweet" crude.*

If they make a decision to start using "sour" crude (indicates changing chemical composition of the crude), this has an effect on the type and frequency of deterioration expected by the equipment" [Fer00] With that in mind, equipment reliability strategies should be reviewed and optimised based on the expected impact of the different factors.

3.9.2 MPMM Implementation

The model provides the vision and the processes required to support a dynamic maintenance management program. It is crucial that the implementation of this model be based on the individual needs of the organisation. Each organisation must evaluate how to best leverage the processes indicated in the model to meet its own strategies, goals, and objectives for maintenance management.

Implementation of this model also must take into account the effort required to optimise value as quickly as possible. The model, as represented, indicates a continual process, which over the long term can provide significant benefits. To see a quicker realisation of benefits, implementation of certain prerequisites is necessary. These prerequisites include a short-term focus on work management basics and initial performance of the proactive elements of the model (e.g. criticality ranking, failure analysis, and equipment reliability strategy development and implementation). Critical factors for successful implementation of this model include [Lau00]:

- Progressive vision for excellence
- Long-term commitment
- Short- and long-term objectives and goals
- Build up basics while extending the model
- Leadership
- Communication
- Training
- Ownership and empowerment throughout the organisation
- Technology

3.9.3 Benefits of the model

Significant cultural changes, cost savings, increases in mechanical reliability, availability, customer value and reduction in life cycle cost can be achieved by the implementation of MPMM. Short and long-term benefits can be expected. Adoption of this model will provide the following representative benefits:

- Common vision for world-class maintenance management
- An excellence model to train all personnel involved with maintenance management
- Breakdown of departmental barriers and elimination of conflicting priorities traditionally found in organisations with a *reactive* maintenance culture
- Migration from *reactive* to *proactive* and planned reliability-centred work and culture
- Reduced cost of ownership
- Increased product value
- Increased product availability
- Decreased maintenance
- Identified areas of focus for reliability improvement

Enhanced reliability of products is a critical element in the survival of today's organisations. This recognition has brought forward the question of how to improve maintenance and reliability of products while simultaneously reducing the maintenance budget and subsequently life cycle cost.

Organisations must continuously search for long-term improvement opportunities. Organisations that adopt a holistic model such as the one presented here will set the marks for maintenance management excellence. It is in the author's opinion that the key to world-class performance is to select and integrate the best practices available and adapts them to each organisation's needs.

3.10 Summary

Product maintenance has been selected as a major cost contributor of life cycle cost. This chapter identifies and discusses the important elements of product maintenance both from the aspect of value and cost. Maintenance activities have been presented and reliability, maintainability and availability have been identified as significant maintenance cost drivers. A number of maintenance strategies have been specified and maintenance optimisation techniques have been discussed. Next, the maintenance methodologies of Reliability-Centred Maintenance (RCM) and Total Productive Maintenance (TPM) were examined with a view to supporting the maintenance management function. The role of Computer Maintenance Management Systems (CMMS) was also investigated.

A Maintenance Process Management Model (MPMM) has been proposed, identifying a seven-step reliability-focused approach providing the necessary elements to support a world-class maintenance management program. Each process guides the organisation to the products and components that are most critical, seeking to understand components prior to failure and putting in place *proactive* maintenance and reliability strategies to cost effectively eliminate the likelihood of failure.

The next chapter will describe and functional requirements and the technical infrastructure necessary to implement a MPMM.

Chapter 4

Technical Infrastructure to Support Maintenance Process Management Model Implementation

4.1. Introduction

Chapter three has presented the requirements and capabilities of a Maintenance Process Management Model (MPMM). This chapter outlines the technical specifications of an infrastructure required to implement MPMM in a selected organisation.
Firstly, the methods and process required to develop the information infrastructure to support MPMM, and then, an overview of the selected organisation and its requirements is outlined. A Reliability and Field Data Management system (RFDM) is then presented, as the solution to the requirements. Finally, the functional specification of the RFDM is outlined using Data Flow Diagrams (DFD).

4.2 Development of Technical Infrastructure to Support MPMM

The Maintenance Process Management Model (MPMM) requires an information infrastructure to support in the management of processes; storage, analysis, and exchange of maintenance related information throughout the organisation[1]. Information system planning begins with the examination of the business plans and structure of the organisation [You87].

An information system can be defined as a set of interrelated components that support and deal with the information that organisations need for making decisions, controlling operations, analysing problems and creating new products or services [Lau00] A new information system is built as a solution to a problem or set of problems the organisation perceives it is facing. It comes from the recognition that advantage should be taken of new opportunities, to perform more successfully. A series of events called *system development* have been carried out on a selected organisation to establish the viability and information system requirements for the implementation of MPMM. This consisted of a structured problem solving with distinct activities, which consist of systems analysis, systems design, programming, and testing.

4.2.1 Systems Analysis

Systems analysis is the analysis of the problem that the organisation is trying to solve with an information system. It consists of defining the problem, identifying its causes, specifying the solutions, and identifying the information requirements that must be met by the system solution. Systems analysis can also be used to identify new information technology opportunities.

The author has carried out an organisational analysis, identifying the primary owners and users of the required data in the organisation. From this analysis, the details of the problems or limitations of existing systems were recognised. This was achieved by examining documents, observing system operations and interviewing key users of the systems. The author identified the need for a new information system infrastructure to support the implementation of MPMM in the organisation. A feasibility study was carried out to determine whether the implementation is feasible, or achievable, given the organisation's resources and constraints. MPMM was determined to be technically feasible for the organisation.

The information requirements of the new system involved identifying who needed what information, where, when, and how. A requirements analysis carefully defined the objectives of the new system and developed detailed descriptions of the functions that the new system must perform. These requirements are specified later in the chapter.

4.2.2 System Design

Systems analysis describes what systems should do to meet information requirements; system design shows how the system will fulfil this objective. The design of an information system is the

[1] The implementation of MPMM is based on the specific requirements and infrastructure of Thermo King Europe.

overall plan or model from that system. It consists of all specifications that give the system its form and structure. It details the system specifications that will deliver the functions identified during the systems analysis. The specification addresses organisational and technological components of the system solution. The design of an information system can be broken down into logical and physical design specifications. Logical design lays out the components of the system and their relationship to each other, as they would appear to the end user. It describes inputs and outputs, processing functions to be performed and controls. Physical design is the process of translating the abstract logical model into the specific technical design for the new system. It produces the actual specifications for hardware, software, physical databases, input/output media, and specific controls.

4.2.3 Programming and Testing

Programming is the process of translating design specifications into software. During this stage, system specifications that were prepared during the design stage are translated into programming code

Thorough testing must be conducted to ascertain whether the system produces the right result. Test data must be carefully prepared, results reviewed, and corrections made to the system. The testing process is divided into three sections, unit testing, system testing and acceptance testing.

Unit or program testing consists of testing each program separately in the system. The process is to guarantee that the program is error free. Testing should be viewed as a means of focusing on finding all the ways that a program can fail. Once pinpointed, problems can be corrected.

System testing is the testing of the functioning of the information system as a whole. It determines if modules will function together as planned and whether discrepancies exist between the ways the system works and the way it was conceived to work.

Acceptance testing provides the final certification that the system is ready to be used in the organisation's information structure

4.3 Organisation Overview and Requirements

Thermo King is a customer-orientated organisation that manufactures temperature control equipment for the transport industry e.g. truck refrigeration units. It is a world leader in its business and is committed to delivering quality products, with high performance, reliability, and efficiency and with low service and maintenance costs. It is the primary industrial partner of the REFIDAM project.

Traditionally Thermo King has used its established brand as a market differentiator and as customer assurance of its products reliability and its ensuing value. However due to increasing market demands and increased competition, the 'brand' is no longer sufficient to retain or increase market share. Thermo King is required to verify the 'value' of its product and as a result a significant interest is being shown in the area of life cycle cost and particularly cost of ownership. Accurate data is required to determine the product's reliability in the field and also to subsequently determine the level of cost associated with the maintenance and availability of the product, i.e. the elements of cost of ownership.

Thermo King requires a system to manage the life cycle information of its product, capable of supporting the maintenance and reliability function of the organisation and consequently supporting the goal of increased customer value.

4.3.1 Product

Temperature control units are a multi-component product, based on electrical and mechanical systems, e.g. sensors, transducers and a microprocessor, compressors, engine, alternators, belt-drive systems. These products are subjected to a broad range of operating conditions, and extreme environments, with an expected life span of about ten years. Due to its demanding application, the product is required to be rigorously serviced and maintained. Maintenance, adds a significant financial burden on the customer. As discussed in chapter three, this will increase the products cost of ownership and subsequently reduces the products customer value.

For these reasons, reliability is critical for a temperature control unit.

4.3.2 Dealership Network

Thermo King units are distributed through a dealership network. These dealerships are private businesses, with no personnel or financial ties with the company. However, strong collaborative ties need to exist, because the dealers sell the units to the final customers and are generally in charge of maintenance and repair of the units. The collaboration with dealers is very important, and it extends to engineering work, where dealers are involved in product improvement, or new product development projects.

4.3.3 Organisation Requirements

Through their collaboration with dealers, the company has the unique opportunity of accessing information on the product that would be generally lost in the hands of unknown customers.

Establishing appropriate communications paths, and collaborating with dealers is a major goal for the company.

Although the units and its components are heavily tested in-house, sometimes, as in many other applications, the only real testing scenario is the field. Information of the operation of the units, the types and modes of failure, and the environmental conditions and stresses, is very valuable in designing new products, assessing maintenance strategies and calculating operating costs. Providing the means for this information to be recorded in a meaningful format and accessible to the engineering personnel is one of the major purposes of the system.

4.4 Development of RFDM System to Support MPMM Implementation

Reliability and Field Data Management System (RFDM) is a software based information management system developed to support the functions of a Maintenance Management Process Model. The system has been developed around the requirements of Thermo King Europe. The architecture of the complete model can be seen in figure 4.1.

Field information is one of the most valuable sources of product information. It is also one of the areas that regular and reliable information is difficult to obtain. Due to the nature of Thermo King's organisational structure, i.e. dealership network, the connection it has with its products after they have being sold and commissioned is almost non-existent. Often the only information available is fragmented warranty statements, which is available only during the products warranty period, frequently just one year. With the expected life of the product being over ten years the amount of untapped performance, failure and maintenance information is extensive

It is essential to track the product throughout it complete life cycle and to achieve this the system is required to have the capability of retrieving the preventive and corrective maintenance data of the product and allow this data to be conveyed, in a specified standard format, on a regular basis to the manufacturer for analysis. A Computer Maintenance Management System and Internet data transfer technology will be used to achieve this.

Reliability Process Management covers a large range of methodologies and tactical activities throughout the product life cycle. An efficient reliability program requires a system that integrates all these methodologies and that provides a framework for efficient operation of the program. This system takes the form of a computerised information system [Oco01]. The information structure need to integrate all the information and data that will be used in the different processes and also has to be designed so that it can store the results of these processes in a convenient format. The information structure will be implemented through the customisation of a Product Data

Management (PDM) System. A number of reliability initiatives and processes have been selected based on the requirements of the application. Some of the initiatives are carried out through the use of software tools, and some others are implemented within the functionality of the PDM system [Oco01].

The *Data Analysis* module facilitates the analysis of the retrieved field information. It requires the use of standard calculations to carry out various reliability and cost calculations

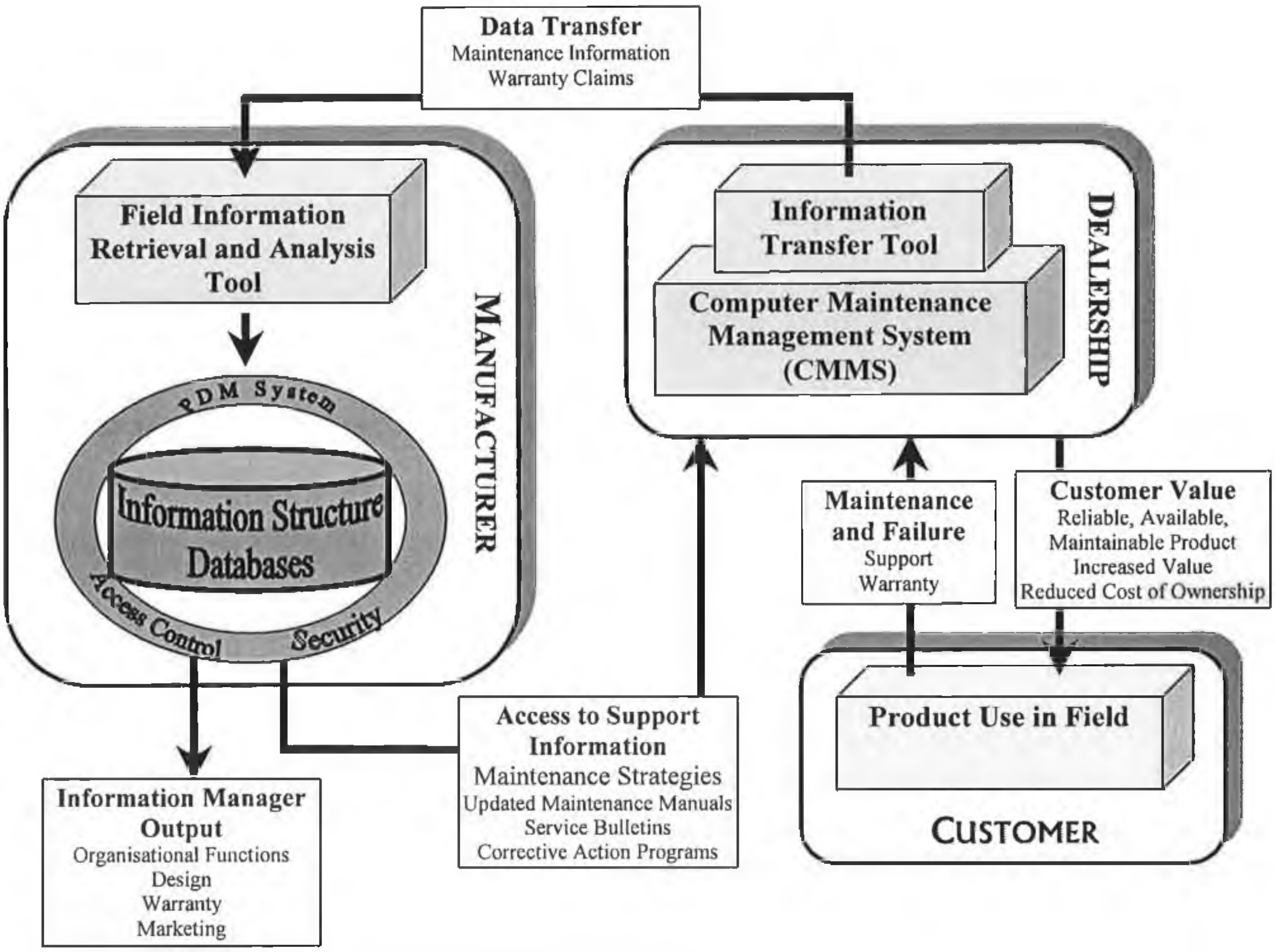


Figure 4.1: Reliability and Field Data Management System

4.5 RFDM Information System Requirements

To fulfil the functional requirements of RFDM three main information system platforms have been selected. The first is in the form of specifically developed software, next is the Internet, and finally a Product Data Management System (PDM). Each will be discussed in relations to their ability to satisfy the requirements of RFDM.

4.5.1 Specifically Developed Software

To achieve many of the required functions of RFDM, specific software had to be developed by the author and Ocon [Oco01]. A tool was required to be developed to manage the maintenance function of the product in the field and to ensure the standardisation of field data and maintenance activities. It is broadly based on a Computer Maintenance Management Systems (CMMS), which are described in the previous chapter. Existing CMMS could not be used due to their inability to be integrated with other system. RFDM requires the ability to integrate with other applications due to the diverse nature and environment of the application.

A tool to transfer information over the internet was also required. Though, the Internet is an existing platform, a tool was required to interact between the CMMS and the Internet file transfer protocols to transmit information.

4.5.2 Internet

The Internet was selected as the platform to facilitate in the information flow between the operating product in the field and the organisation. It was chosen due to its ability to allow communication in an efficient and effective manner. The Internet's worldwide location and its need for only basic hardware and software requirements made it an attractive option. RFDM utilises two of the many functions of the Internet. It uses the File Transfer Protocol (FTP) to transmit maintenance information from the field and it uses the World Wide Web (WWW) to supply information to the field

4.5.3 Product Data Management (PDM)

A PDM system is a very valuable tool to support concurrent engineering practices, by allowing different teams to work in the same projects while assuring security, revision control, and consistency. They also deliver business solutions that support compliance with industry and regulatory standard. PDM provide pre-defined standard reports, as well as fully integrated applications to support activities such as logistics and field service, software development and project management [Tsa93]. The bench marking process involved in the selection of PDM can be found in reference [Oco01].

Extending PDM to Field Support

This thesis has recognised the value of extending the traditional function of a product data management (PDM) systems, which primarily focused on managing engineering drawings and computer-aided design (CAD) files in the design phase of product development. Many organisations now are recognising that the value of product information does not end with the release of a design to manufacturing, but extends throughout the product life cycle into field support where accurate product definition data can be used by service personnel to repair, troubleshoot, upgrade, and maintain working equipment.

In these cases, the configuration of the equipment does not remain static. It evolves throughout the life of the product due to engineering changes, field modifications, and other changes. Without this information in a well managed system, field personnel rely on handwritten notes, marked up drawings, unclear faxes, calls to design engineers, perhaps their own memory, and sometimes lengthy and costly reverse-engineering activities to determine part numbers, design revisions, assembly specifications, and other important equipment data.

This expansion of the scope of PDM is part of the trend toward collaborative Product Definition management (cPDm), with companies expanding their view beyond CAD to management of the entire product definition, from the design phase of product development to the entire product life cycle, and from the engineering department to the extended enterprise.

Companies want to leverage product definition information in areas such as field support because such post-delivery activities are often critical to their success, particularly where products have long life cycles.

cPDm provides an infrastructure for companies to provide these types of services quickly and efficiently, not only lowering their own costs but also ensuring future business through customer satisfaction. Otherwise, delays in field support can result in lost revenue from equipment downtime as well as raise liability and safety concerns for products such as aircraft, for example, where the precise configuration of all planes of a particular model must be quickly determined when major problems are encountered in just one.

To improve service efficiency, companies are implementing cPDm systems that allow technicians to retrieve equipment data at the maintenance site using web-based laptop computers hooked to standard telephone lines. Personnel remotely access up-to-date equipment information in a few minutes instead of the hours or days previously required.

4.6 Functional Specification of RFDM

The functional specification will translate the requirements of RFDM into a defined information system. A functional specification methodology know as *Data Flow Diagrams* {DFD) will be used to specify the structure of the developed system [Whi94]. The purpose of a DFD is to accurately model the functions that the system has to carry out and the interaction between those functions. It provides a method for capturing and documenting the information of the data flow within the system and visualises the logic behind the system. It defines the scope of the system and the relationship between the hierarchies of the diagrams that represent the system. Data flow diagrams uses graphical forms for representing the system's components as presented in table 4.1.

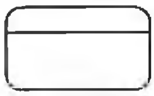
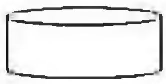
Symbol	Description
	*Processes* are elements that transform or manipulate data within the system. They are represented by rectangles with rounded corners.
	*External Entities* are the elements that provide information or receive information from the system. They are represented by ovals
	*Data Stores* are the elements that store information. They are represented by flat cylinders
	*Data Flows* are the elements that represent the data transfer in the direction of the arrows

Table 4.1 Data Flow Diagram Symbols

Level 0: RFDM Information Structure

The system is broken down into five main levels and a number of sub-levels to best describe its functionality. The RFDM system is required to manage all the data produced by the maintenance activities of a product operating in the field. The data needs to be retrieved, managed and transferred to the reliability function of the organisation, for analysis, and also to facilitate in the information communication to the field. Figure 4.3 shows the structure of the data system.

The structure of the RFDM system is as follows:

- Level 0: RFDM Information Structure
- Level 1: Product Use/Operation
- Level 2: Maintenance Management
- Level 3: Data Transfer
- Level 4:Data Analysis
- Level 5: Information Manager

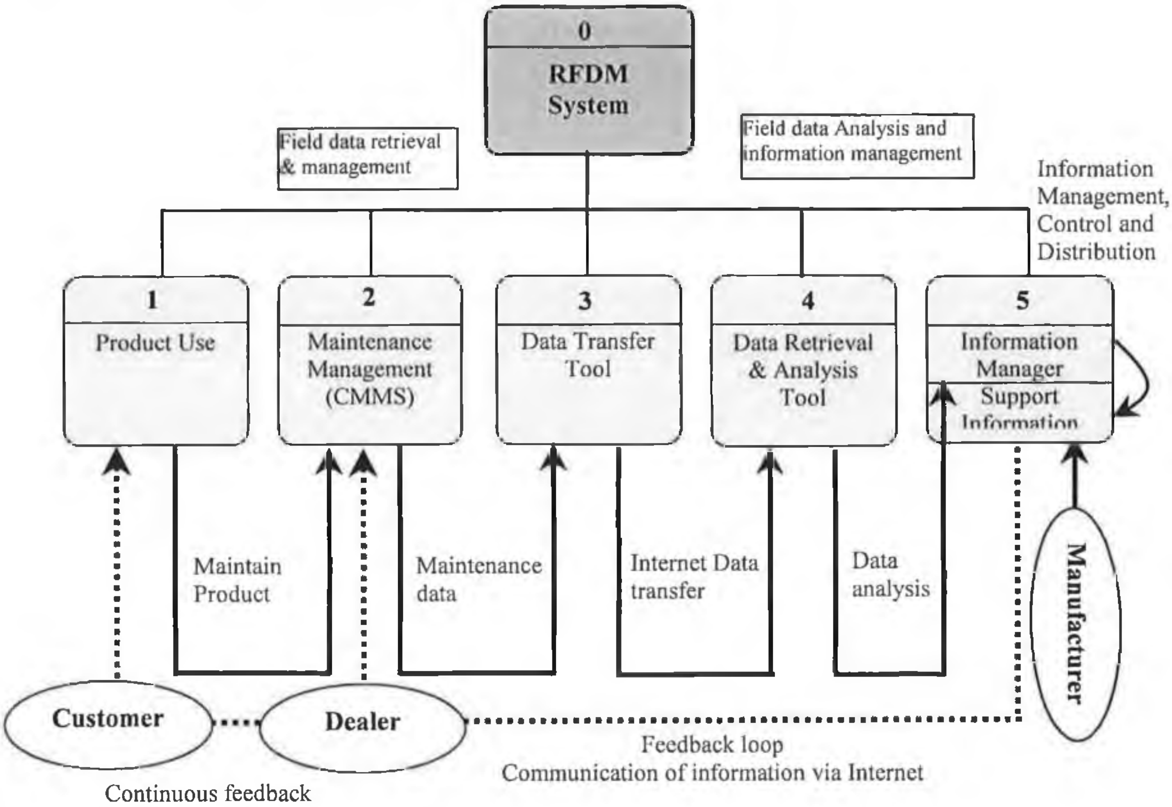


Figure 4.3: Level 0: RFDM Information Structure

Level 1: Product Use

Due to the nature of the product's application, i.e. extreme operating conditions, it requires substantial maintenance, both preventive and corrective. Figure 4.4 illustrates this process.

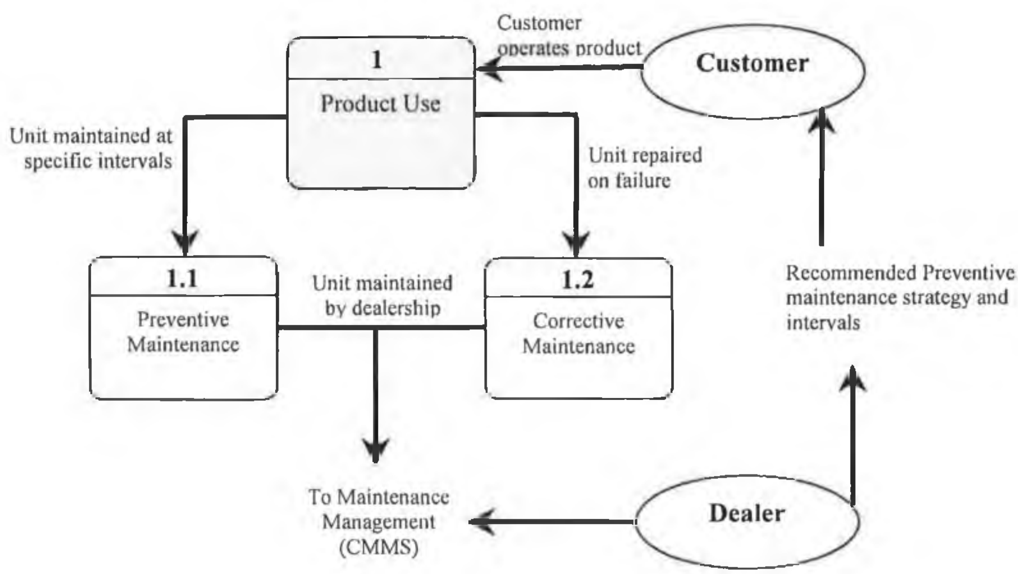


Figure 4.4: Level 1: Product Use

The manufacturer recommends a preventive maintenance strategy and the unit will be maintained by the dealer according to specific procedures and intervals. However, the product can also fail while operating, i.e. between maintenance intervals. In this case the units is brought to the dealer or the dealer may travel to the product (depending on location, etc.) to carry out corrective maintenance.

When the product is sold to a customer it is often done so with a *maintenance contract* i.e. the unit will be maintained by the dealership for a fixed monthly rate. Some contracts may cover only preventive maintenance costs while other may cover all associated maintenance costs. Either way, due to the complexity of the product it is the dealership that will carry out the maintenance work on the majority of products. It is due to this reason that it is viable to retrieve accurate product field data on a regular basis. It is, however important to establish the integrity of the data and ensure complete maintenance and failure history for the product's total life. Fragmented data will lead to inaccuracies in any subsequent analysis.

Level 2: Computer Maintenance Management System (CMMS)

A CMMS assists in the management of all product maintenance activities. It is a computerised information system that is specifically design to deal with the issues that arise when scheduling maintenance activities. CMMS's are often perceived to be no more than a means of scheduling maintenance work. While maintenance scheduling should be part of the function, it should be capable of all aspects of a maintenance department's work. Figure 4.5 illustrates the architecture of a CMMS and details of the functional requirements of a CMMS are outlined next.

Function 2.1: Product Management and Product Register

This is the function, which will facilitate the creation of a product register. The product register will hold comprehensive details of each product. Typical data to be stored will include Product Serial Number, Product Name, Model, Customer Name, Drawing numbers, Purchase Price, Location, Supplier, and maintenance history. For warranty purposes it will facilitate in the registration of the product with the manufacturer.

Function 2.2: Preventive Maintenance Scheduling

The maintenance schedule should have a flexible set up, allowing each product to have a defined maintenance profile which may include details of various periods, skills required, procedures required, estimated job times and when the equipment is available. It should also be possible to link products to the *preventive maintenance procedure library* discussed below. Some systems may require the scheduler to have the capability of checking personnel and equipment availability before it schedules any work.

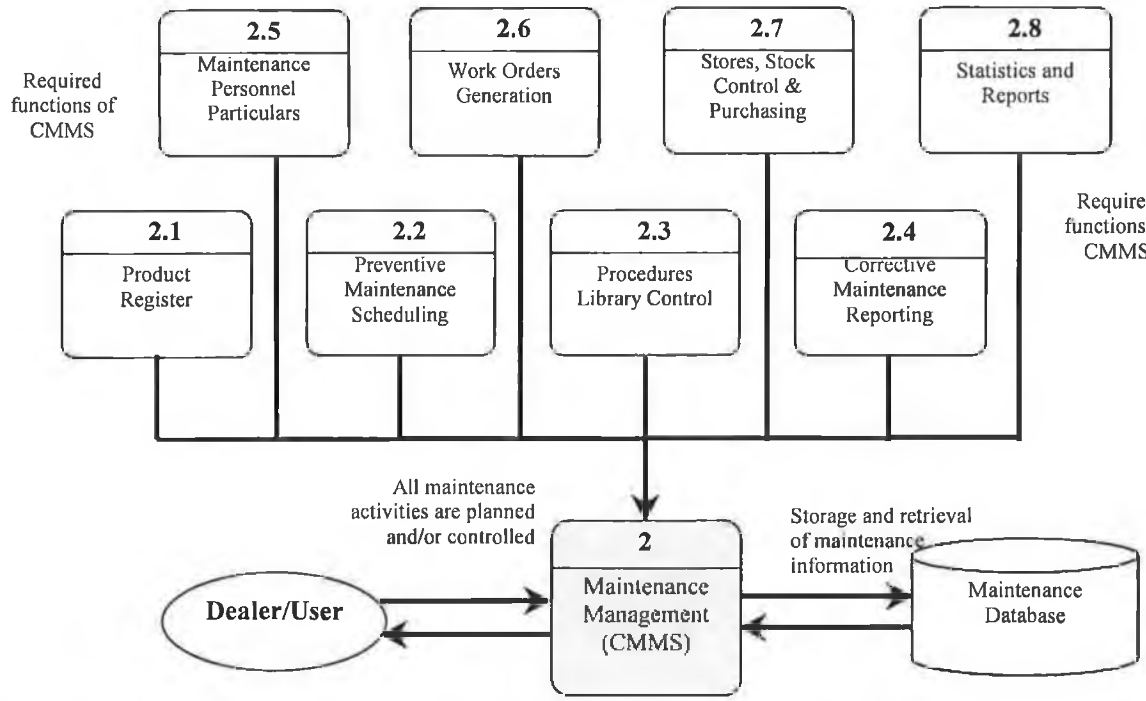


Figure 4.5: Level 2: Computer Maintenance Management System (CMMS)

Function 2.3 Procedure Library Control

The preventive maintenance procedure library is generally a database of all the maintenance procedures required for the maintainable products in the system. In a paper system, records will be held which contain details of preventive maintenance to be carried out on all equipment. Each time a maintenance is scheduled the technician will require to refer to the procedure on file. With statutory or mandatory procedures this leads to document control problems, since inevitably, technicians will retain personal, and perhaps out of date, copies of these procedures.

With a computerised system, up to date procedures can be printed or viewed each time the maintenance is due. Once technicians have been trained in the system they have access to the library at all times and there is no need or inclination for them to keep personal copies. When a change to a procedure is required, it is carried out on the library document, ensuring that all people who subsequently refer to it will see the amended version. If the procedure requires to be modified then this needs to be done once only, all linked products will continue to use the modified version in the library. For example, all the motors in the field may be maintained using a common motor maintenance procedure. If an amendment to the procedure is necessary this is done on the master procedure in the library. All products linked to that procedure would be automatically updated.

Function 2.4: Corrective Maintenance Reporting

All systems should support corrective or unscheduled work reporting. The exact format of this will be dependent on local requirements but should allow maintenance personnel access to an input screen, through which they can report defects or breakdowns. The required input will be clearly defined, so that the reporter is prompted for each piece of information required. Typically this will include the product serial number of the equipment, the failed part no, and brief details of the fault. The system should facilitate the listing of all outstanding breakdown work, allowing this to be allocated and scheduled.

Function 2.5: Work Order Generation and Issue

In addition to the generation of unplanned work orders previously discussed, a means of outputting, that is producing hard copy of planned work orders, will be necessary. The system should allow the planned work orders to be separated into various trades, product groups and locations, before they are printed. Other points to be considered are whether or not the user requires work order formats to be re-configurable. Most companies prefer to be able to design their own work order forms.

Function 2.6: Maintenance Personnel Database

It may be that a maintenance personnel database is required. This is not to be confused with the company personnel database since it will generally only contain details of maintenance personnel. Once again requirements here will differ but typically details will contain name, trade, department, shifts worked, qualifications, special training received, authorisations, etc. This may also be used for time keeping and attendance recording but some users prefer to keep this apart from maintenance records.

Function 2.7: Stores Requisitioning, Stock Control and Purchasing

Most fully integrated packages support some kind of store's management option. One benefit of opting for stock control is that trade groups can be provided with access to the store's database allowing them to find spare part numbers and check stock levels of maintenance spares. Some systems allow spares to be linked to products thus simplifying the search for these and also ensuring that no obsolete spares are held in inventory. Some users consider that the greatest financial returns from a CMMS are to be achieved through improved stock control procedures.

Requisition and purchasing options are also generally offered in maintenance management packages. These are similar to any other computer controlled purchasing packages but once again, being part of an integrated package, they can be used to record and control maintenance spare parts usage. This allows the possibility of automatic reordering to minimum stock levels. These options are not always popular because most companies already have some kind of computerised stock control system in place.

Function 2.8: Statistics and Reporting

In any system, whether it is manual or computer based, the information, which is output from the system, is only as good as that which has been input. In a good system there will be extensive information readily available for fault analysis, costing and work statistics. This is one of the most important functions of a CMMS system. Further descriptions of the information available can be seen in Level 4.

Level 3: Information Transfer Tool

One of the main requirements of the RFDM system is to facilitate in the regular transfer of maintenance information from the field to the manufacturer. The information transfer tool has the purpose of creating the appropriate maintenance files and transmitting them to the manufacturer. Figure 4.6 illustrates this procedure.

Process 3.1

At specifies times the dealer will create a file containing all the maintenance history of the product. See figure 4.7. Due to the fact that the dealership is a private entity, it is essential that there is no ambiguity is the transfer process. The dealer may not want to transfer and data pertaining to costs and profits. Therefore, the dealer creates the file, which will have a specified requirements and structure. For the purpose of maintenance, reliability and costing analysis there is no need to have any cost information from the dealer. Part numbers and Labour hours can be associated with them during the analysis itself. Each new file will be created from the past file creation log date to the present date.

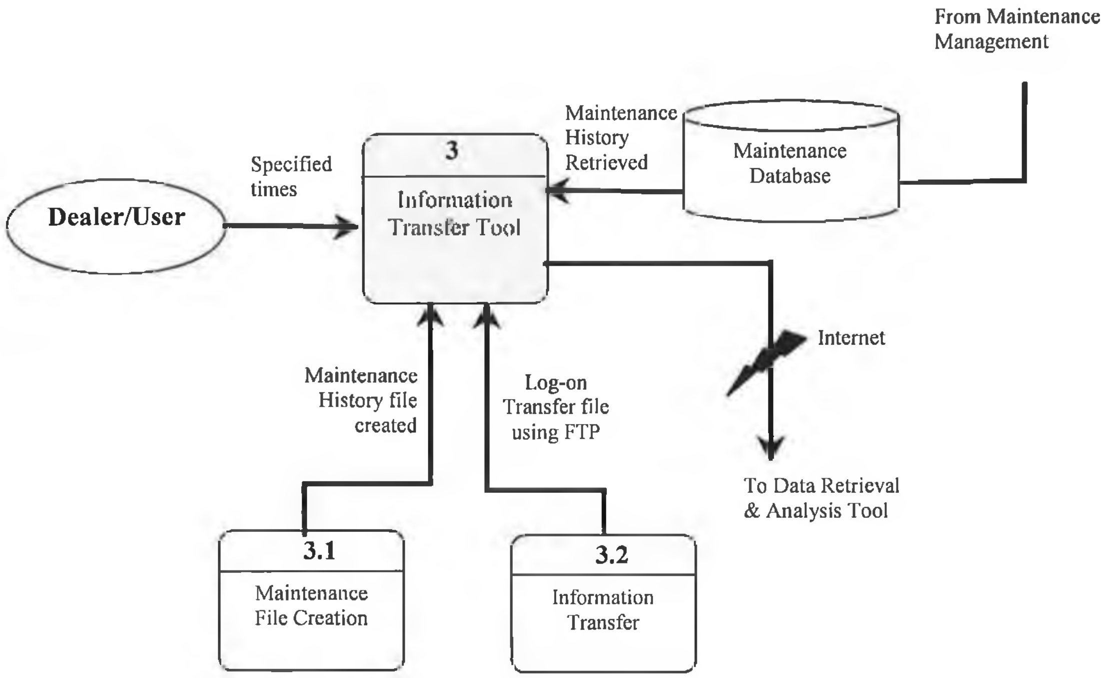


Figure 4.6: Level 3: Information Transfer Tool

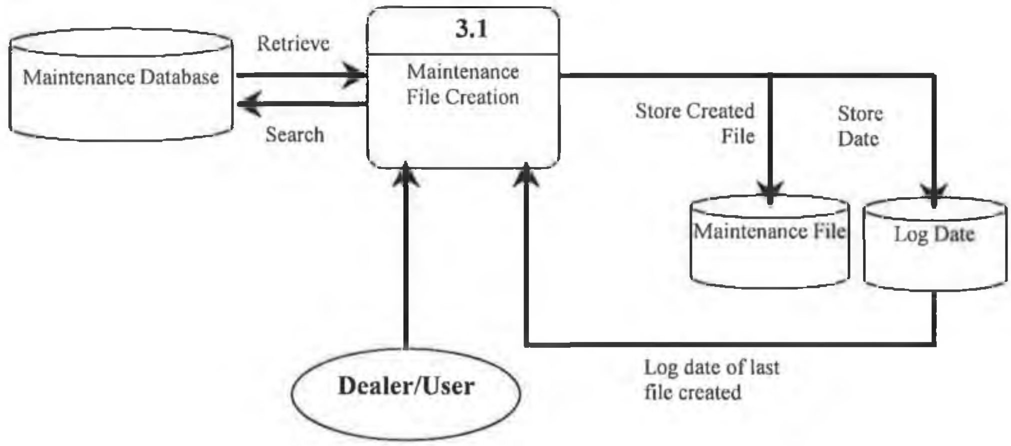


Figure 4.7: Process 3.1: Maintenance File Creation

Process 3.2

At specified intervals, the maintenance files created in process 3.1 are transmitted to the manufacturer. Figure 4.8 illustrated this process.

File Transfer Protocol is used to transfer files across the Internet. These files, which can be text, sound, etc., uploaded from the client computer to the server computer. In this case the dealership is considered the client and the manufacturer is considered server.

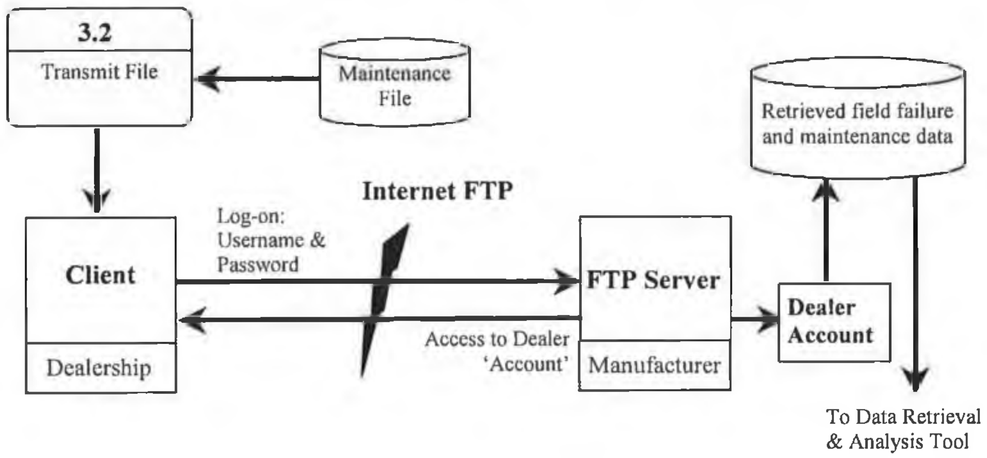


Figure 4.8: Process 3.2: Information Transfer

FTP was designed to let a user connect to a remote system on which the user had an account. After authentication, the user is allowed to navigate through a directory hierarchy and retrieve files. Each dealer or *user* will have a designated space or *account* on the server computer where all maintenance information from that dealer is stored and ready for retrieval during an analysis process

Level 4: Data Retrieval and Analysis

The structure of the Data Analysis Tool is illustrated in figure 4.9. The analysis is carried out on the up-to-date data retrieved from the field. Based on the requirements of the tool, a number of reliability and costing processes are carried out. A detailed description of these processes is carried out next.

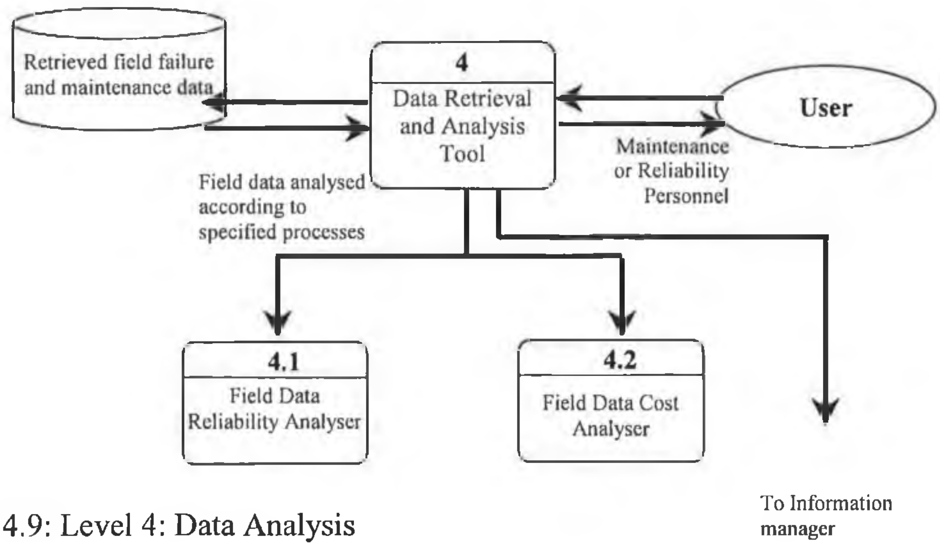


Figure 4.9: Level 4: Data Analysis

Process 4.1 Field Data Reliability Analyser

The field data reliability analyser has the purpose of searching the field data according to search criteria determined by the user. The information is returned to the user and standard reliability calculations can be performed on the data by the tool, or the retrieved can information can be exported to other software packages for further analysis. Figure 4.10 shows the process.

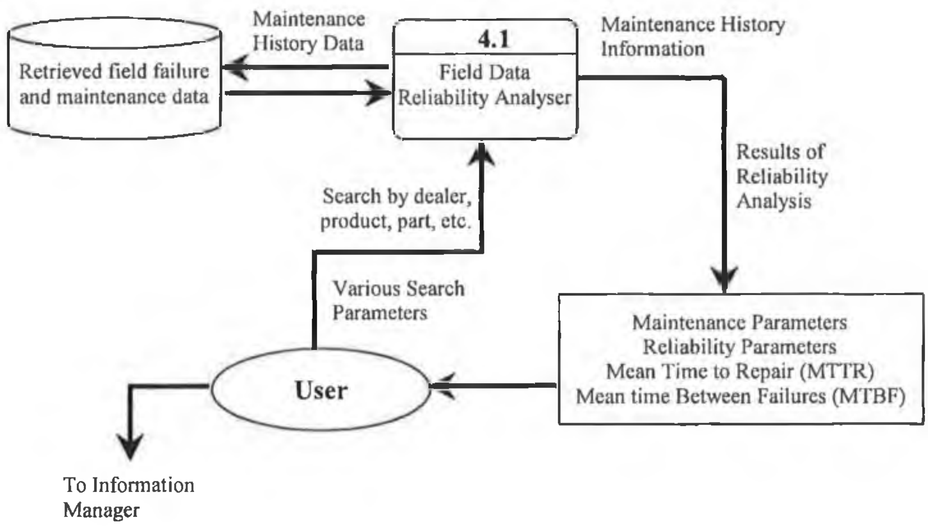


Figure 4.10: Process 4.1 Field Data Reliability Analysis

Process 4.2 Field Data Cost Analyser

The field data cost analyser has the purpose of carrying out a costing analysis on the maintenance field data. It allows the user to search the database using various search criteria. The data returned can be analysed using specific costing calculations. The user also has the ability to change come costing parameters, i.e. the user can input various labour rates and parts prices margin increases. The architecture of the cost analyser can be seen in figure 4.11.

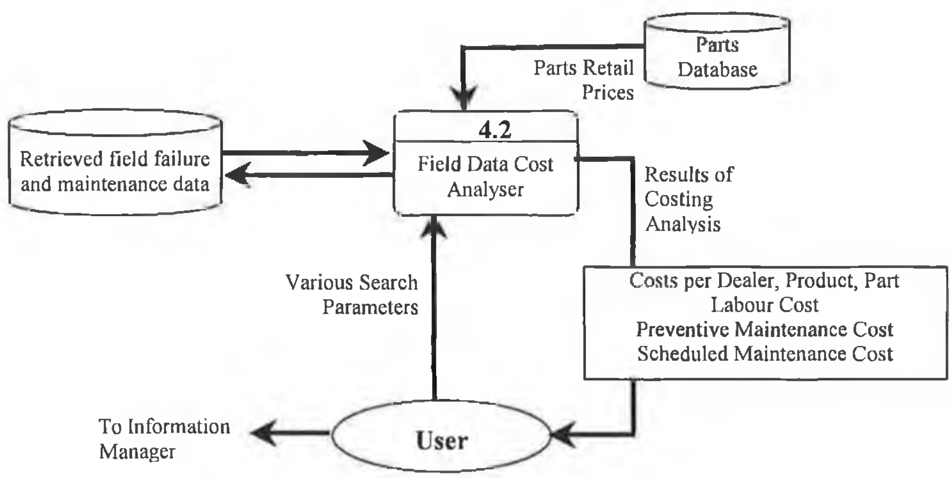


Figure 4.11 Process 4.2 Field Data Cost Analyser

Level 5 Information Manager

The focus of this thesis is on field maintenance management, analysis and support. The information manager is built on a PDM platform, which was researched by Ocon (see reference [Oco01]). The information manager developed by Ocon includes a number of reliability initiatives and process, many of which are of interest to the product maintenance function. This thesis has used the capability of the PDM to be a collaborative support tool as discussed in section 4.4.2. Many of the reliability processes and initiatives discussed by Ocon will be used to support the product in the field. Figure 4.12 illustrates the support facility of the information manager.

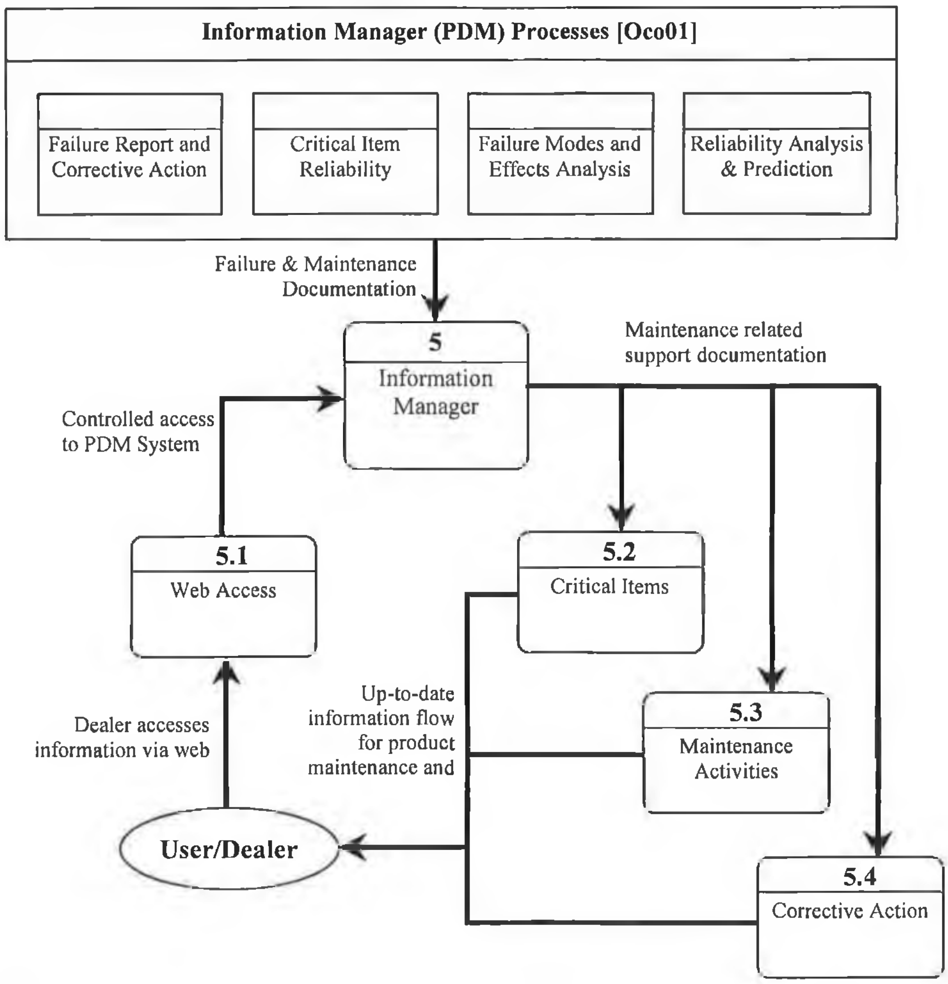


Figure 4.12: Level 5: Web Access to the Information Manager

Process 5.1: Web Access

Through web access the dealer can view up-to-date product documentation from the manufacturer.

Process 5.2: Critical Items

A critical item is a component recognisied by the manufacturer to significantly affect reliability, safety and maintenance costs if it fails. Components in critical item lists require extra awareness during maintenance. This information helps ensure the customer/dealer that a problem has being recognised and is being investigated. Information such as on-going component improvement activity documentation may also be displayed. Further information regarding critical item reliability can be seen in reference [Oco01].

Process 5.3: Maintenance Activities

During a product's life many support activities will be required to change. Components in the product can change, maintenance cycles of components may alter, and maintenance procedures and manuals will be revised. It is often difficult for the support function to maintain its integrity with all these changes occurring. Through the maintenance activity 'window' a dealer can have constant up to date information on product maintenance and support.

Process 5.4: Corrective Action

When a failure has being identified, the development of corrective actions, and the implementation of these actions must take place. The corrective action process allows dealers to view all the documentation necessary to execute the action. Information will include, products affected, work instructions and details of any remuneration entitlement.

4.7 Summary

This chapter presents a technical information system infrastructure to support the implementation of a Maintenance Process Management Model (MPMM) that was presented in the previous chapter. The process involved in the development of an information structure is discussed and the overview and requirements of a selected organisation is outlined. A Reliability and Field Data Management System (RFDM) is presented with the aim of providing the information infrastructure necessary to support the implementation of MPMM in the selected organisation. The main information platforms of RFDM are presented, these are, developed software, the Internet, and a collaborative PDM system. Finally the functional requirements of the system are defined and illustrated using Data Flow Diagrams. The next chapter presents the description of the prototyped RFDM system

Chapter 5

Description of Prototyped Reliability and Field Data Management System (RFDM)

5.1 Introduction

In chapter three a Maintenance Process Management Model (MPMM) was presented. It outlined the processes necessary to achieve a 'best practice' approach to maintenance management. A technical infrastructure required to implement the model was examined in chapter four, and a Reliability and Field Data Management System (RFDM) was developed to implement the MMPM based on the requirements of an industrial partner.

This chapter presents a description of the RFDM prototyped according to those requirements. Firstly, the general structure of the RFDM will be outlined. Next, the use and operation of the system will be illustrated with the aid of a series of user interface screens. These screens will provide a demonstration of the main features of the system

5.2 Reliability and Field Data Management System Outline

The Reliability and Field Data Management (RFDM) system is a complete information management software system for field product maintenance information analysis and support. The system is based on the Maintenance Process Management Model (MPMM) presented in chapter three and technically and functionally specified in chapter four. The RFDM system was developed to implement MPMM in an industrial partner, Thermo King

Europe. Due to the diverse requirements of the system, the user interfaces of the prototyped system can be categorised in the following two modules[1].

- Field Support Module
- Reliability and Cost Data Management Module

The two modules are integrated to form the RFDM system; they are described and illustrated using a series of user interface screens

5.3 Field Support Module

The field support module is the dealer interface with the RFDM system and it contains the elements to support the maintenance function of the product throughout its life cycle in the field. The field support module can be divided into the following sections:

- Field Data Manager
- Data Transfer
- Support Information

Once a user[2] chooses to use this module the system is launched, presenting the user with the starting screen presented in figure 5.1.

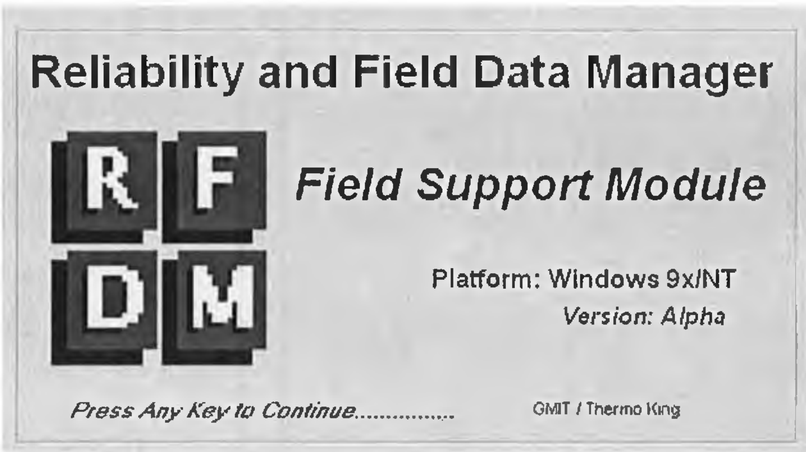


Figure 5.1 Starting the Field Support Module

When the module has successfully launched the user is presented with a main screen, which is displayed in figure 5.2. Depending on the requirement of the user, operating the different buttons will launch the necessary sections of the software.

[1] A module a self-contained assembly used as a component of a larger system

[2] The user of this module is considered the person in charge of maintaining the product, usually a Dealer.

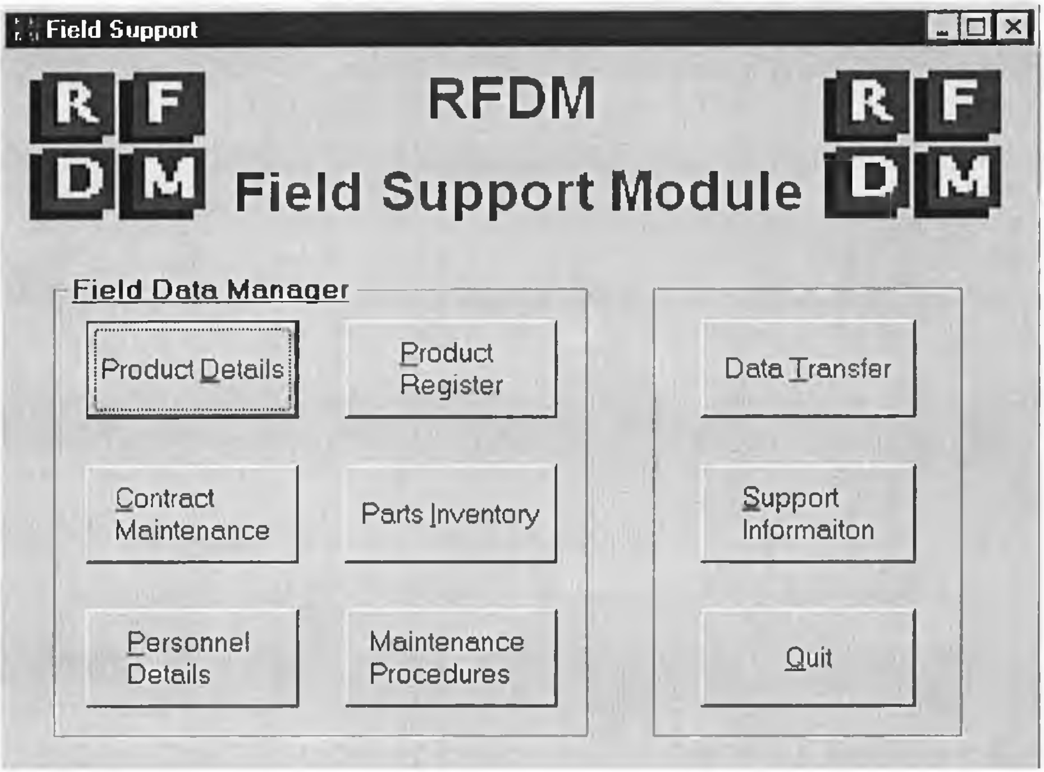


Figure 5.2 Field Support Module front Screen

Field Data Manager: This button launches the maintenance management section of the system. It allows the user to record product maintenance history, requirements and also keep track of the units past, present and future preventive maintenance schedules and procedures.

Data Transfer: This button launches the software that permits the user to transfer product maintenance data across the Internet to the manufacturer for analysis.

Support Information: This launches an Internet/Web based system to support the product in the field. It will provide the user with information from the manufacturer regarding product maintenance routines and information, including up-to-date maintenance procedure and manuals. It will also facilitate the manufacturer to present project information such as critical item warnings and corrective action procedures to the dealer.

5.3.1 Field Data Manager

The Field Data Manager[3] is the tool the user will use to manage the maintenance activities of the product. Depending on the user's needs, a number of tasks can be carried out using the Field Data Manager. Each task is related to the product's maintenance activities.

The *Product Details* buttons opens a widow containing product information including information such as serial no, product type, customer and date in service. It also displays all maintenance activities carried out on that product to date and displays if the unit is in warranty or in a maintenance contract. This window can be seen in figure 5.3.

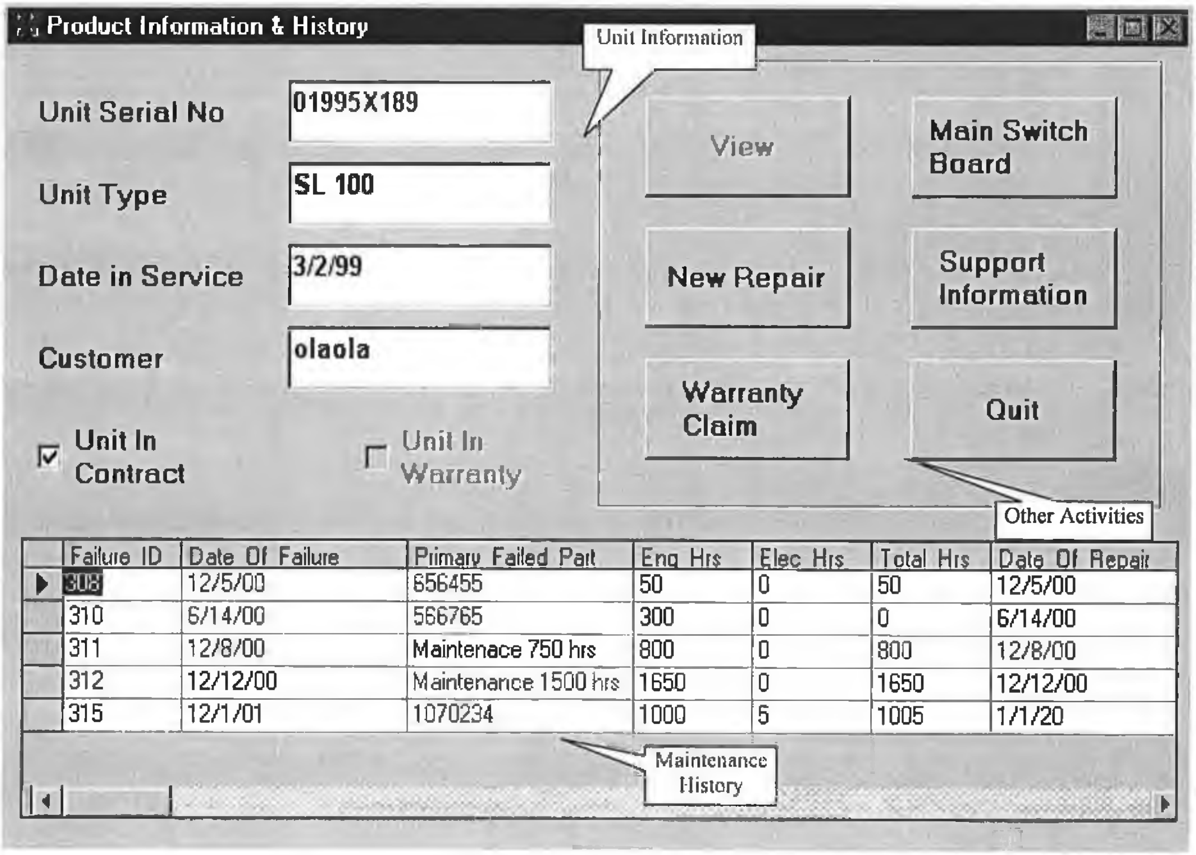


Figure 5.3 Product Details

Figure 5.4 shows the interface the user will see when maintenance information is required to be input into the system. It facilitates the user to input all information associated with a particular maintenance activity and requires the user to specify the nature of the work, i.e. corrective maintenance or scheduled maintenance. An important feature is the *Primary Failed Part* field. This allows the user to input the part responsible for the failure. In many maintenance situations a number of parts will be replaced but only one part will be

[3] RFDM was tested by populating with real Thermo King unit maintenance history. See Appendix C

maintenance situations a number of parts will be replaced but only one part will be responsible for the failure and not necessarily replaced, therefore it will not be included in the data. This is an important factor in and ensuing reliability calculations.

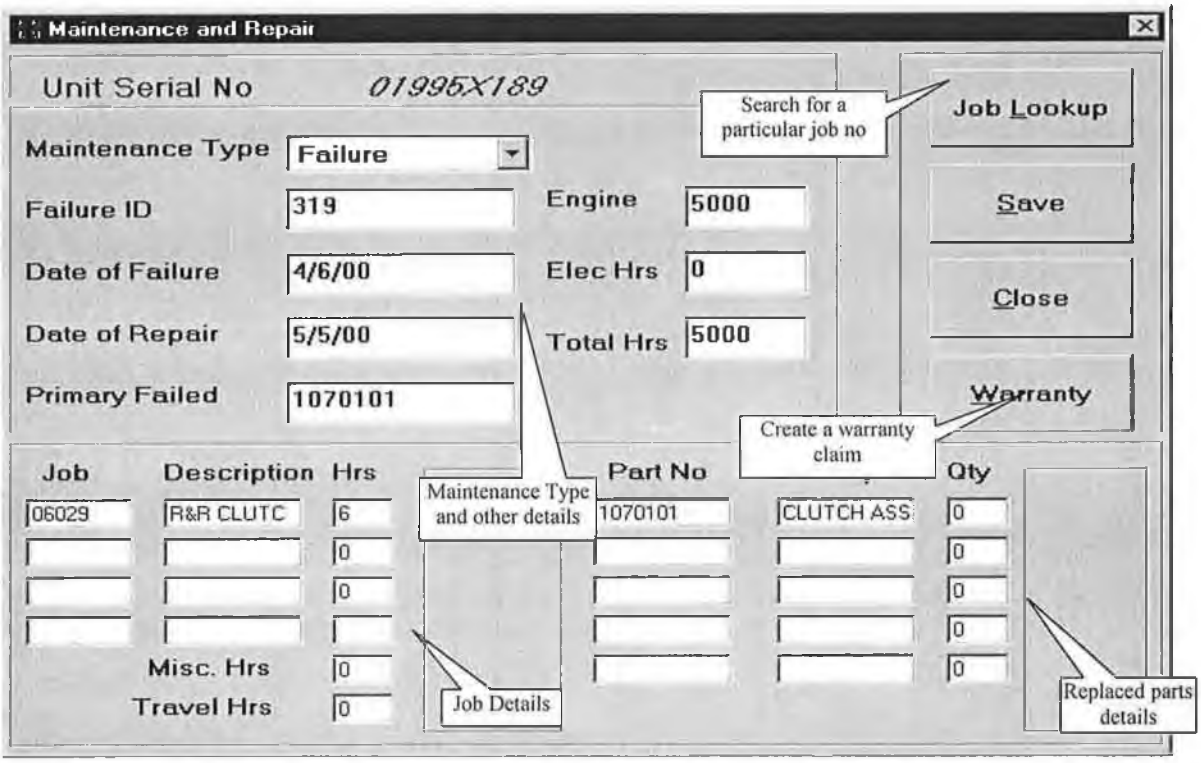


Figure 5.4 Maintenance Particulars

The *Contract Maintenance* button on the Field Data Manager window enables the user to view current contract maintenance details or input new information. Figure 5.5 displays the contract maintenance window. Each contract has a Contract ID and Customer No.

The number of units in the contract is displayed and there is also a facility to input new units into a current contract or create a new contract.

Contract maintenance is an important function of the maintenance activity of a dealership. Products in contract maintenance are an essential factor in accurate reliability and costing calculations. The owner of a product that is not in contract has no obligation to carry out maintenance activities at a recognised dealer. Any work carried out on the product outside a recognised dealership will be 'lost' to the system, therefore the product will have an incomplete maintenance history and therefore should not be used in data analysis.

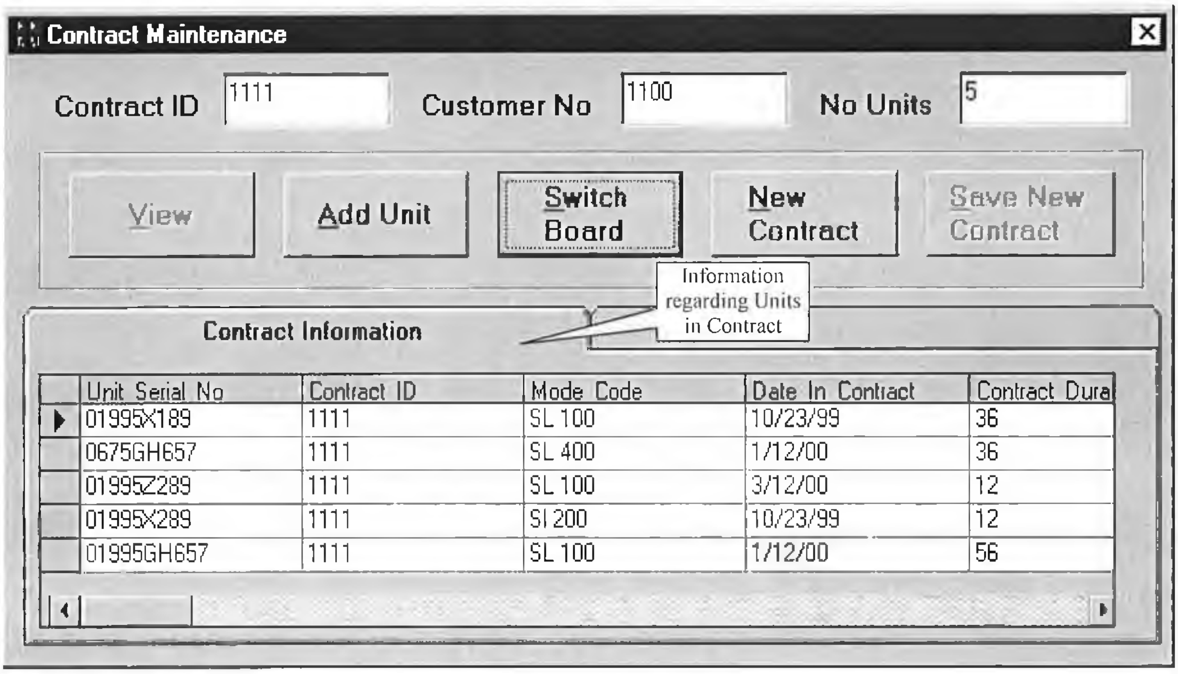


Figure 5.5: Contract Maintenance Window

The Product Register button permits the user to register a product into the system. Figure 5.6 shows the registration window that facilitates such an action.

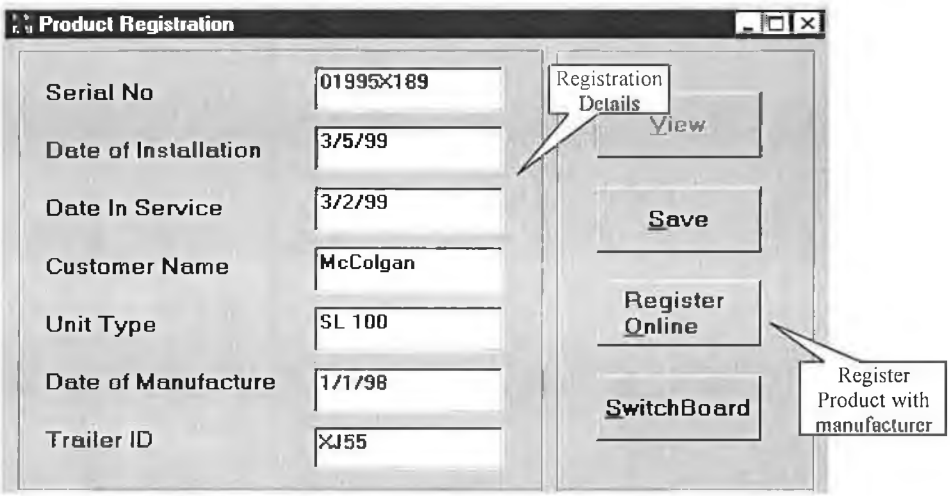


Figure 5.6 Product Registration

This gives general product information such as serial no and customer name. A unit must be first registered before any maintenance activity can be carried out on it using this system. A unit serial that is entered into the system will be considered 'unknown' unless it is first registered here. The system will advise the user as shown in figure 5.7. It is also possible to register the unit with the manufacture using the online registration facility.

Figure 5.8 shows the process. The product must be registered with the manufacturer before a warranty claim will be processed and any compensation paid.

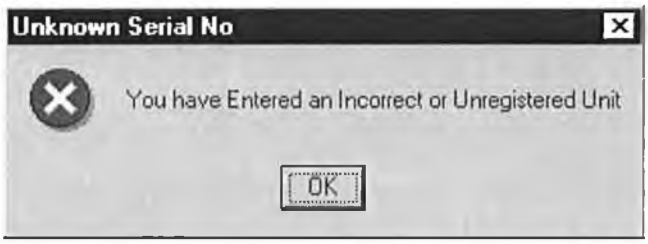


Figure 5.7 RFDM Message Window

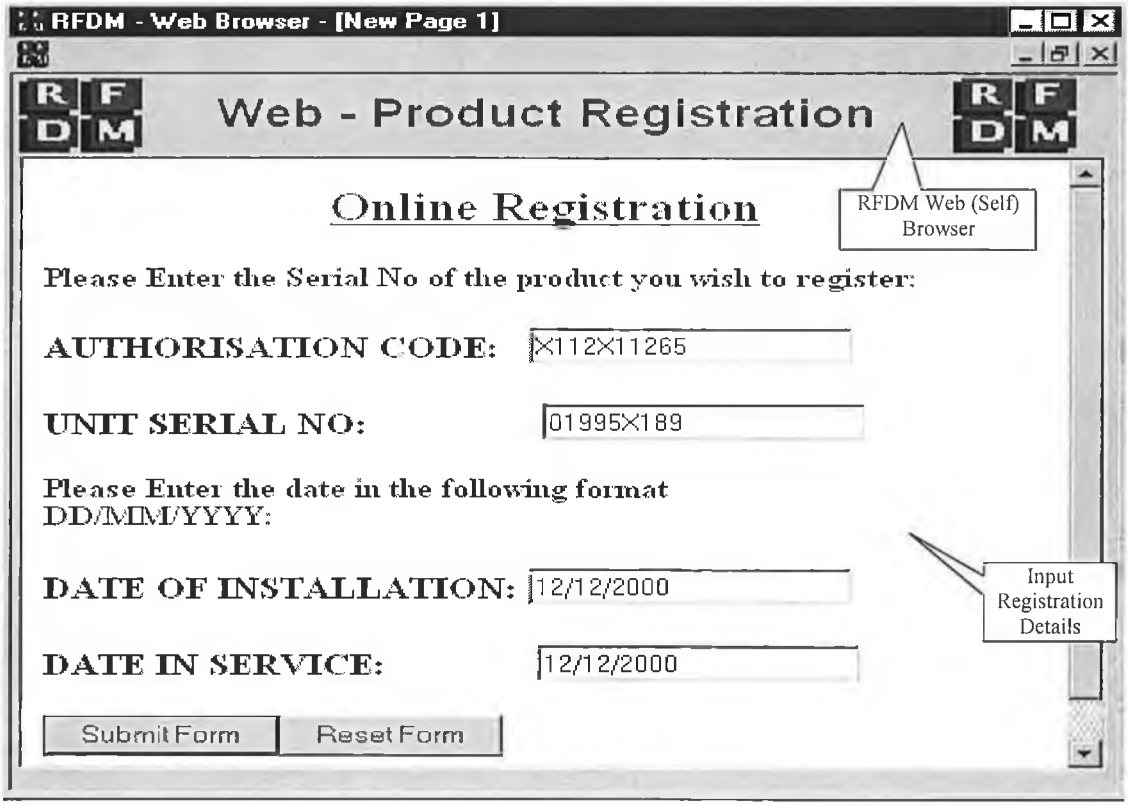


Figure 5.8: Online Registration

5.3.2 Data Transfer

An important feature of the Field Support Module is its ability to provide a tool for the transfer of maintenance information from the field to the manufacturer for analysis. As outlined in chapter four, Thermo King dealerships are private companies therefore any transfer of information proprietary to the dealer must be transparent and unambiguous. This module of RFDM allows the dealer to have full control of the data transfer process.

Before a data transfer takes place the user must create a maintenance file to be transferred. According to a specified and agreed search criteria the dealership's maintenance database will be searched and the requested information will be returned. Figure 5.9 shows the file creation window.

The file transfer process is an ongoing operation, taking place at specified intervals agreed by the dealer and the manufacturer. Only the maintenance data accumulated since the last transfer took place will be created and sent. This will avoid data duplication and reduce the size of the file being transmitted.

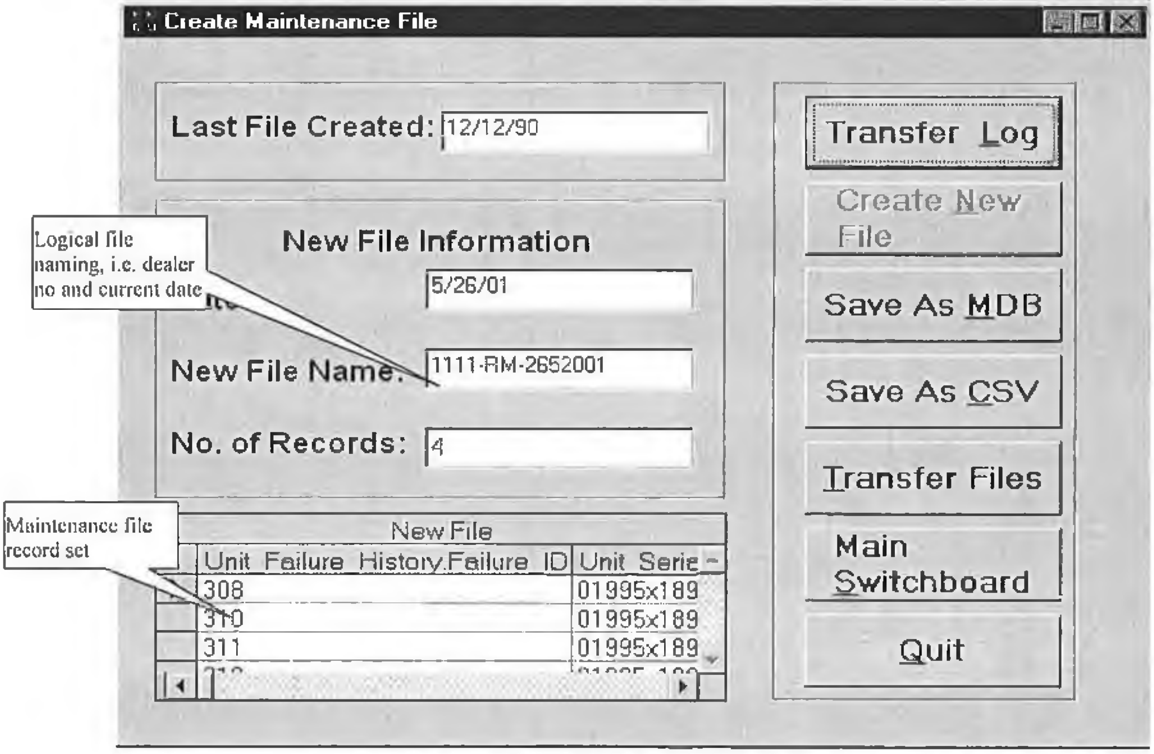


Figure 5.9: Maintenance File Creation for Transfer

When a file has been created the user may then choose to immediately send that file or retain it and send it at a later date. When the user has decided to commence a file transfer process, the manufacturers server must be logged on to. The user operates the *Transfer Files* button and RFDM logs in to the appropriate server. The user is first presented with a login window as shown in figure 5.10.

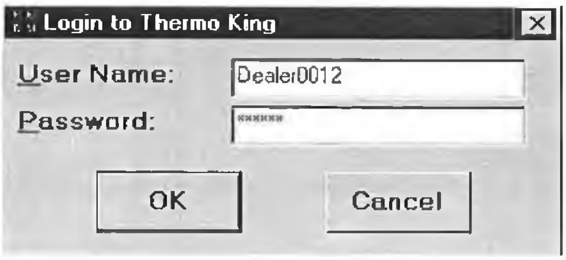


Figure 5.10: Login Window

When the correct username and password is entered the user is given access to the *File Transfer* interface window, which is displayed in figure 5.11.

The user is given access to the appropriate data folder on the manufacturers server. The relevant file is then 'uploaded' to the manufacturer for analysis.

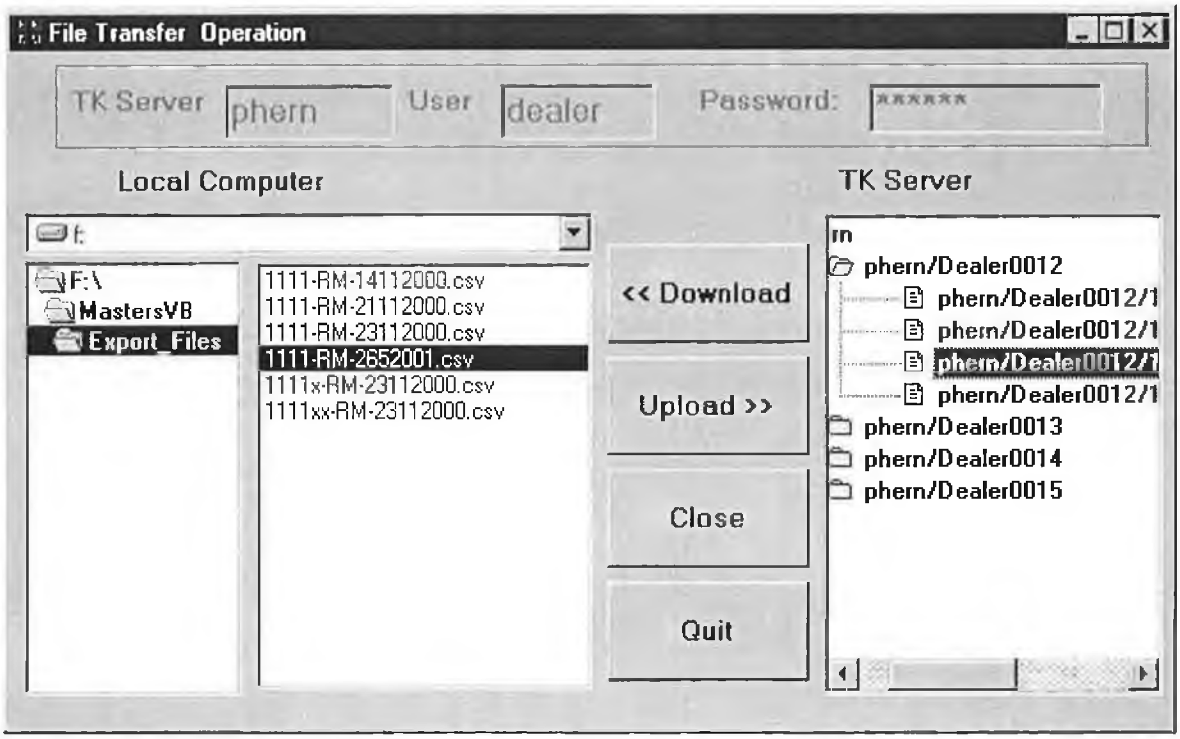


Figure 5.11: File Transfer Operation Window

5.3.3 Support Information

A valuable feature of RFDM is its ability to provide the user with continuously update field support information. This information is provided by the manufacturer and is supplied via the *Information Manager* element of RFDM, which will be discussed later in this chapter. The user accesses this support information by operating the S*upport Information* button on the field support module front screen. This launches RFDM's built in web browser and presents the user with the web page shown in figure 5.12. The user then selects the *Smart-Team-Web* button, which launches a collaborative web-enabled PDM system. This system will provide the user with the necessary support informaiton to ensure efficient product maintenance in the field. The support information provided for the user includes the following information:

- Current maintenance manuals and procedures
- Service Bulletins

- Warranty Bulletins
- Corrective action requirements and procedures
- Critical components

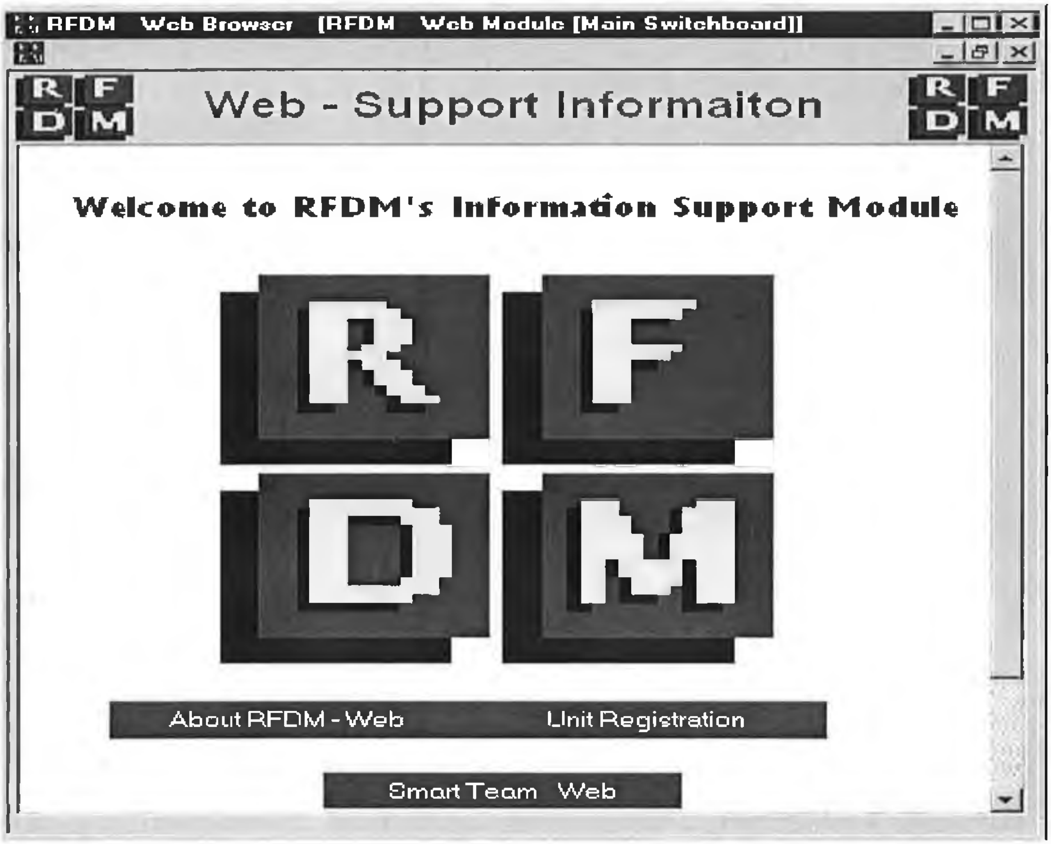


Figure 5.12: Support Information 'Welcome' Screen

The user is assured that the information being viewed is the latest version. The manufacturer is able to communication information to the field without delay. This flow of information guarantees that the product is continuously supported throughout its life cycle. The user can navigate thought the various documentation or search for specific documents and manuals. This reduces the need for the user to store maintenance manuals and procedures, many of which or outdated or of the incorrect revision for the existing product. Figure 5.13 presents the display the user will see when logged on to the system. In this display the user has chosen to view a corrective action process. All the information required to carry out the corrective action will be supplied. The information may be viewed on-screen or may be downloaded and printed out. Figure 5.14 displays a view of an online Service Bulletin. This 'online' method of distributing information avoids the confusion of mass mailing and complaints of undelivered documentation. It guarantees that the customers and the dealers are inline with current manufacturer judgment and philosophy.

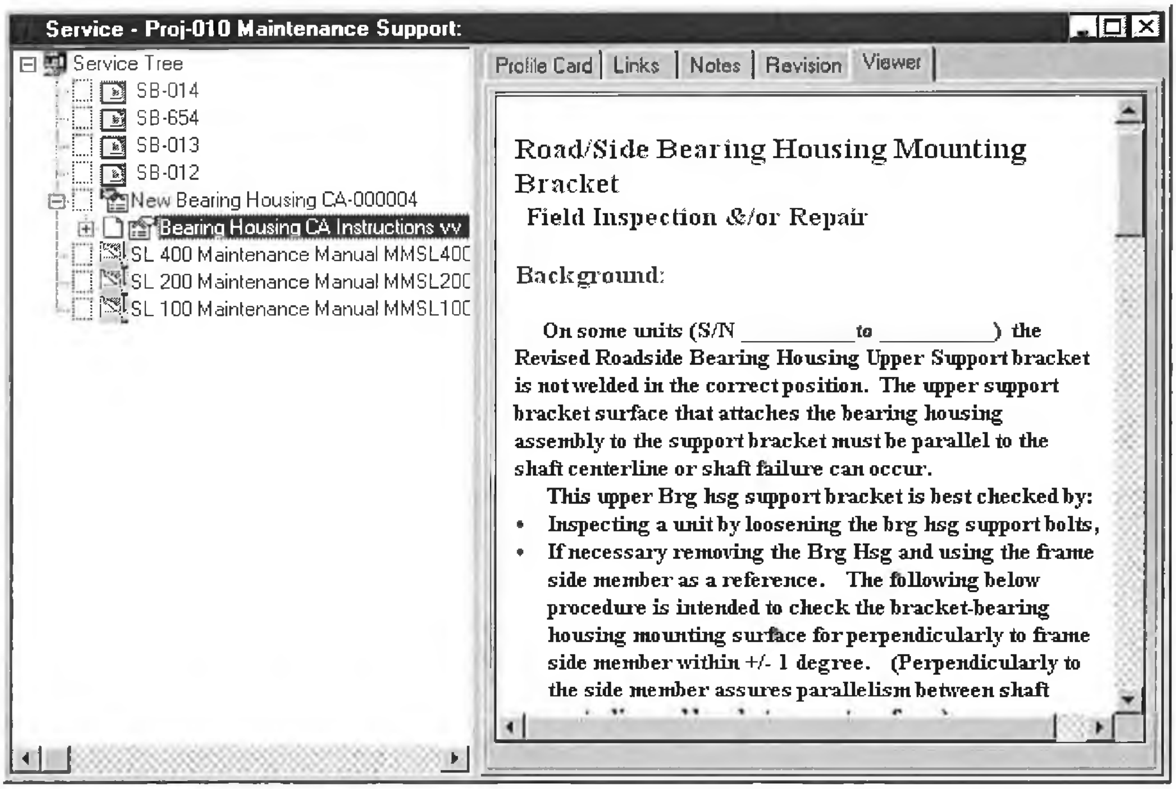


Figure 5.13 Online Corrective Action Instructions

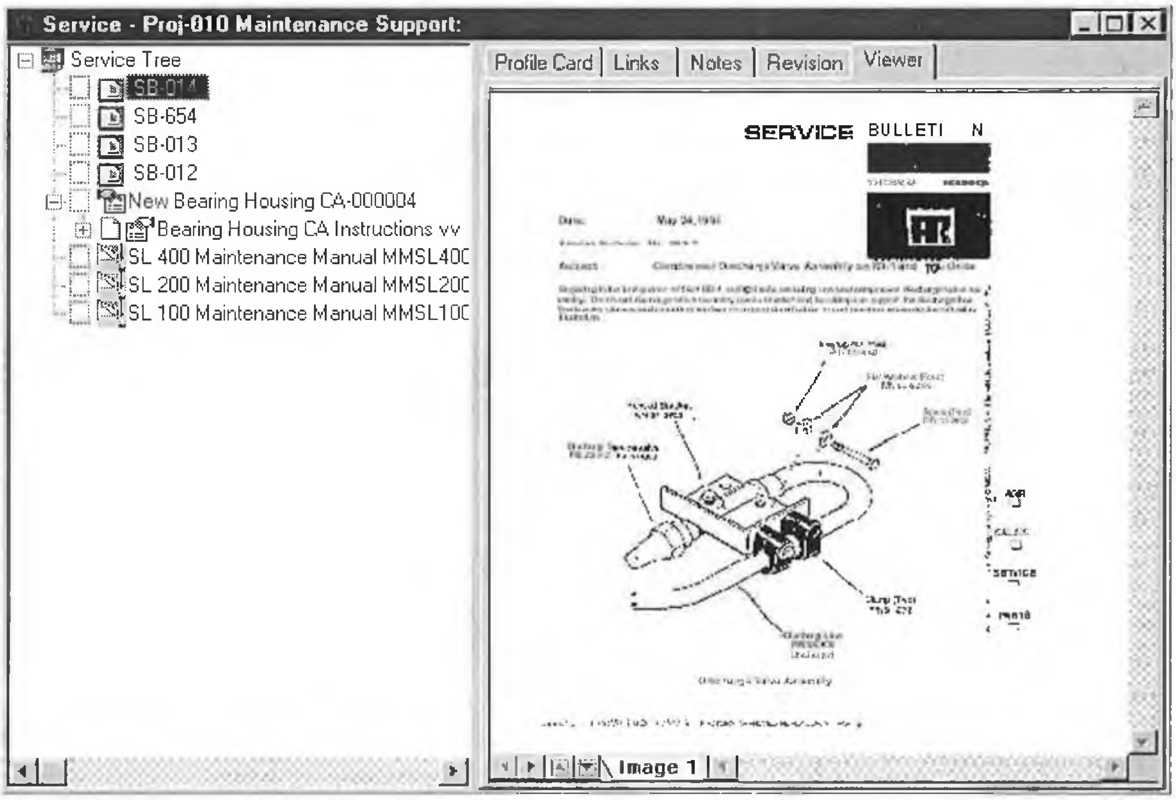


Figure 5.14: Online Service Bulletin

5.4 Reliability and Cost Data Management Module

This module contains the manufacturer-side interface with the RFDM system. Figure 5.15 shows the front screen that a user[4] will see. A number of tools have been selected to carry out the activities and processes described in previous chapters of this thesis.

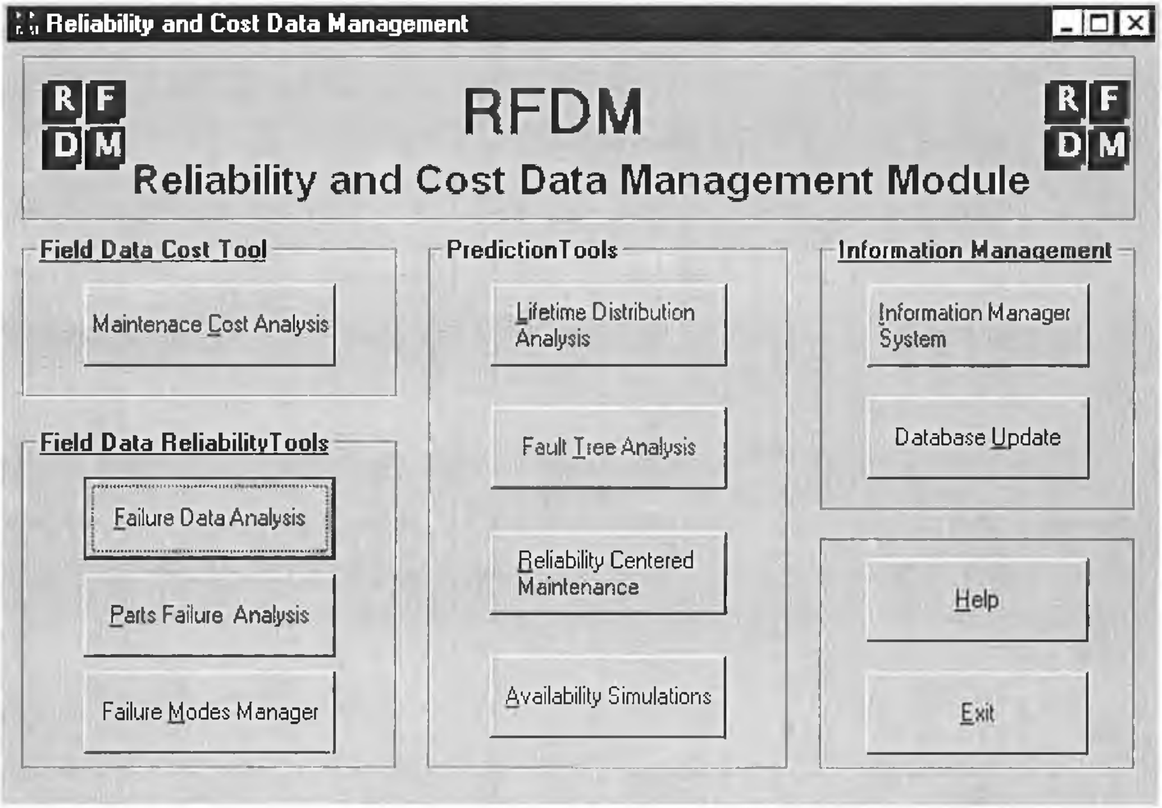


Figure 5.15: Reliability and Cost Data Management Module front screen

Each tool has the ability to support or improve the maintenance/reliability function of the product operating in the field. The operations are divided into three categories. By operating the different buttons in each category the user can access various tools and applications to support the maintenance function. Each function is summarised next and will be explained in detail for the remainder of the chapter.

Field Data Tools

The *Cost Analysis* button launches the software developed to perform life cycle cost analysis on the retrieved product maintenance data. The *Failure Data Analysis* and *Part Failure Analysis* buttons launches the software developed to perform reliability calculations

[4] The user of this module is considered to be an engineer working on the manufacturer's side of the system

on retrieved maintenance data. The *Failure Modes Manager* is developed software that manages identified failure modes, which are stored for reference and knowledge building.

Prediction Tools

These are a number of software packages integrated into RFDM to carry out further reliability prediction, simulation and costing analysis. Some of these are *Weibull++*, to perform lifetime distribution analysis, *FTA*, to carry out fault tree analysis, *RCM*, to support the requirements of reliability centred maintenance, and *AVSim*, an availability simulator.

Information Manager

The information manager system is the PDM system stores all maintenance related documentation and reference data. This system has two main interfaces, the dealer-side and the manufacturer-side. These are called *information support* and *information manager* respectively.

5.4.1 Field Data Cost Tool

The Field Data Cost Tool[5] is a software tool developed to retrieve maintenance data and carry out basic costing calculations according to specified parameters. Figure 5.16 displays the various searching parameters that can be use in an analysis.

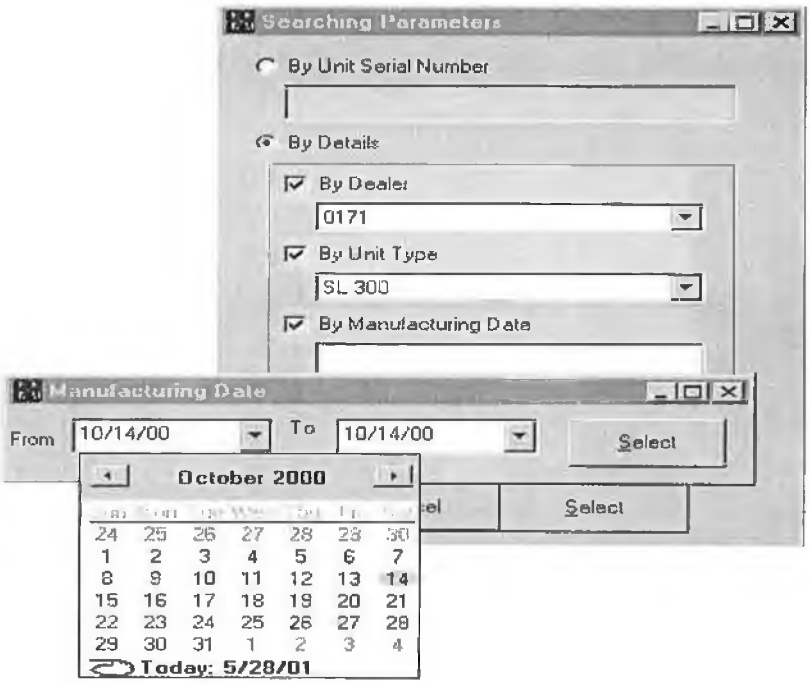


Figure 5.16: Searching Parameters

[5] A sample of the data used in these calculations is supplied in Appendix C.

Once the required search parameters have been entered into the system the tool searches the database and returns the results. The user can then enter costing parameters as shown in figure 5.17. These parameters can be altered to vary the cost impact of the different elements and also to test the costing for data sensitivity. Figure 5.18 and Figure 5.19 shows the results of the different analysis as calculated by the tool.

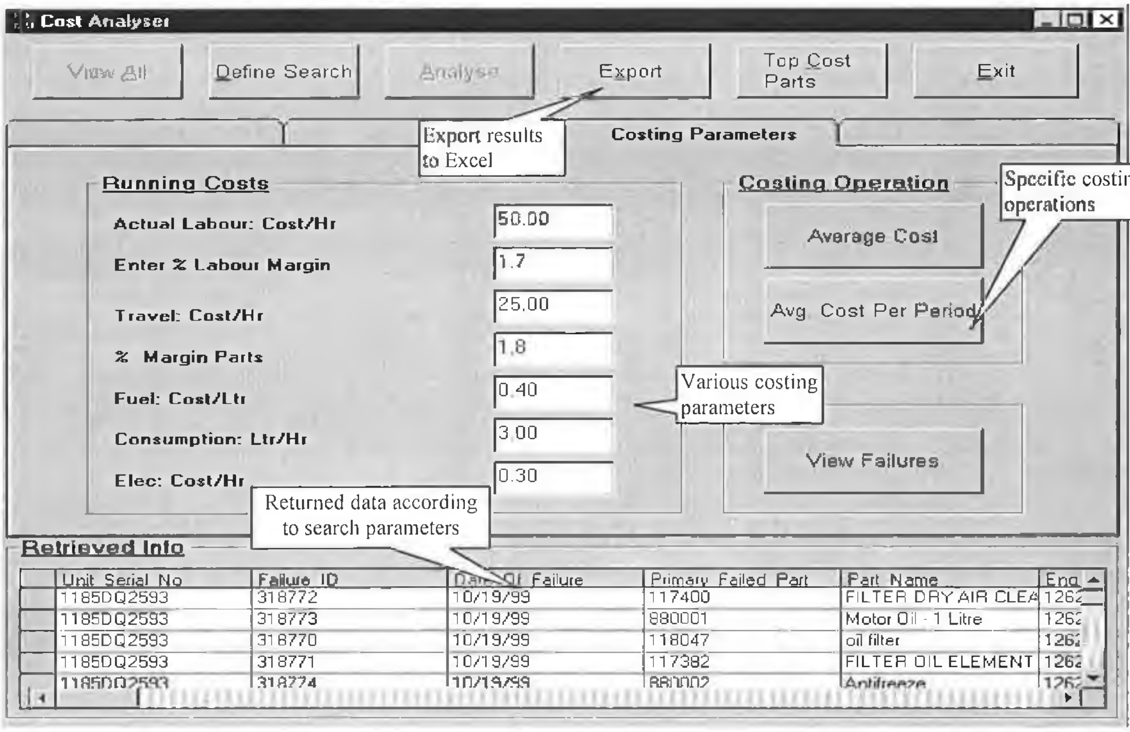


Figure 5.17: Costing Parameters

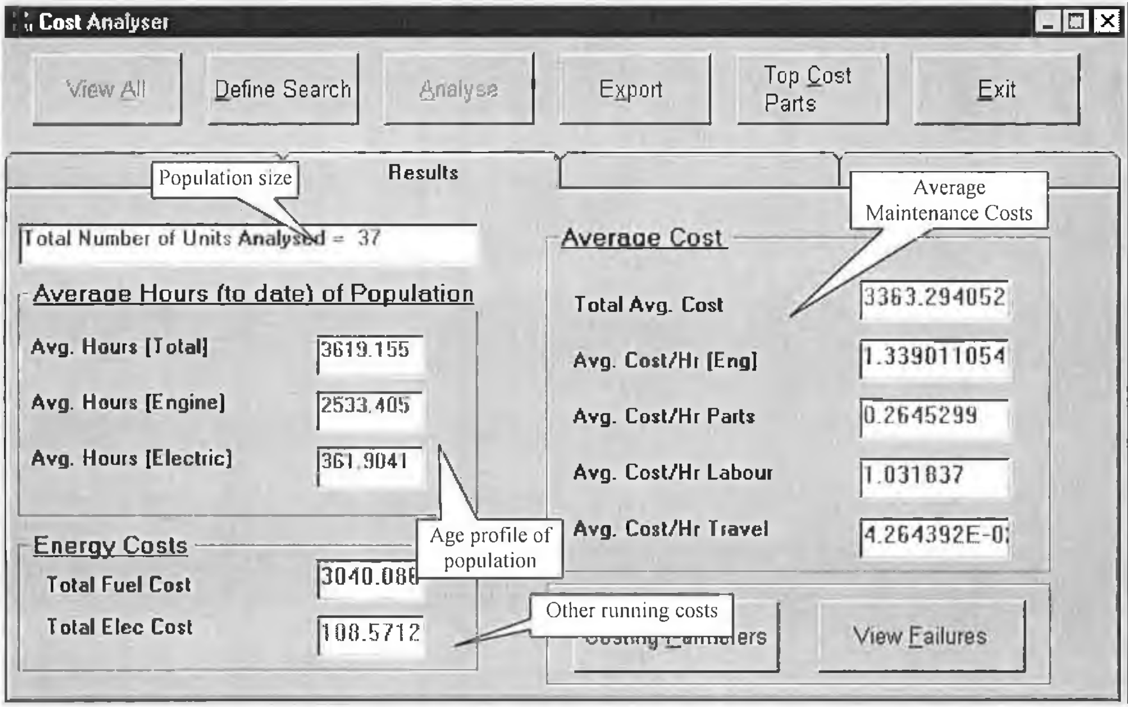


Figure 5.18 Summary of Costing Results

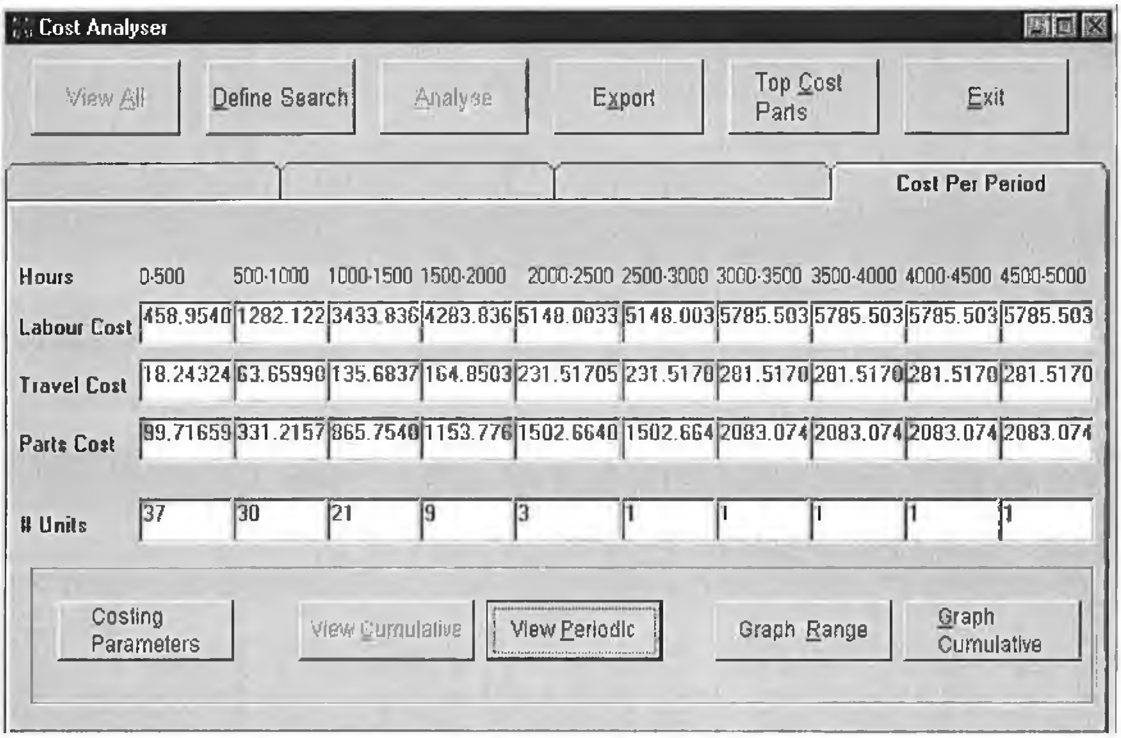


Figure 5.19 Periodic Costing Results

The results can be exported to other application, such as MS Excel for further analysis or the user can avail of the graph feature of the tool to display the various results in graphical format. An example of which can be seen in Figure 5.20

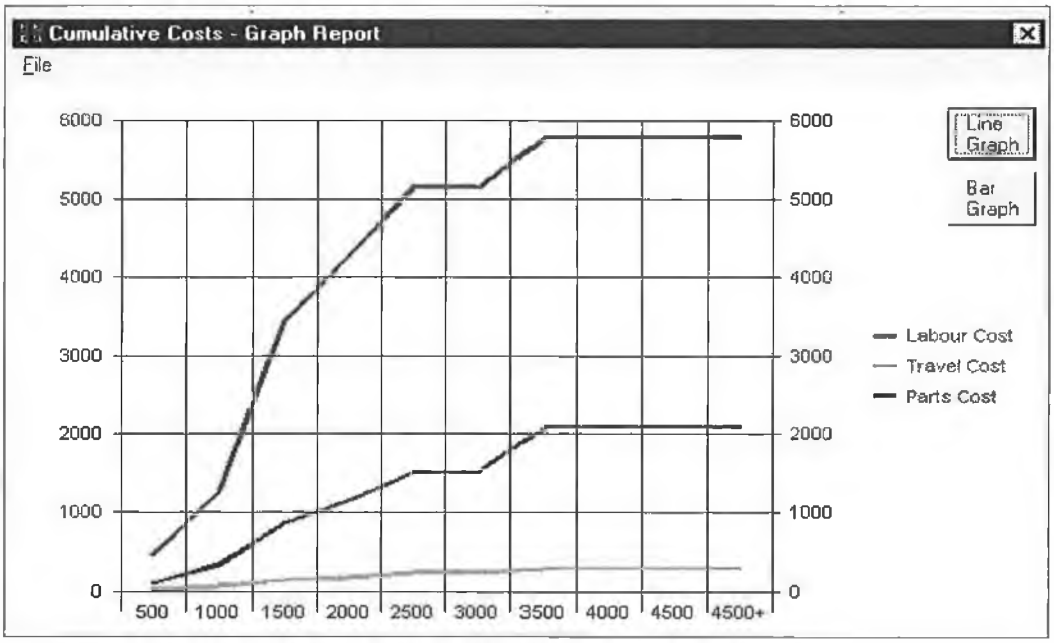


Figure 5.20 Graph Report of Cumulative Cost

5.4.2 Field Data Reliability Tools

The Field Data Reliability Tools category of RFDM anticipates the requirements of an engineer, facilitating reliability calculations to support the maintenance and reliability functions of the product in the field. An analysis of maintenance data will present the manufacturer will the following capabilities:

- Improve current maintenance strategies
- Increase product reliability
- Anticipate maintenance requirements
- Provide product support
- Provide customer value
- Reduce maintenance costs (and cost of ownership)

A description of each of the tools will be given next

Failure Data Analysis

The Failure Data Analysis tool allows the user to perform searches and calculations on the maintenance data retrieved from the field. Figure 5.21 shows the failure data analyser interface screen

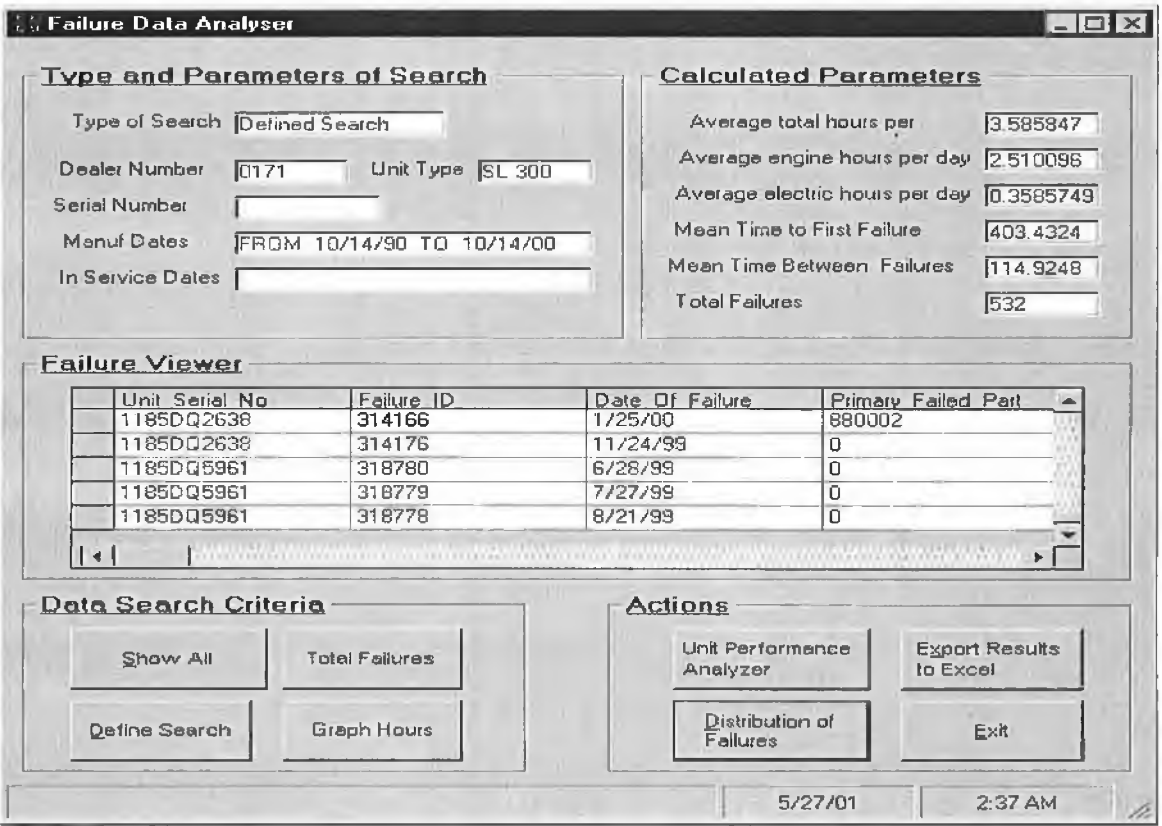


Figure 5.21 Failure Data Analysis

This interface allows the user to define various search combinations based on different criteria. The returned data is analysed and various results are obtained. These results may be used as reliability and maintenance parameters in subsequent calculations and in other applications. These results can be graphically represented or exported to excel for analysis. This information is valuable in planning various product maintenance strategies and choosing critical products for further examination.

Parts Failure Analysis

The parts failure analysis retrieves information associated with part or components. The user interface of this tool is shown in figure 5.22. This is an important aspect of any maintenance data calculations.

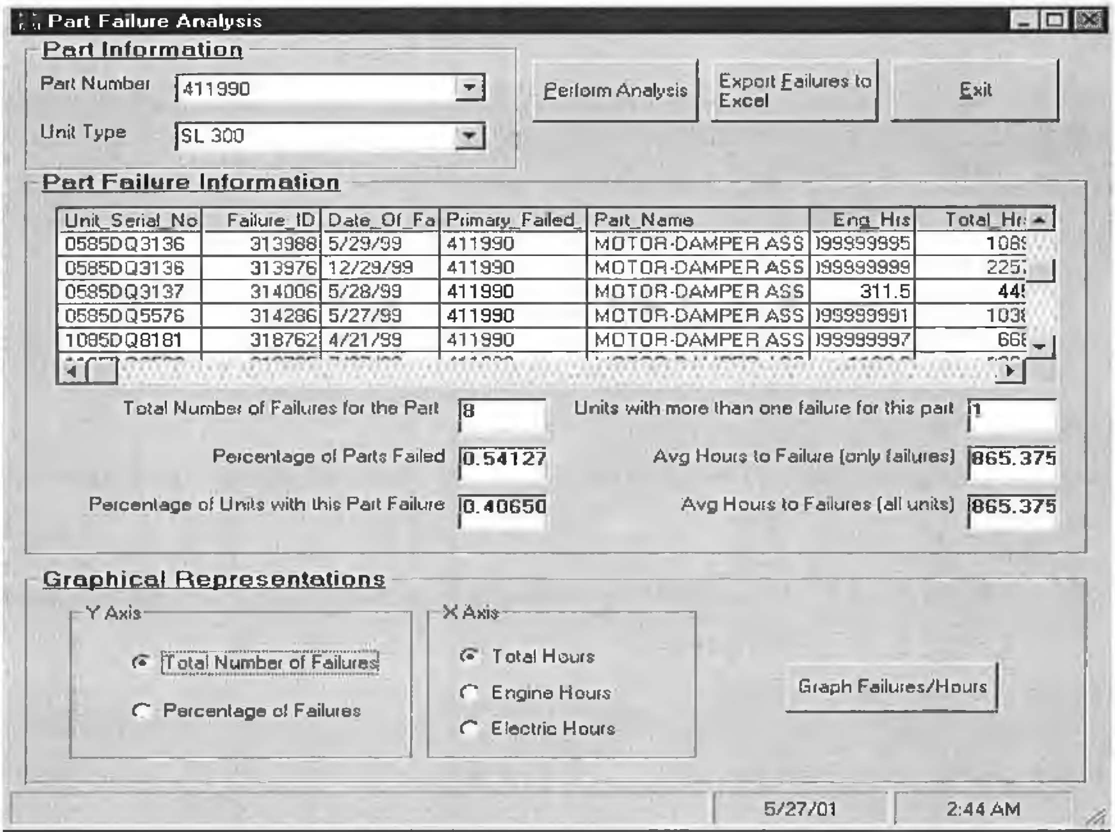


Figure 5.22 Part Failure Analysis

Using the information from this analysis will allow the user to generate results to support any decision making process that involves individual components or subsystems. This information can be used to predict the reliability of new similar components or develop new maintenance strategies for current components. Critical components can be identified and component improvement or replacement projects initialised.

Failure Modes Manager

The failure modes manager is a tool, which supports the user in identifying component failure modes. A database of failure modes is continuously maintained and updated. Figure 5.23 displays the user interface.

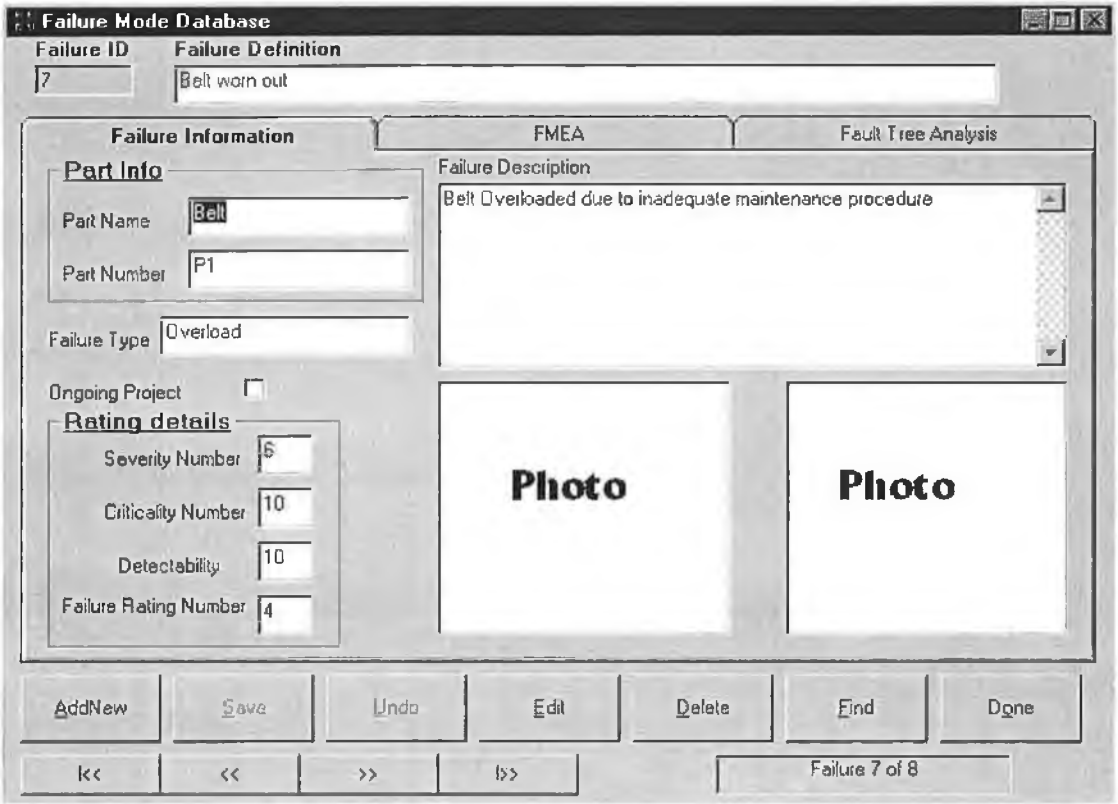


Figure 5.23 Failure Modes Database

These failure modes are retrieved from different locations, in-house testing, OEM reports, field information and FMEA. The information contained in this manager can be relayed to the field so that dealers/customers can clearly identify each mode of failure correctly. If a particular failure mode occurs regularly in a particular component then action may be deemed necessary.

5.4.3 Prediction Tools

Through the RFDM interface the user has access to a number or software packages for reliability, maintainability, availability and cost prediction. These include:

- Lifetime distribution analysis of data.
- Fault Tree Analysis modelling
- Availability Simulators

5.4.4 Information Manager

The Information Manager section of RFDM provides the user with the ability to store and manage the maintenance and reliability related documentation and reference data. It also facilitates the user to update and control the information distributed to the customer/dealer through the *Support Information* section discussed previously. The information manager discussed is supported by a PDM system, the customisation of which is presented by Ocon in reference [Oco01]. Figure 5.24 shows the interface the user utilises to add information to the information manager.

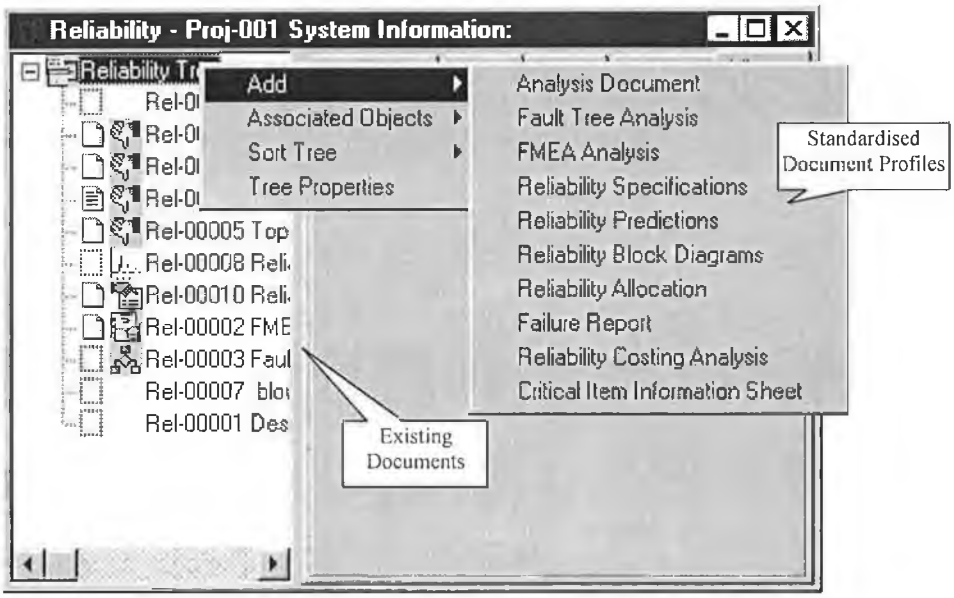


Figure 5.24 Adding information to the Information Manager

The various files generated by the field data tools and various other maintenance and reliability activities can be added to the system. The user chooses the required document profile and is presented with a standardised *profile card* where a summary of information is entered. Figure 5.25 shows the profile for an FMEA document. Using the *details* tab on the screen the user can add all documentation relevant to the FMEA to the system. When the file (and all relevant information) has been added to the system, it is stored in the system's vault[6]. Figure 5.26 shows the Information manager's built-in viewer to display a critical item document added to the system.

A user can access all information in the system, providing they have the appropriate access levels. Various search criteria can be used to locate a required document. Each field in the profile card acts as a search parameter in the system.

[6] Provides a physical storage system for the data and documents, with security levels and controlled access.

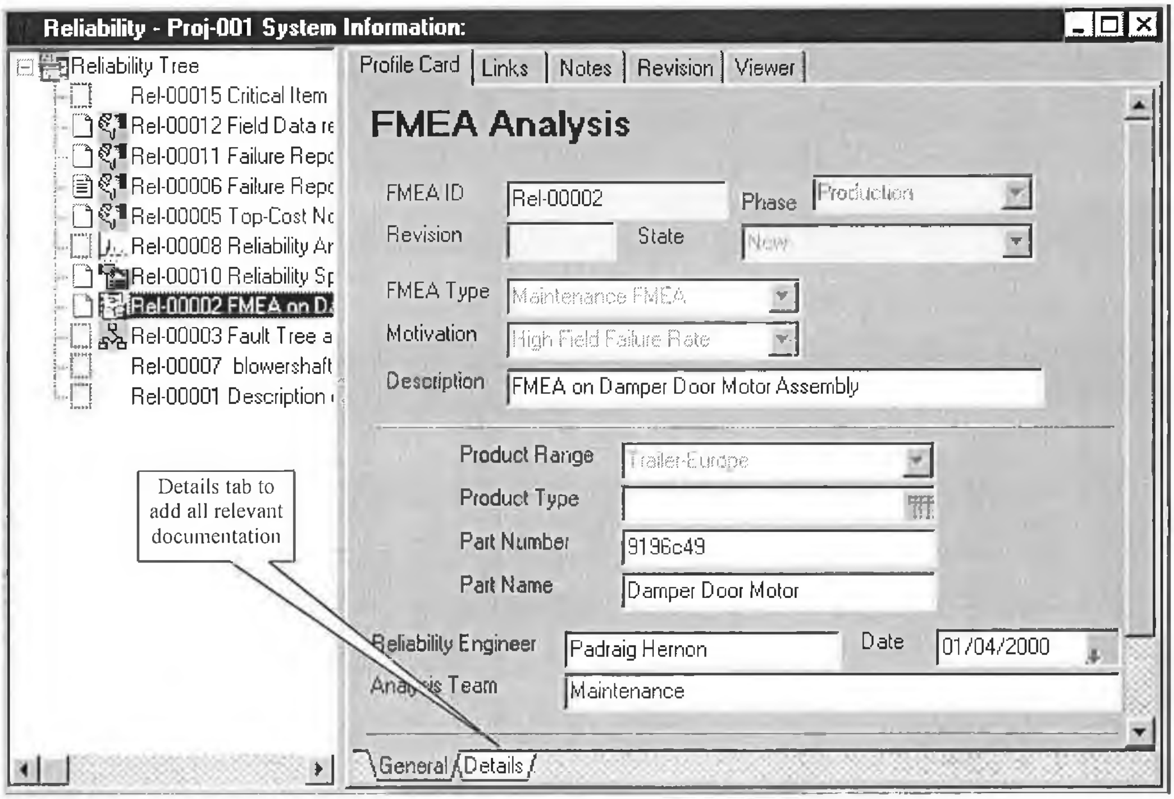


Figure 5.25 FMEA Analysis Profile Card

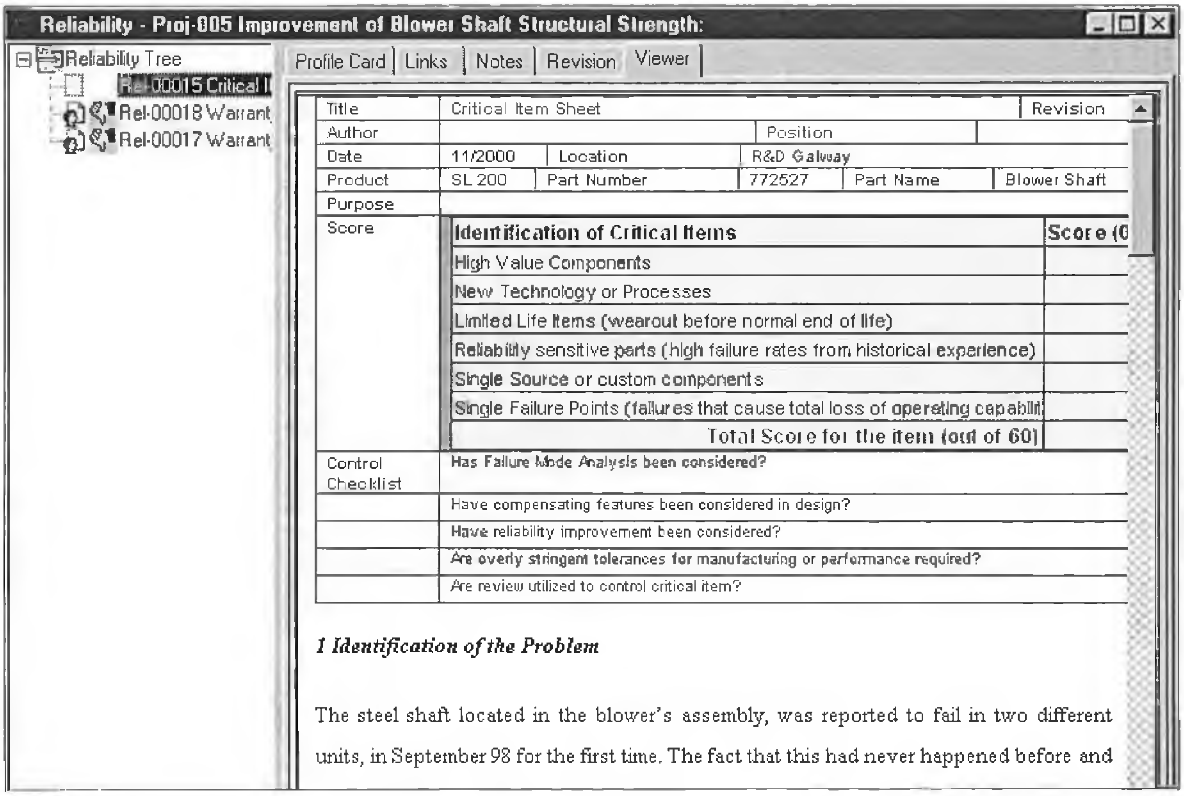


Figure 5.26 Corrective Action Document

The information can store all relevant information regarding product and components. Figure 5.27 shows standard information entered into the system. This information can be used to improve maintenance strategies and improve product reliability in the field.

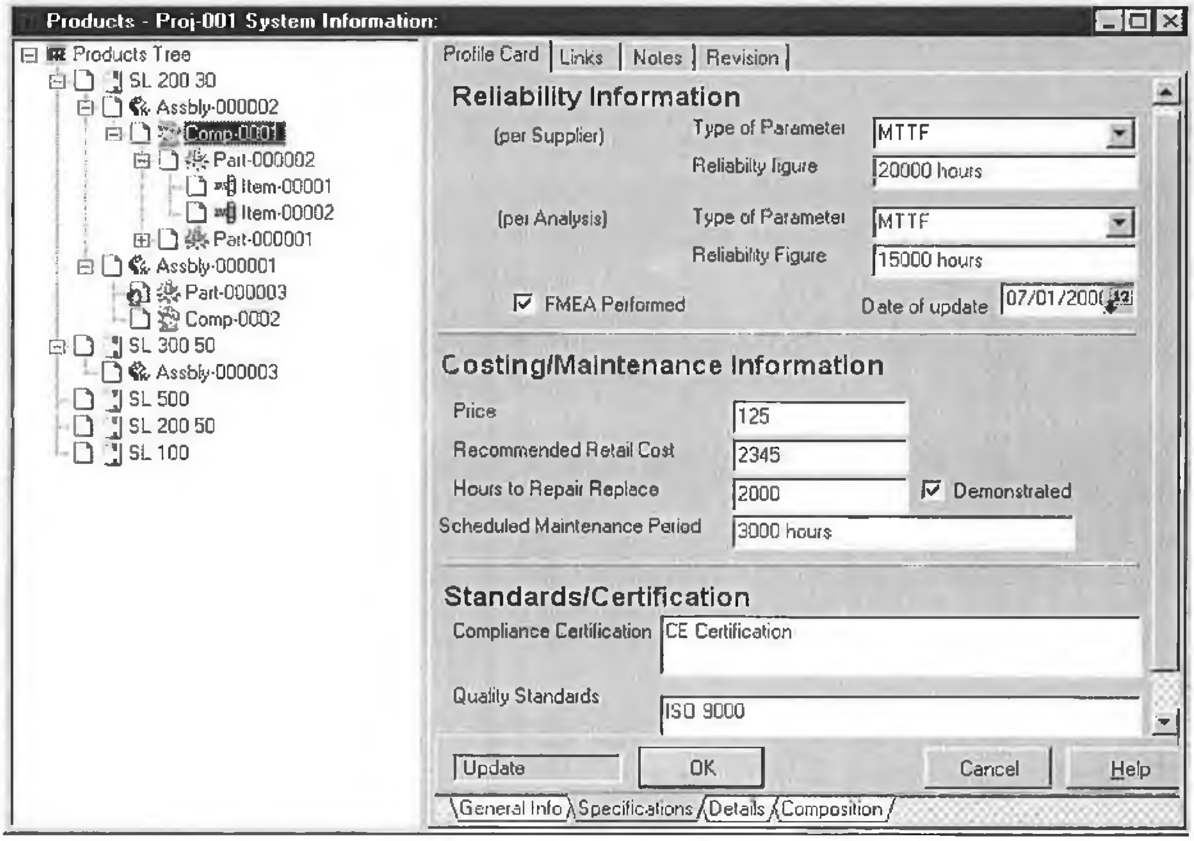


Figure 5.27 Component Information

Support Information

Support Information was discussed during the description of the Field Support Module. However, to ensure this information is current it must be continuously updated and managed. The relevant information must incessantly be available to support the product in the field. The *Information Manager* is used to accomplish this.

All relevant maintenance and support information can be input into the system and accessed via the RFDM's *Support Information* element, by the field personnel, i.e. dealer and field service engineers. Figure 5.26 displays the interface for adding information to the *Service* section of the Information Manager. This information is then immediately available to the field. The information available to support the maintenance and support function of the product in the field include:

- Maintenance Manuals
- Filed Test Instructions
- Corrective Action

- Service and Warranty Bulletins
- Component Information
- Recommended Maintenance strategies

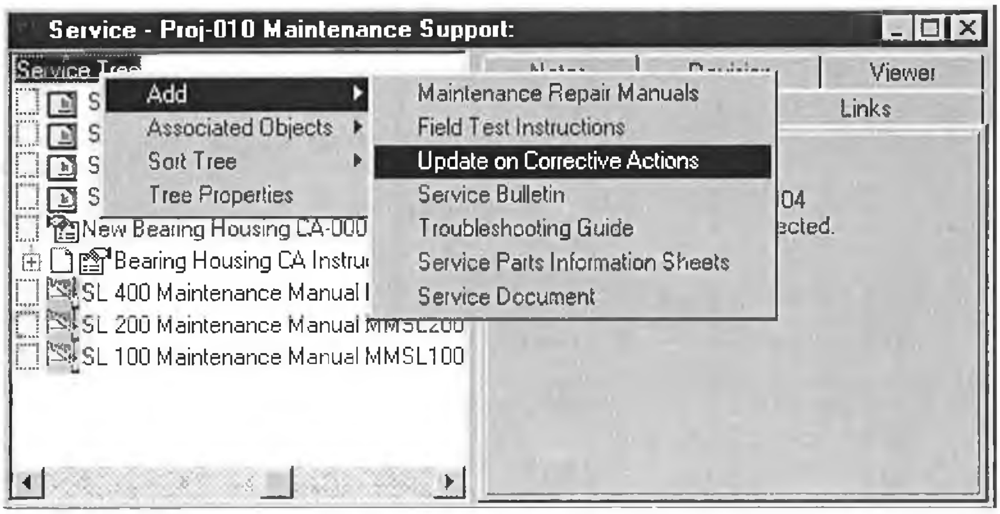


Figure 5.26 Adding Support Information

5.5 Summary

This chapter has illustrated a prototyped Reliability and Field Data Management (RFDM) which was developed to satisfy the requirements of a Maintenance Process Management Model (MMPM) presented in chapter three and technically and functionally specified in chapter four. These specifications and requirements were based on the organisational structure of the industrial partner, Thermo King Europe.

RFDM is describes from a users perspective and deals with the requirement of the various users of the system. The Field Support Module is the subdivision of RFDM that interfaces with the person responsible for the maintenance and support of the product, usually a Thermo King Dealership, providing the user with tools to carry out those functions efficiently. The Reliability and Cost Data Management Module illustrates RFDM from the manufacturers perspective, providing the user with tools and methodologies to analyse field data, manage maintenance and reliability information and finally supply the appropriate information to the field.

Chapter six will present conclusions and recommendations that have resulted in the development of the models and system discussed in this thesis.

Chapter 6

Conclusions and Further Development

6.1 Thesis Summary

The research carried out in the development of this thesis is focused on the areas of customer value, life cycle cost and product maintenance.

Firstly the thesis reviews the concept of customer value from the two broad positions of the traditional approach and the modern approach. The traditional approach focused on using the 'brand' as a market differentiator, an approach that depended on customer loyalty to maintain market position. The brand is seen as the secure way to ensure product value and reliability. Due to the increased demands of the modern market environment, the traditional concepts and tools are no longer sufficient to create sufficient quality drivers. New tools and methodologies are required and the author has proposed a *Product Lifetime Value* approach, where customers are encouraged to view value from a product lifetime perspective. The value driver being life cycle cost and particularly cost of ownership.

The research then concentrates on life cycle cost, investigating the relevant applications, activities and procedures. Chapter two concludes with the presentation of a life cycle cost model, which includes the various components and their relationship to both manufacturer and customer and to the links to customer value. Maintenance is introduced as a significant life cycle cost driver and potential value driver.

The research then focused on the area of product maintenance. Chapter three conducts a thorough study into the area of maintenance. Maintenance activities are presented and reliability, maintainability and availability selected as significant maintenance cost drivers. These areas are then examined comprehensively. Maintenance strategies, optimisation techniques and methodologies are discussed in detail, culminating in the development of a best practice Maintenance Process Management Model (MPMM), which is presented at the end of chapter three. Figure 6.1 illustrates the relationship between the initial areas of study, i.e. customer value, life cycle cost and product maintenance, and the resulting development of MPMM.

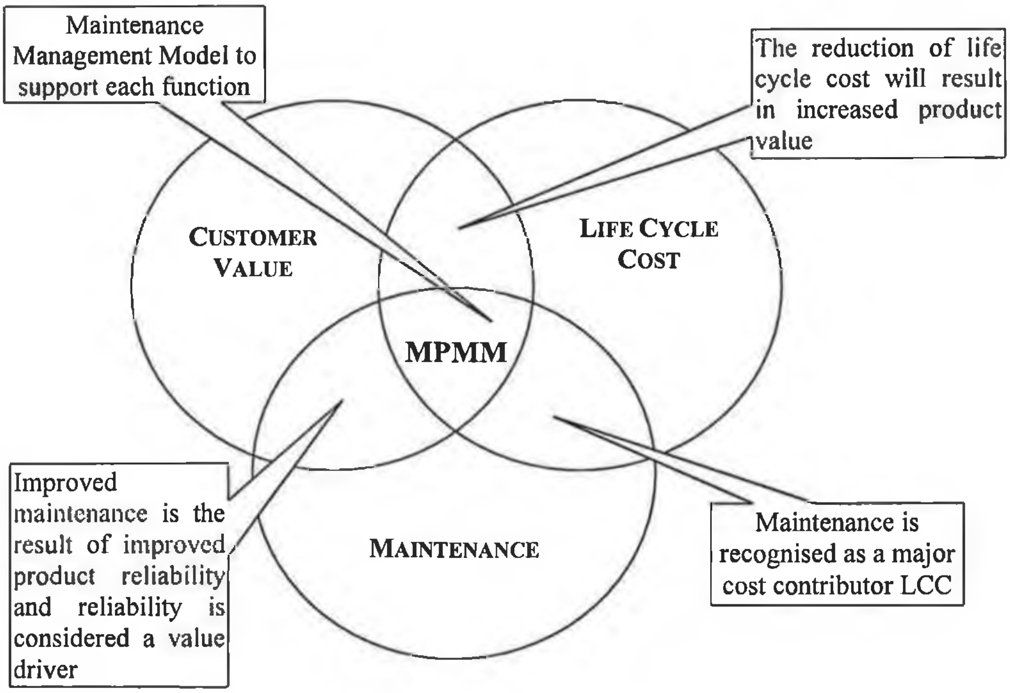


Figure 6.1 Summary of relationships between thesis research areas

Chapter five describes the specifications of the technical infrastructure required for the implementation of the Maintenance Management Process Model. The specifications are based on the requirements of Thermo King, the REFIDAM project's industrial partner. To support the implementation of MPMM according to the industrial partner's organisational structure, a Reliability and Field Data Management System (RFDM) is developed and it is functionally specified. The prototyped RFDM is described in chapter five. It consists of a software system with a *Field Support Module*, to manage and support the product's maintenance activities in the field and to facilitate in the transfer of maintenance data to the manufacturer for analysis. A *Reliability and Cost Data Management Module* to analyse, manage and distribute the maintenance data results and conclusions. This chapter presents the conclusions of the thesis and proposes further development of the system.

6.2 Results

The research carried out in this thesis and the models presented has resulted in the development of an information management system with the following features:

- Manage the maintenance function of the product in the field
- Facilitate the transfer of maintenance data from the field to the manufacturer
- Support the maintenance function with current information and documentation
- Provide the tools necessary to analyse the maintenance information
- Manage maintenance information and documentation

The system is composed of two main modules, i.e. Field Support Module and Reliability and Cost Data Management Module. The former provides the interface for the dealer and the latter provides the interface with the manufacturer. Both systems are incorporated in a single system called RFDM. Figure 6.2 illustrates the overall structure of the system.

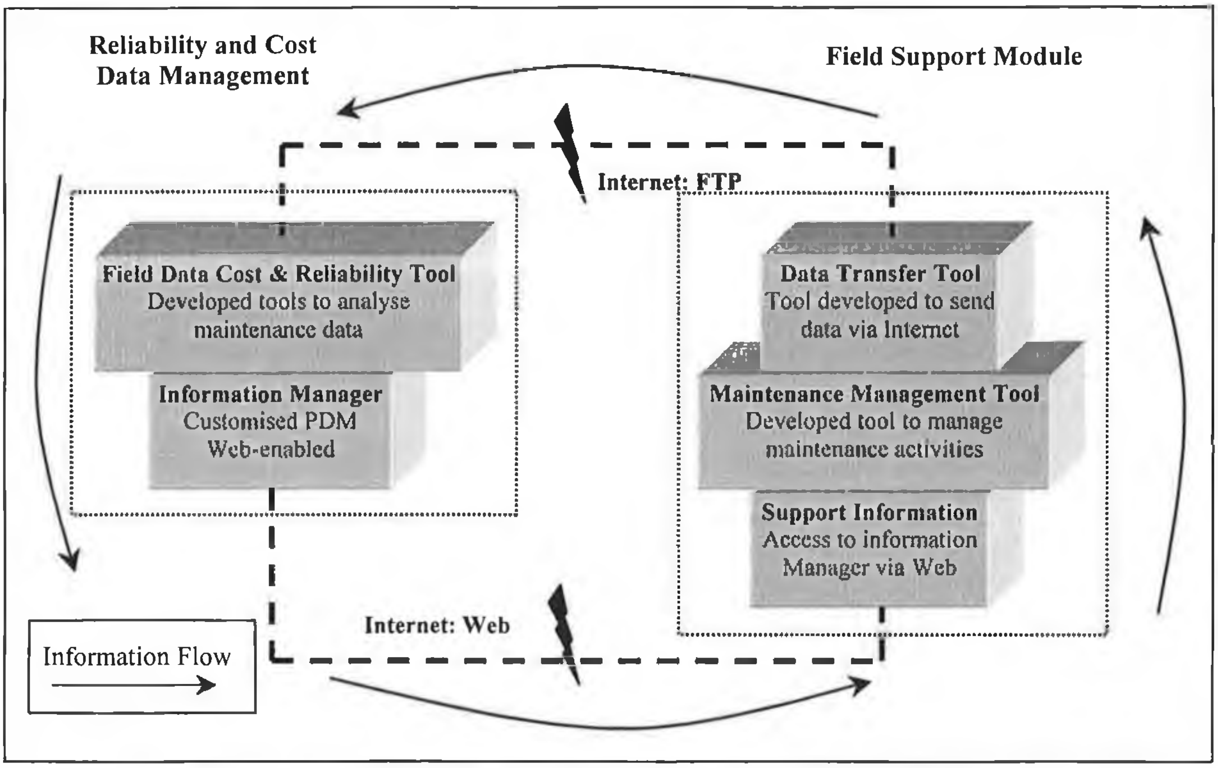


Figure 6.2 Overall structure of RFDM

The function of the various subsystems is described next.

Data Transfer Tool: The tool uses a specifically developed Internet based, File Transfer Protocol (FTP) platform to support regular (or continuous) transmission of maintenance data from the field to the manufacturer for analysis.

Maintenance Management Tool: This tool is a purposely-developed tool to assist in the maintenance activities in the field. It is based on a Computer Maintenance Management System (CMMS) framework, with a built-in web browser or 'self-browser' to access the *Support Information* section. The self-browser is a component of RFDM, therefore no external browser application is required, i.e. Microsoft Internet Explorer or Netscape Navigator.

Support Information: This uses the self-browser to access the appropriate section of the web-enabled Information Manager. This provides the user with current maintenance and support information, such as, maintenance manuals and procedures, corrective actions and component updates.

Field Data Tools: These are specifically developed tools, with the purpose of analysing the large quantities of maintenance data retrieved from the field through the Data Transfer Tool. The data can be searched using various parameters and analysed to produce maintenance, reliability and costing results.

Information Manager: This is a customised PDM platform vital to manage information and processes within the manufacturer's organisation. Ocon carried out the primary customisation of the PDM within this project and further details can be found in reference [Oco01]. Appropriate field support information can be made available in the field by using the PDM's web-enabling facility.

6.3 Conclusions

The following conclusions were identified during the research carried out in the area of customer value and life cycle cost.

- It has become apparent that the investment in creating a product 'brand' is no longer a guarantee of long-term defensible advantage in the market place. The tools of the traditional brand-set and its brand management structure are incapable of delivering modern customer value.
- The modern environment requires a new framework on which to build customer value. The author proposes a product lifetime value management approach by building relationships with customers to encourage them to look at value over time and not at a series of individual transactions. Where value is expressed as the ratio between perceived quality and price, the price being viewed from a life cycle cost and perspective.

- There are two main perspectives from which life cycle cost (LCC) can be viewed, the manufacturers perspective and the customer' perspective. When LCC was traditionally applied, is usually focused on the manufacture's perspective, and often the manufacturers perspective did not lead to an optimum for the customer a new approach to life cycle cost, called cost of ownership was introduced. This thesis interprets LCC as follows: LCC equals acquisition cost plus all other operation and support costs, where all pre sale costs incurred are included in the acquisition cost. Therefore LCC equals Cost of Ownership.

- Life cycle cost analysis (LCCA) can be carried out using various activities and procedures. There is no standard way to carry out a costing procedure. However, the process should be transparent to everybody involved. All assumptions should be made clear before the presentation of the results.

- LCCA can be accomplished using a number of previously developed cost models. However, there is no single model, which has been accepted as standard. There are several factors for having no single model, these include: existence of many different types of data collection systems and many different types of equipment.

- The author presents a generic cost model, illustrating the various cost components and the relationship with the manufacturer and the customer, and their relationship with customer value. Maintenance is selected as a significant element of life cycle cost and customer value.

The research into customer value and life cycle cost has led the author into the area of product maintenance. By researching the various maintenance activities, optimisation techniques, methodologies and management, the following conclusions have been established.

- Maintenance or equipment lifetime optimisation is a prime candidate to simultaneously increase product reliability, effectiveness, and profitability; and reduce life cycle cost.

- Overall maintenance performance measures that combine availability, equipment output, and lifetime cost are necessary for prioritising resources. Measures must originate from market conditions and business objectives, point to opportunities for increased profitability, and lead to optimised conditions.

- There is a major requirement for accurate traceable information. Such as data to calculate MTBF and means with which to ascertain the exact reason of failure for all components. If improvements are made to material or processes, there must be a way to match the results with expectations. An effective model for equipment optimisation is required
- Reliability-Centred Maintenance (RCM) is a strategic methodology for determining the most appropriate maintenance strategy where each component is systematically analysed to identify their failure modes, so that appropriate tasks can be assigned.
- Computer Maintenance Management Systems (CMMS) are being increasingly used to mange and control equipment maintenance.

From these conclusions the author recognised the need for development of a best practice reliability-centred model for maintenance management. The author has presented a Maintenance Process Management Model (MPMM) with the following features.

- The model presented integrates processes to create a world-class approach to maintenance management.
- The model is divided into separate processes and sub processes showing the high–level flow between each. Criticality ranking, failure analysis, equipment reliability strategy development, equipment reliability strategy implementation, work management and external processes are the elements that comprise the model

Throughout the whole research process the author cooperated closely with REFIDAM's[1] industrial partner Thermo King. This interaction led to the development of a technical infrastructure to support the implementation of MPMM based on the organisational structure and requirements of Thermo King. Appropriate information systems were investigated and a system called Reliability and Field Data Management System (RFDM) was developed and prototyped. It has the following features

- Support the maintenance activities of a remote and mobile product in the field
- Facilitate in the feedback of regular maintenance data from the field to Thermo King
- Provide tools to analyse the maintenance data to provide reliability, maintainability availability and life cycle cost results

[1] See thesis prologue.

- Manage the maintenance, cost, and reliability information based on a number of selected initiatives [Oco01].
- Support the product in the field by providing current maintenance and support information to the field.

The system was regularly tested for functionality at Thermo King and as a result both the model and the system was frequently altered. The prototyped RFDM was presented and demonstrated to Thermo King management and the following issues were recognised.

- The flow of information from the field depended on the support of the dealerships. The dealerships are private entities and are not obliged to supply Thermo King with the data. The author ensured that the data transfer operation in the Field Support Module of RFDM was transparent and unambiguous, requesting the dealer to undertake the task manually highlighted the fact. This process could be automated at a later date when the dealer was assured and confident in the process. The fact was highlighted further by the fact that the prototyped Field Support Module had no costing capability, therefore management could ensure the dealer that there was no proprietary cost information returned to the manufacturer. In an operational module cost and invoicing capabilities should be included.
- Educating dealers in the importance of using the system and that the process would result in direct benefit to themselves is essential. The availability of a Computer Aided Troubleshooting guide was recommended to reduce dealer apathy. This is further discussed in the next section.
- The RFDM should have the capability of integrating within the organisation's current information Management System. Since RFDM has a PDM module it should have the capability of amalgamating with the organisation's ERP system.
- RFDM is based on set structures, initiatives, and processes; it is therefore crucial that it is seen as a 'friendly' tool, to support the engineers and the dealers in carrying out their job in a more effective and efficient manner. It should be seen as a tool to reduce the workload, not increase it by adding arduous activities and procedures.

6.4 Further Development

The system developed by this thesis and by Ocon [Oco01] has significant possibilities for further development. The main developments make use of wireless communication to track and control the product in the field. Examples of these are described next.

- Integration of wireless and GPS technology into the system so that the product could be tracked and controlled remotely. Customers could locate their product and communicate with it
- Interaction and control of key actuators via control algorithms in the mobile product, and the generation of live data whilst in service, for the development of practical models of product performance, so that efficiency and quality of operation could be improved [Roc01].
- Development of built in test equipment (BITE) and intelligent field devices linked to the RFDM Field Support Module could be used to measure key maintenance variables in an operating product. This would aid maintenance decisions, maintenance diagnosis and repair of the mobile products.
- Development of wireless based services to diagnose product faults. Technicians could monitor faults remotely and obtain solutions. These solutions could be conveyed to the product user so as to prevent a possible catastrophic failure.

Figure 6.2 illustrates the complete integrations.

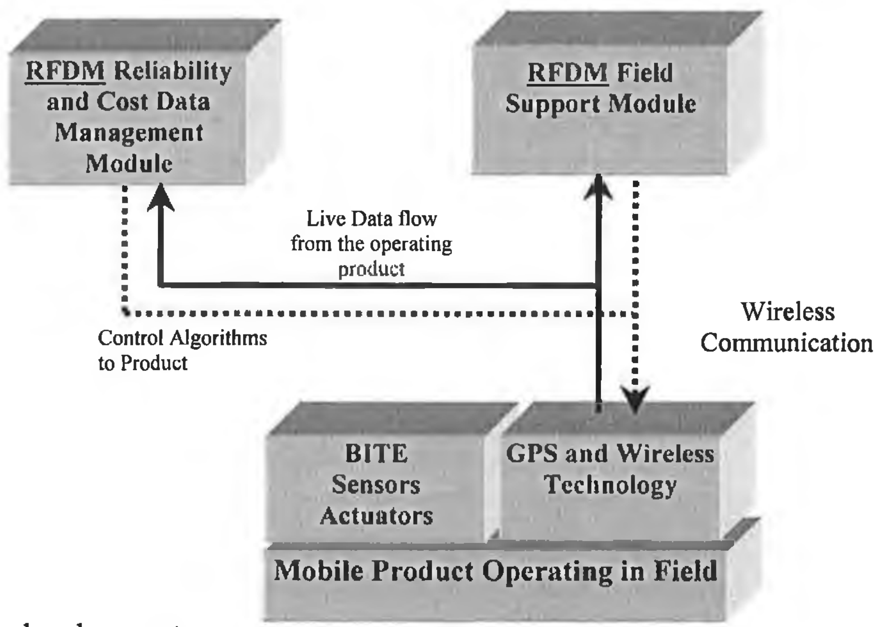


Figure 6.2: Further developments

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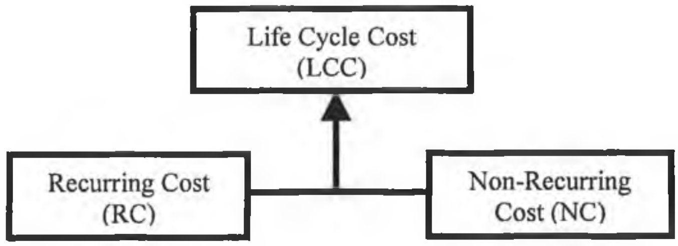
Appendix A:

Life Cycle Cost Models

Reich's Cost Model [Rei80]

This cost model involves the two major components of life cycle costing, recurring and non-recurring costs. The Life Cycle Cost is expressed as:

$$LCC = RC + NC$$



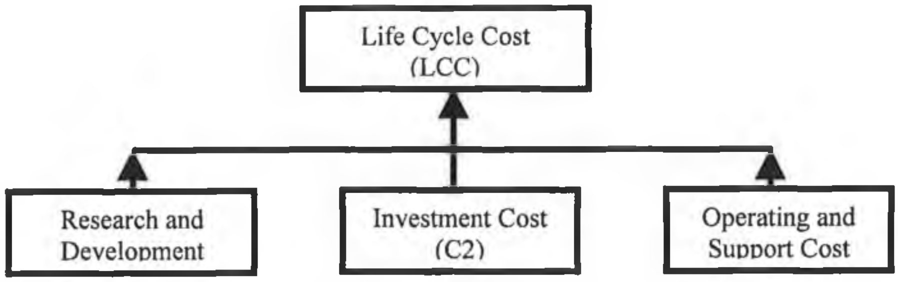
Where LCC is the life cycle cost, RC is the recurring cost, and NC is the non-recurring cost. The components of the recurring cost, RC, are as follows:

- Cost associated with maintenance
- Cost associated with manpower
- Operating cost
- Inventory cost
- Support Cost
- The components of the non-recurring costs are:
- Cost of training
- Cost of research and development
- Procurement cost
- Cost of improving reliability and maintainability
- Support Cost
- Qualification approval cost
- Cost of installation
- Transportation Cost
- Cost of test equipment
- Cost of life cycle management

Earles' Life Cycle Cost Model [Ear81]

The following cost model is a simple cost model that was developed by the US Army for costing of military equipment

$$LCC = C1 + C2 + C3$$



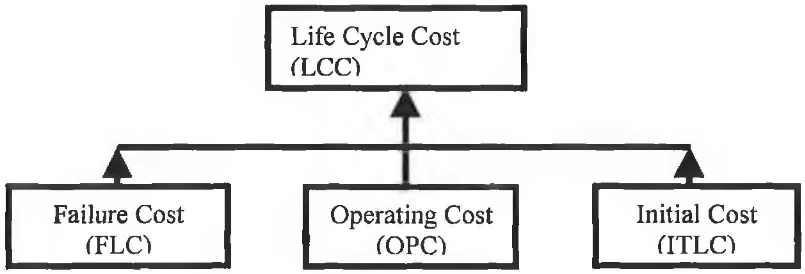
Where LCC = Life cycle cost, C1= research and development cost, C2 = investment cost, and C3 = operating and support cost. The investment cost C2 is further broken down as:

- Non-recurring investment cost
- Production cost
- Engineering changes costs
- System test and evaluation cost
- Data cost
- Production phase management cost
- Site activation cost
- Initial training cost
- Initial spares and repair parts cost
- Transportation costs
- Other investment cost
- The operating and support cost, C3 is broken down into:
- Military personnel cost
- Consumption cost
- Depot maintenance cost
- Material modification cost
- Other direct support cost
- Indirect support cost

Dickenson's Life Cycle Cost Model [Dic76]

This model expresses the life cycle cost of a system with no redundancy as:

$$LCC = FLC + OPC + ITLC$$



Where LCC = Life cycle cost, FLC = Failure Cost, OPC = Operating Cost, and ITLC = Initial Cost. ITLC is made up of one time capital investments. Cost components such as expendables, preventative maintenance, etc. are included in OPC and FLC is made up of repair costs and other operational losses attributed to system failure.

The failure cost FLC is defined by:

$$FLC = \frac{(CAF)(SLT)}{MTBF_s}$$

Where CAF is the cost of average failure, SLT is the systems life in hours, and $MTBF_s$ is the systems mean time between failures expressed in hours.

The cost of average failure is:

$$CAF = PC + CMAL + (MTTR_{AR} + T_R)CLS + (MTTR_{AR} + T_R)CPH$$

Substituting Equation (2.2) into Equation (2.1) yields

$$LCC = OPC + ITLC + \frac{(CAF)(SLT)}{MTBF_s}$$

Letting $HFL = CAF / MTBF_s$ in Equation (2.5) yields

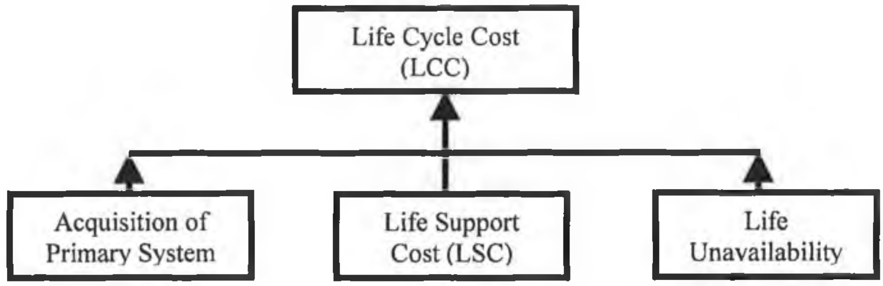
$$LCC = OPC + ILTC + (HFL)(SLT)$$

Where HFL is the failure loss cost rate expressed in £/hr.

IEC's Life Cycle Cost Model [IEC92]

The Swedish National Committee proposed the following cost model to the International Electro technical Commission:

$$LCC + LCA + LSC + LUC$$



Where LCA = acquisition cost of primary system, LSC = life support cost, and LUC = life unavailability cost. They are broken down into the following components:

$LCA + CIE + CIC + CIM$

CIE = initial equipment cost

CIC = primary system commissioning costs

CIM = acquisition management cost

$LSC = CIR + CYC$

CIR = investment in resources for operation and maintenance of primary system.

CYC = yearly costs of operation and maintenance of the primary system and necessary auxiliary equipment

$LUC + CYU + CYL$

CYU = yearly costs due to unavailability, including waste due to failure and compensation due to downtime

CYL = yearly losses of income due to unavailability of the primary system

The acquisition cost in this model consists of all investment costs required before the system is put into operation. Operating cost consists of all ongoing costs associated with the operation of the system, including scheduled maintenance. Failure costs consists of all the costs arising from system failure, this includes repair cost, downtime cost and liability cost. Failure cost can be modelled as:

$$\text{Annual failure cost} = \sum_{j's} \left(\frac{T_{op}}{MTBF_j} \right) \left((A_j + B_j T_j) + (D_j + MTTR_j) \right)$$

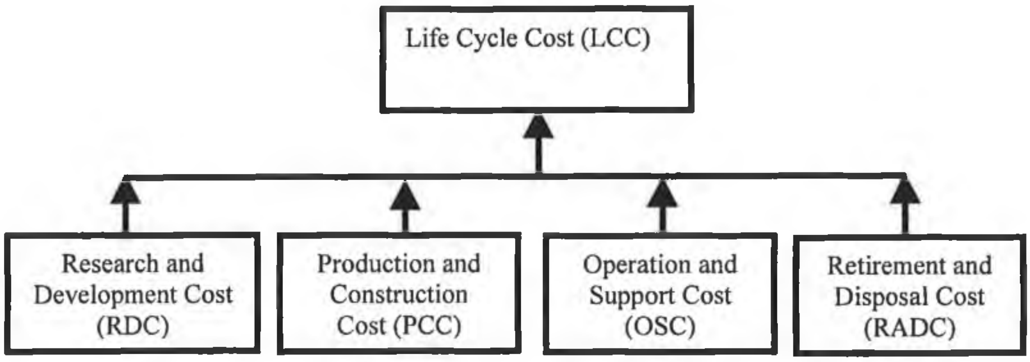
Where T_{op} = operating hours per year of system, $MTBF_j$ = average MTBF of mode j failures in the year, A_j = duration-independent costs arising from each mode j failure, e.g.

transport, B_j = loss and compensating expenses per hour of downtime due to mode j failure, T_j = average downtime due to mode j failure, D_j = repair labour cost per hour for a mode j failure, and $MTTR_j$ = Mean Time to repair for a mode j failure.

Blanchard's Life Cycle Cost Model [Bla78]

This cost model consists of four major components. Mathematically the life cycle cost is expressed as:

$$LCC = RDC + PCC + OSC + RADC$$



Where RDC is the research and development cost, PCC is the production and construction cost, OSC is the operation and support cost, and RADC is the retirement and disposal cost. The research and development cost, RDC, can be estimated from the following relationship:

$$RDC = \sum_{i=7}^{7} RDC_i$$

Where RDC_i is the *i*th cost component of the research and development cost

$i = 1$ is the product planning

$i = 2$ is engineering design

$i = 3$ is system test and evaluation

i = 4 is system life cycle management

i = 5 is system software

i = 6 is product research

i = 7 is design documentation

The production and construction cost, PCC, is expressed as

$$PCC \sum_{i=5}^{5} PCC_i$$

Where PCC_i is the *i*th cost component of the production and construction cost:

$i = 1$ is manufacturing

$i = 2$ is quality control

$i = 3$ is construction

i = 4 is industrial engineering and operational analysis

i = 5 is initial logistics support

The operation and support cost, OSC, is expressed as:

$$OSC = \sum_{i=1}^{3} OSC_i$$

Where OSC_i is the ith component of the operation and support cost:

$i = 1$ is system distribution

$i = 2$ is sustaining logistic support

$i = 3$ is system operations

The retirement and disposal, RADC, is given as

$$RADC = SURC + [\alpha(UMA)(IDC - RV)]$$

Where

SURC is the system ultimate retirement cost

RV is the reclamation value

IDC is the cost of item disposal

α is the factor for condemnation

UMA is the number of unscheduled maintenance actions

Appendix B

Life Cycle Cost Analysis Economics

Depreciation

Method one is know as the straight-line method. It assumes a linear decrease with time in the value of the product. During the useful life of the product an equal amount of money is charged for depreciation each year. The yearly depreciation charge is given by:

$$CH_{DY} \frac{AC - SV}{SL}$$

Where

AC is the acquisition cost of the product

SV is the salvage value of the property

SL is the service life of the property in years

CH_{DY} is the yearly depreciation charge

The book value of the property at the end of year k can be obtained from the following equation:

$$BVP_K = AC - k(CH_{DY})$$

Where

BVP_k is the book value of the product at the end of year k

k is the number of years in actual service

Depreciation method two is known as the declining-balance method. In this method the depreciation cost is a fixed percentage of the book value at the start of the year. Even though the yearly depreciation cost is different for each year, the value of the fixed percentage deprecation factor remains the same throughout the products service life. This method writes of the products cost early in its life at an accelerated rate and corresponding depreciation charges close to the final years of service. The deprecation factor is defined as:

$$DR = 1 - \left(\frac{SV}{AC}\right)^{1/SL}$$

Where

AC is the acquisition cost of the product

SV is the salvage value of the property

DR is the deprecation factor

The book value BVP_k, of the product at the end of year k is

$$BVP_k = AC(1 - DR)^k$$

The yearly depreciation charge, YDC_k, is given by

$$YDC_k = \lfloor BVP_{(k-1)} \rfloor DR$$

Where

BVP$_{(k-1)}$ is the book value of the product at (k - 1) years

Method three is know as the sum-of-the-years-digits (SYD) method. Similar to method two, this method returns a larger depreciation charge during the early-life years of the product than during the later years. The yearly depreciation charge is given by

$$YDC = (AC - SV)\left[\frac{SL - k + 1}{1 + 2 + 3 + 4 + \ldots + SL}\right] = (AC - SV)2(SL - k + 1)/SL(SL + 1)$$

Where

AC is the acquisition cost of the product

SV is the salvage value of the property

SL is the service life of the property in years

YDC is the yearly depreciation charge

k is the number of years in actual service

The book value, BVP$_k$, of the product at the end of year k is expressed by

$$BVP_k = 2(AC - SV)\left[\frac{1 + 2 + 3 + \ldots + (SL - k)}{SL(SL + 1)}\right] + SV$$

Future Worth

This formula is the used to calculate the value of a sum of money at a point in the future, that is, the principle sum of money plus the interest due.

$$FW = TA_m = (PA)(1 + i)^m$$

Where

FW is the Future Worth

PA is the principle sum

i the compound interest rate per period

m is the number of interest periods

Present Worth

From equation (2.1) the present worth of a future sum of money is given by the following equation:

$$PW = PA = \frac{FW}{(1+i)^m}$$

Where

PW is the present worth

Present Value with Given Escalation and Discount Rates

When annual cost in today's money, as well as, escalation and discount rated are known, the following equation can be used to calculate present value:

$$PV = \frac{ANC(1+j)}{(1+i)} + \frac{ANC(1+j)^2}{(1+i)^2} + \frac{ANC(1+j)^3}{(1+i)^3} + \ldots + \frac{ANC(1+j)^m}{(1+i)^m}$$

Where

PV is the present value

ANC is the annual cost in today's money

j is the average compound escalation rate per year

i is the average compound discount rate per year

m is the number of years

Appendix C
Sample Data

Thermo King sample data used to populate and test RFDM

Failure_ID	Unit_Serial	Date_Failure	Primary_Failed_Part	Part_Name	Eng_Hrs	Total_Hrs	Elec_Hrs	Labour_Hrs	Travel_Hrs	Net_Part
299635	0285DQ2856	30/11/99	D85605		1719.9	2457	246	4	0	0
299626	0285DQ2856	14/12/99	333097	gasket	1738.1	2483	248	2.5	0	2.34
299672	0285DQ2894	28/10/98	0	VEH DRIVE KIT-MERC 814-V/F	615.3	879	88	1.5	0	0
299662	0285DQ2894	16/12/99	047168	EPROM	1591.8	2274	227	1	0	58.43
299660	0285DQ2894	25/01/00	780336	BELT	1733.9	2477	248	4	0	4.78
299666	0285DQ2894	06/07/99	117382	FILTER OIL ELEMENT DUAL	1117.2	1596	160	3.5	0	16.7
299667	0285DQ2894	06/07/99	880001	Motor Oil - 1 Litre	1117.2	1596	160	0	0	34
299663	0285DQ2894	23/11/99	0	VEH DRIVE KIT-MERC 814-V/F	1528.8	2184	218	2	0	0
299716	0285DQ2895	23/03/99	0	VEH DRIVE KIT-MERC 814-V/F	808.5	1155	116	1.5	0	0
299711	0285DQ2895	15/09/99	880001	Motor Oil - 1 Litre	1226.4	1752	175	4	0.5	34
299721	0285DQ2895	26/10/98	0	VEH DRIVE KIT-MERC 814-V/F	546	780	78	1.5	0	0
299720	0285DQ2895	19/11/98	410741	SENSOR-TEMP	706.3	1009	101	2	0	48.89
299707	0285DQ2895	18/10/99	0	VEH DRIVE KIT-MERC 814-V/F	1320.9	1887	189	1.5	0	0
299708	0285DQ2895	15/09/99	780928	BELT	1226.4	1752	175	4	0.5	38.64
299724	0285DQ2895	04/08/98	0	VEH DRIVE KIT-MERC 814-V/F	325.5	465	46	1.5	0	0
299701	0285DQ2931	08/09/98	0	VEH DRIVE KIT-MERC 814-V/F	379.4	542	54	1	1	0
299684	0285DQ2931	11/10/99	780336	BELT	1286.6	1838	184	0	0	4.78
299697	0285DQ2931	30/01/99	0	VEH DRIVE KIT-MERC 814-V/F	562.8	804	80	1.5	0	0

Failure_ID	Unit_Serial	Date_Failure	Primary_Failed_Part	Part_Name	Eng_Hrs	Total_Hrs	Elec_Hrs	Labour_Hrs	Travel_Hrs	Net_Part
299700	0285DQ2931	21/10/98	562330	BANDWRAP 7IN.NYLON P100	451.5	645	64	1	0	0
299691	0285DQ2931	28/08/99	0	VEH DRIVE KIT-MERC 814-V/F	1116.5	1595	160	1	0	0
299737	0285DQ2932	12/03/99	0	VEH DRIVE KIT-MERC 814-V/F	817.6	1168	117	1	0	0
299742	0285DQ2932	11/08/98	0	VEH DRIVE KIT-MERC 814-V/F	377.3	539	54	1.5	0	0
314226	0285DQ4663	14/01/00	880031	Freon - R404A	1323	1890	189	37	2	120
314225	0285DQ4663	14/01/00	665750	DRIER ORS	1323	1890	189	0	0	0
314223	0285DQ4663	21/01/00	880002	Antifreeze	1323	1890	189	2.5	0	25
314222	0285DQ4663	21/01/00	333096	gasket	1323	1890	189	0	0	2.88
314224	0285DQ4663	14/01/00	412071	BOARD-RELAY	1323	1890	189	0	0	308.16
314228	0285DQ4663	29/12/99	D85855		1292.9	1847	185	2	0	0
314229	0285DQ4663	21/12/99	0	VEH DRIVE KIT-MERC 814-V/F	1289.4	1842	184	1.5	0	0
314239	0285DQ4663	22/02/99	0	VEH DRIVE KIT-MERC 814-V/F	547.4	782	78	1.5	0	0
314232	0285DQ4663	01/12/99	700173	KIT PULLEY IDLER REPAIR	1255.1	1793	179	2	1	44.46
314253	0285DQ4664	20/01/99	0	VEH DRIVE KIT-MERC 814-V/F	471.1	673	67	1	1	0
314255	0285DQ4664	27/10/98	0	VEH DRIVE KIT-MERC 814-V/F	263.2	376	38	1.5	0	0
314259	0285DQ4704	19/08/99	0	VEH DRIVE KIT-MERC 814-V/F	618.8	884	88	1.5	1	0
314258	0285DQ4704	28/10/99	0	VEH DRIVE KIT-MERC 814-V/F	693	990	99	2.5	0	0
314260	0285DQ4704	15/07/99	880031	Freon - R404A	551.6	788	79	3.5	0.5	45