CRANFIELD UNIVERSITY

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MODELLING THE IMPACT OF REDUCED VARIABILITY OF MACHINE TOOL DOWNTIME

SCHOOL OF APPLIED SCIENCES

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MODELLING THE IMPACT OF REDUCED VARIABILITY OF MACHINE TOOL DOWNTIME

SUPERVISOR: DR RICK GREENOUGH

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for the Degree of Master of Research

ABSTRACT

A model is presented, which allows a machine tool in a service arrangement to be simulated. The impact of machine tool downtime and the sensitivity of machine performance to the services provided may be modelled and optimised. SHOAM, developed by the Boeing Company, is used to make the model and modified to make it applicable for use with a machine tool. SHOAM is a tool which uses discrete event simulation to analyse the performance of an aircraft in a realistic operational setting, allowing the benefits of using health management technologies, which use vehicle condition based information to predict failures and plan the support services, to be assessed.

Machine tool industry members are interviewed to gather information on typical operational scenarios involving advanced machine tools and the approaches to the services provided to maintain them. These reveal the highly user-driven nature of the machine tool service industry, with users specifying the services they desire, the costs of which are then added to machine sales for a premium. Machine maintenance is often neglected by users who value short-term productivity gains over longer-term performance and manufacturers are therefore unable to guarantee performance based contracts. This neglect and the variability in machine tool environments are found to impede the development of machine reliability.

The information from the interviews, in concert with a literature review of equipment service management is used to develop the behavioural requirements. A new model is then created using elements from SHOAM. Fundamental changes are made to the way SHOAM models operational scenarios and the response to condition-based information to represent the current behaviour in the machine tool industry. Typical machine tool services are included, which allows the costs and benefits of using health management technologies to be compare to existing machine services. These technologies are found to increase machine tool operational reliability and make a significant contribution to reducing lifecycle costs.

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GLOSSARY OF TERMS

PHM	Prognostics and Health Management
CBM	Condition Based Maintenance
RCM	Reliability Centred Maintenance
RBM	Risk Based Maintenance
PM	Preventative Maintenance
IVHM	Integrated Vehicle Health Management
SHOAM	System Health and Operational Analysis Model
PICAM	Probabilistic IVHM Cost-benefit Analysis Model
MTA	Manufacturing Technologies Association
LCC/P	Life Cycle Cost/Profit
FMECA	Failure Mode and Effect Criticality Analysis
ABC	Activity Based Costing
CM	Condition Monitoring
VDM	Value Driven Maintenance
BSC	Balanced Score Card
MSG	Maintenance Steering Group
LRU	Lowest Replaceable Unit
MCM	Machine Condition Monitoring
IMS	Intelligent Maintenance System
MOE	Measure of effectiveness
MTBF	Mean time between failure
MTTR	Mean time to repair

1. INTRODUCTION AND BACKGROUND

This chapter introduces the increasing importance of services to the UK machine tool industry, which forms the industrial context of the research. The aims of the Integrated Vehicle Health Management programme (IVHM) are presented as is the System Health and Operations Analysis Model (SHOAM), the modification of which is the one of the main objectives of the project. Finally, the aims, objectives and thesis structure are given.

1.1 Machine Tool Industry in the UK

Markets for machine tools in the UK have traditionally been turbulent, driven by the fluctuating investment in the manufacturing sector. The establishment of competition from low labour cost economies in the industry has increased pressure on the already limited margins of domestic producers, who themselves face export disadvantages. Manufacturers have reacted with increased specialisation of machine functions and technological complexity which allows them to target hi-tech niche markets. Maintenance and services are also increasing in importance for manufacturers as a way of adding long-term value to individual sales to provide a more stable income.

When supplying such services to the machine user, persistent difficulties are often encountered which impede the development of machine tool service markets. There are many factors causing these difficulties such as improper management values and inefficient maintenance organisation. Maintenance of machines has traditionally been viewed as a cost to be minimised or avoided; invested in when the economic climate is good and neglected when times are bad. Servicing tasks are also managed blindly, with little or no knowledge of equipment condition, leading to wasted components and unplanned downtime. The impact of maintenance is always weighed against the immediate costs of the maintenance activities, so increases in future manufacturing efficiency are rarely traced to the maintenance services that originated them.

1.2 The Integrated Vehicle Health Management Programme

For airline companies, the costs of keeping an aircraft on the ground and not in flight can be considerable, not only because a piece of capital intensive equipment is not creating value, but also due to the high tariffs charged by airports for holding the aircraft. Companies therefore try to minimise turn around times at airports and keep aeroplanes in the air as much as possible. This requires that the activities and services conducted at airports be carefully planned and executed. Service and operations planners therefore try to ensure that the required resources are available at an aircraft's destination ready for when it arrives, so that servicing time is minimised. Unforeseen problems aboard aircraft which require significant maintenance present a nightmare scenario for an airline, especially if the necessary resources are unavailable immediately or at an incorrect destination.

IVHM is a programme initiated by Boeing which aims to use prognostics and health management (PHM) systems to accurately asses the health of an aircraft in flight (Ofsthun, 2002). This information can be relayed to maintenance and operations planners to manage maintenance resources and vehicle use more effectively. There are potentially many benefits to IVHM implementation. Services can be carried out in a more cost effective manner, at a more appropriate time, reducing maintenance costs and increasing overall vehicle availability. Ofsthun (2002) notes the potential for improving aircraft operational performance as aircraft can be matched with greater accuracy to a operational environments and the reduction of aircraft servicing for reducing the lifecycle costs of an aircraft.

IVHM is not restricted to aircraft applications and will be useful where monitoring the current system health and planning maintenance services are required. Indeed many automobiles today already have fault diagnostic and prognostic systems installed to inform the driver of the health status of components in the vehicle. The driver can then plan for the necessary services to keep the car in a working condition. Capital intensive, precision or advanced machine tools are an industrial application which may also justify investment in expensive PHM technologies. The availability and performance of such machines is usually vital for the efficiency of a production facility, given the large investment and skills needed to acquire and operate one. Maintenance and servicing will therefore be critical not just to achieve a high machine utilisation, but also for manufacturing efficiency and organisational success.

The System Health and Operations Analysis Model (SHOAM) is a tool developed to support the IVHM program that enables aircraft builders and IVHM planners to design and simulate different IVHM solutions and assess their effectiveness over the aircraft lifecycle. Analysts can then determine and optimise a service strategy and the necessary resources. The model creates fleets of aircraft with specific reliability characteristics and uses discrete event simulation methods to simulate the aging of each aircraft in a realistic operational setting. Systems on the aircraft then fail, which require maintenance and servicing. Different prognostic and diagnostic technologies can then be installed on these systems and the sensitivity of fleet performance and maintenance resources to these different solutions simulated over the lifecycle of the aircraft. The most effective techniques can then be distinguished, reducing the risk of investment in expensive IVHM technologies. The development of tools similar to SHOAM for use with specialised or complex machine tools can directly benefit productive efficiency because it might allow manufacturers and service planners to asses the impact of failures upon the operational performance of the machine tool.

1.3 Summary of Thesis Aim and Objectives

The aim of the project is create a model using Boeing's SHOAM tool which can evaluate the operational impact of failures upon the quality of service delivered by an advanced machine tool. The effectiveness of different maintenance and service techniques may then be assessed using the model. Objectives to achieve this aim include researching typical operational scenarios featuring a machine tool performing at a given service level, so that the modifications to the SHOAM model accurately reflect the industrial context. Boeing experts will need to be consulted so that a familiarisation with the model can be achieved. Finally, the SHOAM model itself will be modified to make it applicable for a machine tool as part of a manufacturing and supply system.

1.4 Thesis Structure

The thesis begins with a brief overview of the current trends in the UK machine tool industry. The increased importance of services and the development of advanced machines which forms the industrial context of the research are also explored. A literature review follows immediately, which examines some of the problems experienced by equipment producers when providing services. New and current approaches to machine maintenance are explored, as are some of the current PHM technologies available. The research methodology provides an overview of the research aims, objectives and programme, which is followed by the interviews of industry members. The interviews gather information on the operational environment of advanced machine tools and these provide the requirements of the model. Some of the changes to the SHOAM tool are highlighted and finally, the model is tested and evaluated.

2. INDUSTRIAL CONTEXT

This chapter introduces the machine tool industry in the UK which provides the industrial context to the research. The structure of the industry is discussed along with the current markets and trends for machine tools. Current issues within the machine tool industry are examined, some of which will be dealt with in more detail in the next chapter.

2.1 UK Market for Machine Tools

Almost all manufacturing industries use machine tools as part of their production process in some form and consequently, machine tools vary considerably in type and application. Markets for machine tools can therefore be segmented by different characteristics, but the prevailing approach used is based on the processed material. This research concerns machine tools used for working metals, but they are also essential to process wood, stone and other materials. The Manufacturing Technologies Association (MTA) defines a metalworking machine tool as “a power driven machine, not portable by hand when in operation, which works metal by cutting, forming or physico-chemical machining”.

The position of machine tools as capital goods in the supply chain means that market demand is driven by investment confidence, finance and capacity utilisation in the UK’s manufacturing sector (MTA, 2008). The pattern of demand therefore takes on the form of a business cycle, as the market is subject to investment fluctuations in the economy (Figure 1). This susceptibility to investor confidence also exposes machine tool markets to political and economic influences, creating large fluctuations in business between years as well as over a long term cycle.

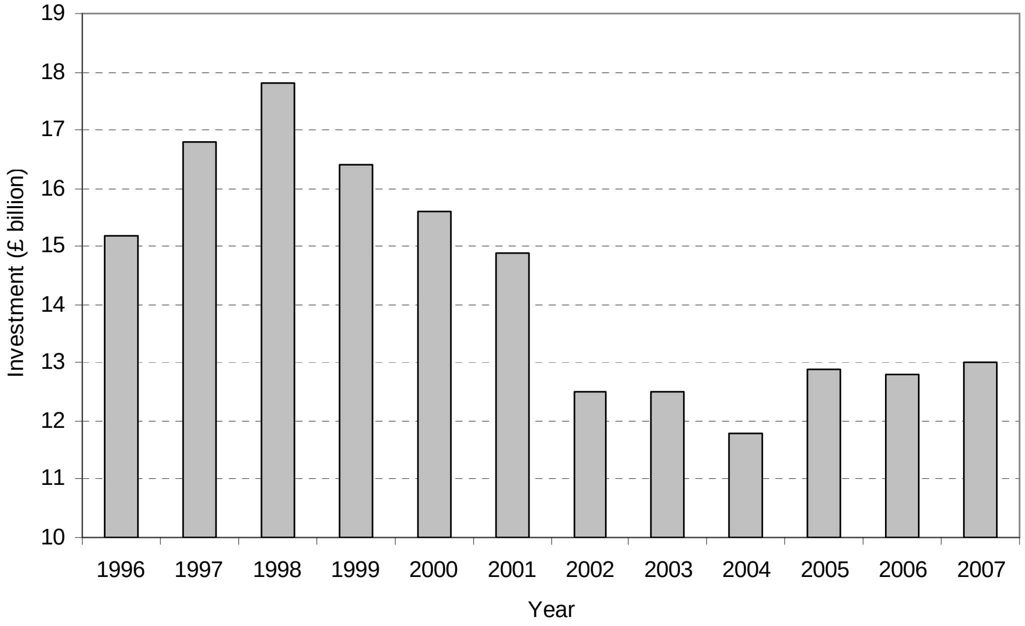


Figure 1: UK manufacturing investment in capital equipment (Source: MTA, 2008)

The largest consumers of machine tools in the UK are the automotive and aerospace industries, accounting for roughly 75% of end users (Figure 2). Investment from these two sectors will have the biggest impact on the demand for metalworking machine tools and they themselves are exposed to political and economic conditions. The September 11th 2001 terrorist attacks on the United States, for example, caused a 12% fall in aerospace turnover in 2002, despite increases during the 3 preceding years and the 3 years following. Aerospace sectors both in the UK and America underwent considerable consolidation and employment reduction during the 1990s with a resulting contraction in demand and consolidation down the supply chain. Despite this however, Mintel (2006) reports that the supply chain in the aerospace industry remains highly fragmented, with subcontracting and delegation spread over many levels of suppliers.

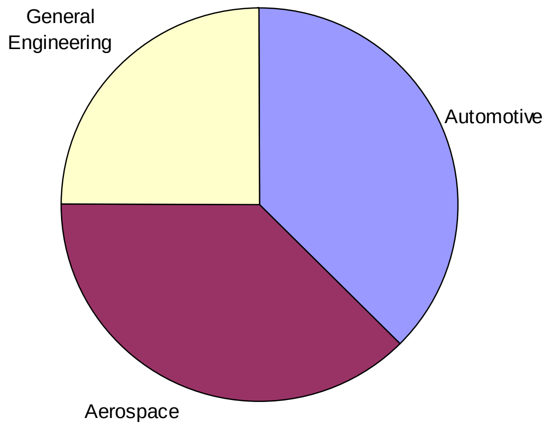


Figure 2: Machine tool market by sector (%) (Source: Mintel, 2006)

2.2 UK Machine Tool Industry & Trends

There are many challenges facing the machine tool industry in the UK from both national and international sources. The UK machine tool industry makes up only 1% of total world production, competing with Japan, China and Germany who account for over 50% between them (MTA). These countries however, tend to specialise significantly between types of machines, with Japan supplying most of the worlds machining centres and lathes and Germany the leading supplier of physio-chemical machines. Many providers in the UK are therefore either subsidiaries of larger international producers or simply third party suppliers of machines produced by them. According to Mintel, high interest rates in the UK compared to Europe have reduced domestic demand for machine tools and a strong pound sterling has impeded exports. Domestic producers also face increasing competition from low labour-cost economies in East Asia and Latin America, yet due to the inherently large size and weight of machine tools, they retain some advantages in transportation costs.

Despite these challenges the industry has, until recently, managed to reduce the trade balance and exports exceeded imports from 2003 to 2006 (Figure 3).

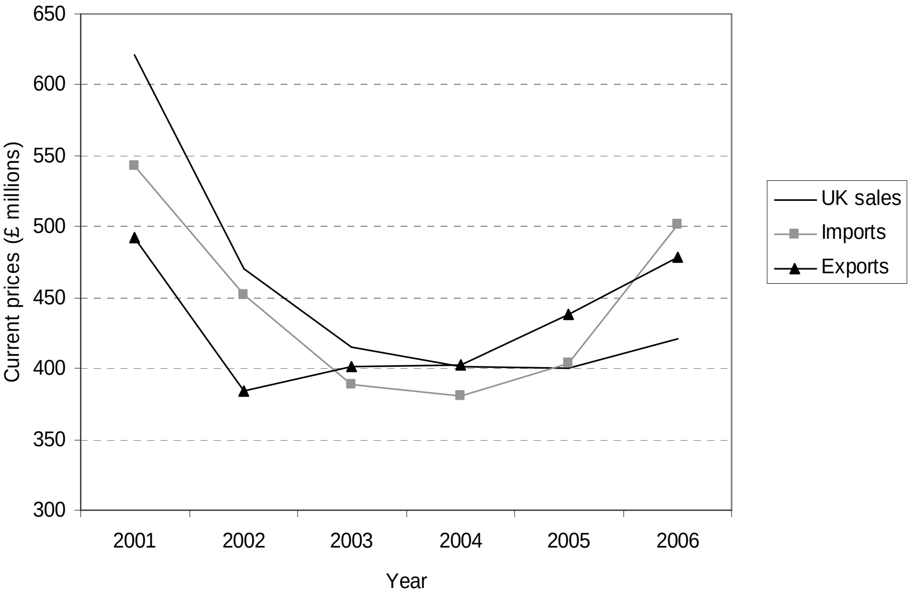


Figure 3: Trends in UK metalworking machine tool production and sales (Source: MTA, 2008)

This improvement has been helped by the ability of UK manufacturers to continue operation with lower margins on machines, but also due to gradual specialisation of machine functions and types and an increased technological complexity (The Engineer, 2006). This hi-tech approach is a response to the low labour cost economies entering the industry and allows UK producers to target high value niche opportunities in machine tool markets and concentrate on specific sectors. UK manufacturers producing advanced, automated machine tools for complex and precision applications can exploit the technological advantages the UK enjoys and add value to their machines through the flexibility and high quality provided.

After sales services are also gaining importance to the industry as a source of added income and some machine tool manufacturers are trying to move beyond the role of equipment providers to service providers (Mintel). Services, particularly maintenance, installation and training can be offered to customers to add more value to individual machine sales, whilst differentiating the provider from competitors according to criteria not based on the machine alone. Contracts for these services supply continued revenue for the provider over the life of the machine and improve product experience for the machine user. Markets for services should also be far more stable than those for the machine tools themselves as these services are less susceptible to fluctuations in manufacturing investment.

There are clear advantages for domestic manufacturers when providing services including proximity, language and expertise. The increasing technical sophistication of the machines themselves complements the emphasis on services due to the complexity of operation and repair and the desire of the user to get the maximum performance out of the machine. An emphasis on services then, may offer the UK machine tool industry a competitive advantage over the international competition and a solution to some of the issues it currently faces.

2.3 Summary

Machine tool manufacturers in the UK have traditionally had to struggle against severe market turbulence, caused by the susceptibility of machine tool demand to confidence in manufacturing investment, which in turn, is highly vulnerable to political and other economic influences. The establishment of competition form low labour economies has added to these challenges and caused domestic machine producers to adopt new strategies to compete. This includes machine specialisation and technological complexity, to exploit niche markets and the increased emphasis placed on services, which add value to individual machine sales and provide a more stable income.

3. LITERATURE REVIEW

This chapter will examine the current maintenance and service environment for machine tools and the broader problems of providing them for industrial equipment. Maintenance is clearly a critical service to any piece of equipment and is one the main focuses of SHOAM. Maintenance however, is often managed in too simple or too narrow a way as to be effective in the long term, so the current and emerging approaches to maintenance and other equipment services management will be explored. The effectiveness of an IVHM-style application will also depend on the PHM technologies and their integration into a complex machine tool. Since these technologies are continuously changing and improving, some of the current diagnostic and prognostic tools available will be explored.

3.1 “Servitization” in Manufacturing

Since the late 1970s a trend in organisational development has seen both manufacturers and service providers throughout the world placing a greater emphasis on the services offered which support their main value adding activities. Vandermerwe and Rada (1988) describe this change as “servitization” of business, with the establishment and maintenance of customer relationships being the main emphasis. Indeed, the demands of the customer have been the main drivers of servitization, aided by deregulation, technological development and increased competition in markets (Vandermerwe and Rada, 1988). Servitization can impact organisational competitiveness in different ways. By extending their enterprise along their respective value chains, firms may effectively set up barriers to competitors and third parties, as well as increase business competitiveness through service differentiation and extending product or service lifecycles. For manufacturers, Johansson and Olhager (2003) observe that providing downstream services such as finance, maintenance and spares can make a real improvement to profitability; if the range of services offered is appropriate for the maturity level of a company’s service business. They term this alignment ‘industrial service profiling’ and develop a framework that allows the correct service profile for a manufacturer to be identified, with those at the most mature levels attracting new customers and driving profitability through the services provided.

Markeset and Kumar (2005) examine the support strategies of advanced industrial product manufacturers, such as those of precision machine tools. The conventional relationship between the customer and supplier is identified where the customer receives the machine, whilst services, such as maintenance and spares, are added for an additional premium. They differentiate this approach to an alternative whereby the manufacturer delivers a defined performance of the product. In the first case the services provide an income to the manufacturer as the customer pays for those activities which deliver the performance. This can be defined as low maturity level on Johansson and Olhager’s framework. In the latter case, which would be defined as ‘mature’, the services necessary to deliver performance are built into the overall contract cost. The advantage of this approach is a better integration of the product with the value proposition to the customer, as the manufacturer must optimise the processes which the customer is interested in. This clearly requires much greater cooperation with the customer, as the operational conditions of the product must be known to the manufacturer if effective performance is to be delivered. In both cases, the lifecycle cost of the product should be minimised, as this results in lower operational and maintenance costs, as well as extended product life (Markeset and Kumar, 2005).

Martin (1997) identifies 3 types of maintenance contract commonly employed when outsourcing the maintenance function (Table 1). These include a “simple work package contract”, in which the customer retains maintenance planning and control themselves. This is similar to the conventional relationship identified by Markeset and Kumar (2005) and Martin notes the short term duration of these types of contracts. A performance contract can also be defined whereby the customer is guaranteed the performance of a machine based on availability. This conforms to the performance based relationship defined by Markeset and Kumar (2005) and this contract type is distinguished by its complexity. A facilitator contract type is also identified by Martin where the manufacturer retains ownership of the machine or system and the customer rents it for periods of time. The duration of these contracts is longer than the other types and the knowledge and experience needed to operate the machine is the responsibility of the manufacturer. This last type of contract however, might go beyond what might commonly be defined as a maintenance contract.

Table 1: Maintenance contract types, adapted from Martin (1997)

Contract Type	Service offering from manufacturer	Complexity	Duration	Knowledge base of customer
Work package	Simple fixed number of activities, some preventative maintenance	Low	Short term	High
Performance	Uptime guarantee, physical measurement and maintenance of performance	High	Medium term	Medium
Facilitator	Management of machine tool lifecycle and all functions	Low	Long term	Low

3.2 Manufacturing Services Paradox

Despite the potential benefits of servitizaion, many manufacturers particularly machine tool and other equipment providers have failed in their attempts to generate higher returns based on the transition to service provider. Gebauer et al. (2005) describe this as a paradox because the gap in the financial gains from the services provided between successful and unsuccessful firms is large, despite equal investments in their respective service businesses. The causes of the paradox are complex and numerous. Gebauer et al. (2005) identify a lack of managerial motivation as a major contributor, due largely to the intangibility of services and the perceived risk and uncertainty of investments in their development. The latter also describes the attitudes of customers, who are reluctant to share knowledge of their operations; a prerequisite to developing effective services for industrial products. Organisational factors include an improper identification of customer value and needs. This relates to the service profile alignment framework developed by Johansson and Olhager (2003), who note that the range of service offerings will change throughout the lifecycle of the equipment, as will the development of the customer relationship. Gebauer et al. (2005) also find that manufacturers who successfully make the transition to service provider have a clearly defined service strategy, with the product becoming only part of the total service offering, not the central component.

Through an empirical study of equipment manufacturing companies, Ojasalo (2007) highlights the conflict over resources that can develop between the traditional manufacturing operations and the developing service business, which is also compounded by the perceived lack of value at the management level. For these equipment providers, the maturity level of the service business is found to be low on Johansson's and Olhager's framework and only those services necessary for the efficient maintenance and operation of the machines will initially be demanded from customers. These include maintenance, spares and some training.

As well as noting similar problems to Gebauer et al., Brax (2005) emphasises the rate at which servitization takes place. If the shift takes too long, then conflicts over resources and other internal contradictions within an organisation will develop causing the process to stall. Brax (2005) agrees with Gebauer et al. that strategy is one of the most problematic areas for servitization, but instead highlights the conflict of interest between the management and operational levels of the customer and the service strategy offered. Management are found to understand total product lifecycle costs and so appreciate the strategic benefits of the services offered by manufacturers. Operators within the customer’s organisation however, were found to be maximising machine uptime and decreasing short term costs meaning many immediate maintenance tasks were skipped, damaging the service performance.

3.3 Maintenance

Effective management of reliability and the maintenance services supporting advanced industrial products are clearly critical to the operational performance of the machine tool user and all those with a stake in the equipment performance. Maintenance is therefore not a strategic option for companies as they are dependent on the performance of the whole supply chain and as such, process reliability is also a measure of customer satisfaction (Madu, 2004). The alignment of the maintenance and service functions with other processes to meet changing stakeholder requirements is considered by Söderholm et al. (2007), who adopt both a managerial and a process view to look at maintenance. The first approach is used to build a model of maintenance management, where the changing requirements of the stakeholders are translated into 3 elements of maintenance management: core values, methods and tools. Core values are viewed for the total system and can include the goals of the organisation’s long term strategy. Methodologies are those used to achieve the goals, such as reliability centred maintenance (RCM). Söderholm et al. (2007) suggest tools which can be used in each methodology and will therefore be largely dictated by the choice of methodology. The maintenance management hierarchy is shown in Figure 4.

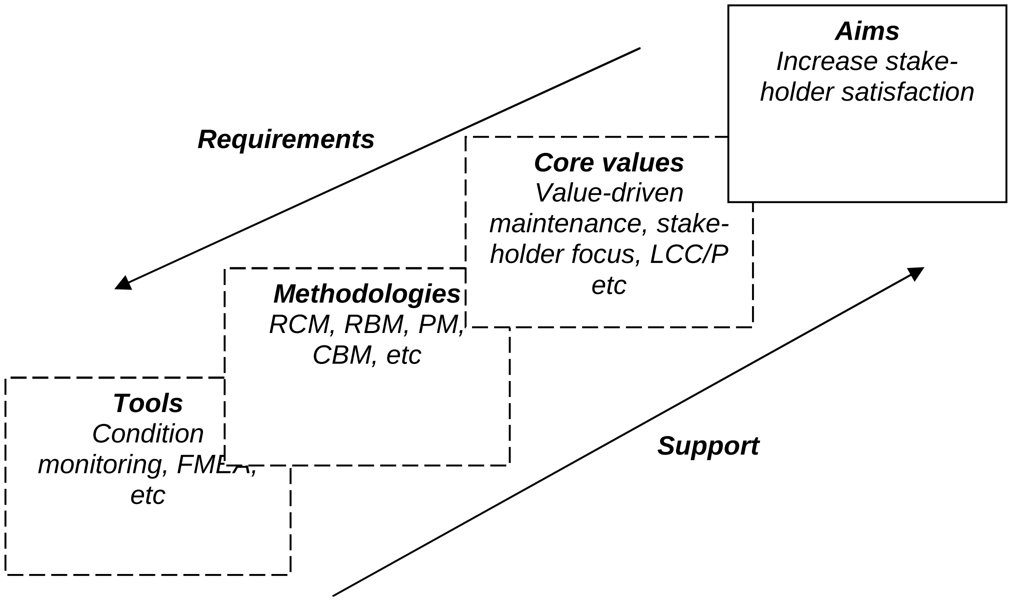


Figure 4: Generic model of maintenance from a management perspective (Adapted from Soderholm et al., 2007)

It is clear from the model that as stakeholder requirements change, the methodology and tools used will also change to reflect these new needs. Failures are therefore defined by both equipment problems and failure to meet stakeholder requirements; hence the latter can drive change in the approach to maintenance adopted. As customer needs change over the entire lifecycle of a product, maintenance and services must also change if they are to support the product "from cradle to grave" (Madu, 2004). Although not specified by Söderholm et al., the lifecycle costing, value-driven maintenance and balanced score card approaches discussed below will likely fall into the core values category.

3.4 Value of Maintenance and Services

Maintenance and services are clearly vital for both equipment and organisational performance, but are often poorly understood and managed. Some of the current and emerging approaches to maintenance are therefore reviewed.

3.4.1 Lifecycle Costing and Profit

According to Tsang et al., (1999) the traditional view of maintenance as ‘the process of fixing broken things’ is too narrow and instead, maintenance should be viewed as physical asset management, in that the scope of management extends over the whole lifecycle of the equipment in the production environment. Sherwin (2000) also emphasises the impact of the maintenance function on the product lifecycle because focusing on short term savings may have a negative impact on the future performance of a system. Calculating the contribution of maintenance tasks to lifecycle costs and lifecycle profits (LCC/P) is recommended as this will take into account the future as well as present costs. This is particularly important for product support services as improvements in system reliability and hence quality (Madu, 2004) will often be claimed as a result of improved production and not of effective maintenance. Sherwin even suggests that production schedules be changed to improve LCC/P, but this may cause further difficulty if the maintenance function is external to production.

Hayek et al. (2005) calculate the LCC/P for a piece of complex rotating equipment. Some systems will contain thousands of components making reliability calculations and cost driver optimisation costly and time-consuming, especially if parts are removed and maintained. In accordance with reliability centred maintenance (RCM) theory, Hayek et al. identify the critical parts which drive maintenance activities by performing a Pareto analysis of the Weibull trends for each module. The whole system is considered as a series of connected modules and a module is defined at the level where it can be removed and serviced, helping to reduce the number of parts in the analysis. The Weibull trends are then used to simulate the aging of parts in operation and to estimate the optimal combination of modules which maximise equipment availability. The decision to either refurbish modules or replace them with new ones presents a trade-off for lifecycle costs against availability.

Mirghani (2003) explores some of the difficulties of costing a maintenance activity and finds that supporting activities such as planning, design, work scheduling, etc are not easily traceable to any particular service activity. These are labelled maintenance overheads and will present a considerable cost for a service supplier in a support environment. Their allocation to maintenance tasks can be performed in a number of ways and for Mirghani, activity-based costing provides the best method. Activity based costing (ABC) calculates an overhead rate per activity based on the cost drivers for the activity area and the demanded and budgeted costs during 'normal' operating conditions. This allows a more strategic approach to maintenance as a trade-off can be made between different maintenance costs.

Emblemsvåg (2003) also purports the use of activity based costing in LCC/P calculations due to its process orientation, which allows both the internal organisational costs and external costs such as the environment to be factored in. Emblemsvåg highlights the role LCC/P plays in an effective design process as the only efficient way of handling costs but asserts that LCC/P must take risk and uncertainty into account to be useful. The different perspectives which may be taken when viewing a product's LCC/P are also examined by Emblemsvåg, himself adopting both a product perspective (Figure 5) and a marketing perspective. The latter represents the growth, maturity and decline for a product type whereas a product lifecycle incorporates the production, operation and disposal activities of a single product.

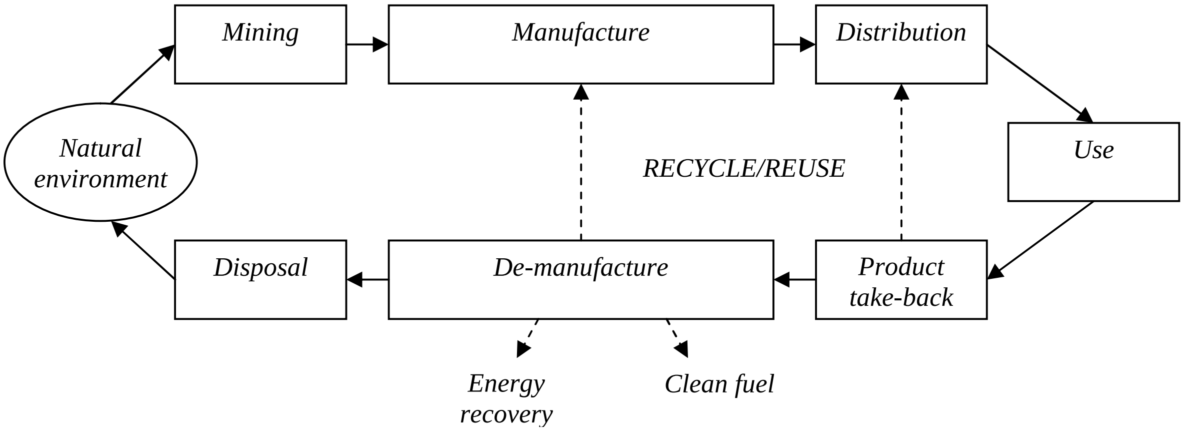


Figure 5: A generic product lifecycle (Source: Emblemsvåg, 2003)

3.4.2 Value Driven Maintenance

The need for a more holistic view of maintenance and operations has led to the development of the value concept in maintenance and the value-driven maintenance (VDM) method. One reason, as contended by Liyanage and Kumar (2003), is that in high risk, capital intensive industries, maintenance management needs to go “beyond its pure financial implications” in order to suit changing business conditions. Companies must increasingly recognise the impact from and sensitivity to non economical values such as the environment and society which alter an organisation’s strategy over different time periods. Absence of data, uncertainty and the risk inherent in these factors render the traditional approaches to operations and maintenance management unsuitable.

Liyanage and Kumar (2003) develop a value-based model of operations and maintenance management (Figure 6) from observations of the petroleum industry. The model comprises 4 propositions of what constitutes a value-adding activity and a steering model which defines the importance of each value proposition with the causal relationships shown between them. They apply the model to an oil and gas production asset, noting issues of responsibility and authority in its application. The first issue looks at the system in its entirety where the scope of responsibilities for operations and maintenance must be clearly defined.

The second issue recognises that authority must be given to those in operations and maintenance to carry out necessary actions. In a support service environment, the responsibilities of the service provider must be defined and authority given to meet these requirements. The responsibilities of the service consumer may also need to be defined with respect to the performance of the service to avoid the conflicting interest problems encountered by Brax (2005).

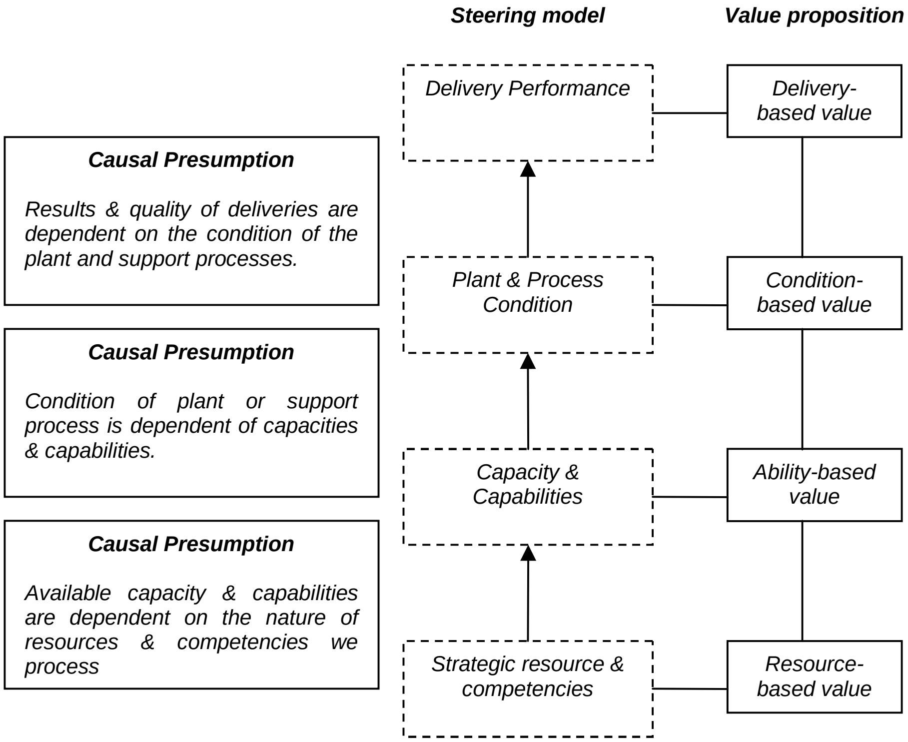


Figure 6: A value based view of operations and maintenance configuration (Adapted from Liyanage and Kumar, 2003)

Rosqvist et al. (2007) take a less holistic view and distinguish between operations and maintenance, stating that “maintenance has no intrinsic value”. Instead, they emphasise the supporting role maintenance plays to the strategic objectives of the organisation. These organisational objectives become tactical at the plant level, which in turn, are supported by the maintenance objectives. This hierarchy is shown in Figure 7.

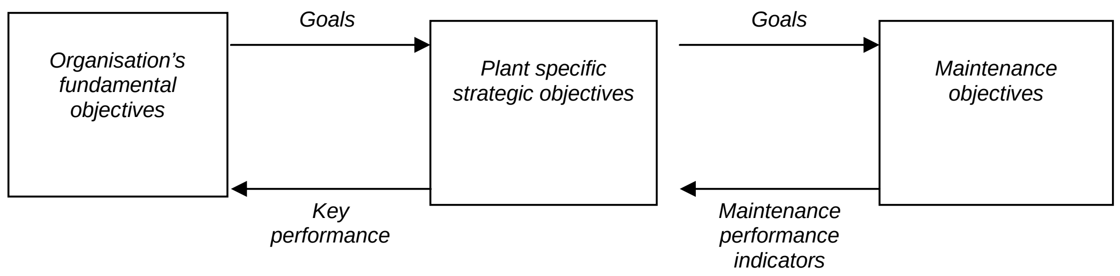


Figure 7: Companies fundamental and strategic objectives at the plant level, adapted from (Rosqvist et al., 2007)

Rosqvist et al. use this hierarchy in a value-driven maintenance planning technique, where the maintenance objectives are adjusted to support the organisational strategy through adjustment of the plant level tactics. Operations level performance is considered as leading to plant level performance, allowing risks at the operational level to be associated with the strategic objectives of the organisation.

Another approach to value driven maintenance has been developed by Mainnovation where the term value is adapted from financial literature; defined as the sum of all future free cash flows (Haarman, 2005). There are four drivers of value; safety and environment, cost control, resource allocation and asset utilisation, all of which can be influenced by maintenance. Again, no intrinsic value of maintenance is identified and the supporting role which maintenance plays in creating value is similar to that used by Rosvist et al. (2007). The four drivers are used to identify the "value potential", which will be based on the prevailing business conditions, such as controlling costs through reduced spares or machine availability. The maintenance competences or methodologies are then configured to match the value drivers (Figure 8). Each maintenance method is changed to suit organisational objectives. For a service support environment, the service supplier will most likely possess some, if not all of the maintenance competences shown in Figure 8. This approach can therefore be used by maintenance planners to effectively show that the services they provide help to create value for the equipment user.

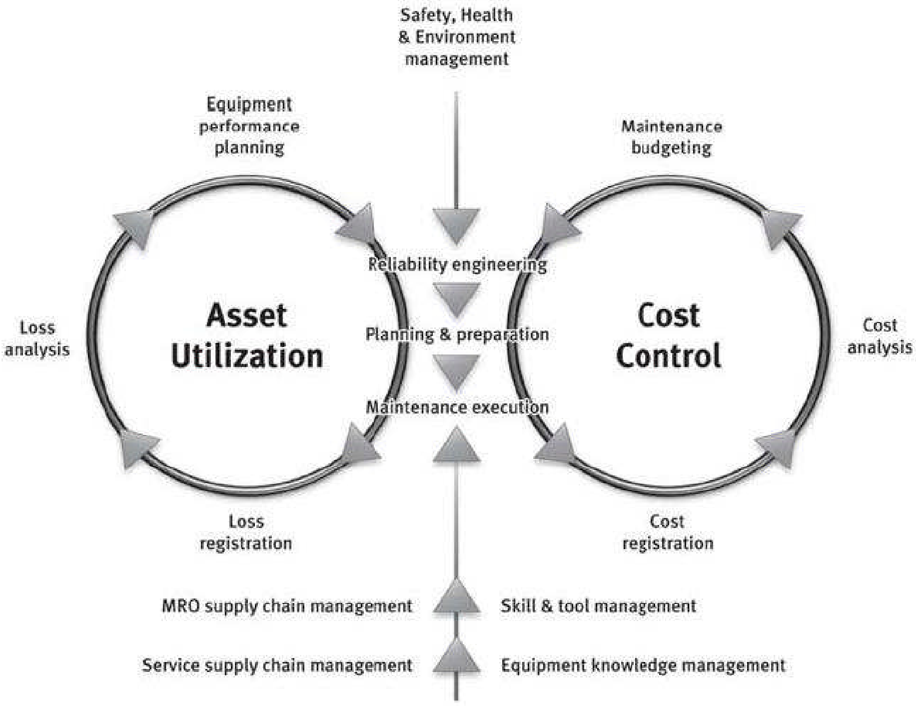


Figure 8: Competencies in value driven maintenance (Source: Haarman, 2005)

3.4.3 Balanced Score Card

A popular method of measuring performance at the operational level with respect to the organisational strategy is through the use of balanced score cards (BSC). Indeed, both Liyanage and Kumar (2003) and Rosvist et al. (2007) use BSC in their value-based maintenance approaches. The BSC approach to measuring maintenance performance was developed, because the commonly used “diagnostic measures” do not link system performance with longer term business strategies (Tsang, 1998). In a BSC based system, action plans are created to meet a long term strategy. Performance is ensured by measuring different perspectives including growth, financial, customer, and internal processes. Each balanced score card will be bespoke to each organisation and there is no generic framework. Key performance indicators are used to quantify the above measures, although Tsang recognises that some “soft” measures such as customer satisfaction may be harder to put into numbers. Tsang et al. (1999) give examples of some key performance indicators for maintenance such as “reduce maintenance cost by 30% in 2 years”, which complements the financial perspective above.

3.5 Maintenance Methodologies

The policies outlined below have been differentiated from the above because they focus more on the technical management of maintenance performance and therefore are less holistic in their view of maintenance as a service, although there is clearly overlap between them.

3.5.1 Reliability-Centred Maintenance

Reliability-centred maintenance (RCM) aims to maintain the reliability of a particular function by identifying its maintenance requirements in an operating context. Reliability centred maintenance typically begins by analysing the failure modes, effects and criticality (FMECA) of a system to determine which of the constituent subsystems or components are to be reviewed and the importance of each subsystem reliability. RCM evolved from the maintenance steering group 1 (MSG – 1), which was formed to oversee development the development of the Boeing 747 aeroplane (Maubray, 1997). The second MSG lead to improvements in the scheduling of maintenance activities for other aircraft. Despite its age, RCM remains one of the more common approaches used to manage maintenance and services.

Wessels (2003) uses reliability-centred maintenance to schedule activities to optimise maintenance cost verses production losses from failures. This is achieved by identifying the lowest replaceable unit (LRU), similar to that defined by Hayek et al. (2005), and calculating the reliability for each. Non-detectable deterioration of the system is then simulated to estimate the operational duration so that components can be replaced before their estimated breakdown. This eliminates the need for preventative data collection and minimises corrective maintenance costs. The transition to a “failed” state is therefore assumed to be instantaneous, but given advances in condition monitoring and uncertainty, Eisinger and Rakowsky, (2000) argue that forcing a two-state response can be inefficient.

Zhou et al. (2004) integrate condition monitoring to determine the exact hazard rate for a deteriorating system and schedule maintenance accordingly. The cost of breakdowns and failures are assumed to be greater than preventative maintenance (PM) due to production losses, where PM aims to prevent a failure from occurring. This may be too simplistic however, because the losses from failure could easily be less than the costs of a PM action if that action is at an inconvenient location or production schedule. Zhou et al. find that as the system ages more frequent PM tasks are required. Their model is based however, on the behaviour of a complete system rather than a series of discrete components or modules. Inclusion of components with different failure rates might affect their observations as these components can be replaced and repaired discretely.

Saranga and Knezevic (1999) attempt to predict the reliability of a system using condition-based maintenance (CBM), but include the possibility of failure to detect a fault. Maintenance is performed when a significant deterioration in performance is detected, allowing different failure mechanisms to be modelled and appropriate condition monitoring tools selected. This assumes an instantaneous transition to a failed state again, which may not exist or represent a trade-off in a support service environment. Their model allows a CBM policy to be determined to meet a specified reliability level which may be useful for an equipment manufacturer. Sherwin (2000) is critical of RCM, claiming that its aims are too narrow. According to Sherwin, the reliability of a system is shaped by the maintenance policy and is not inherent to any particular system under maintenance. This is especially true when the performance of components in complex systems is manageable with PM and CBM policies which renders complete “system overhauls” used by RCM to be uneconomical.

3.5.2 Risk-Based Maintenance

Risk-based maintenance (RBM) is similar to RCM, but expanded so that the consequences of decisions and failures affect the scheduling of services. Khan and Haddara (2003) define risk as: probability of failure × consequence of failure and the level of risk determines the maintenance policy which is used. Dey et al. (2004) use a risk-based methodology for the maintenance strategy of offshore oil and gas pipelines. Failures of small unreliable lines have a lower impact on the environment than larger ones, failures of which could be disastrous. Different maintenance tools can then be selected to match the associated level of risk. Evaluating environmental and social impacts however, will be difficult to accomplish in a quantitative manner. Dey et al. use the “experiences and opinions of selected experts”, which may be highly subjective. Khan and Haddara categorise consequences into four losses: system performance, financial, human health and environmental loss with an acceptable level of risk identified for each. Similarities to the value-based methods discussed above become apparent and RBM may become an important tool in value-based methodologies.

Consequences should be easier to quantify for precision machine tools limited to production environments because losses will rarely extend to non-economical factors such as the environment or society. The definition of risk used above however, associates a single consequence with the failure of a component. Todinov (2006) argues that this will rarely be the case as “component failures are usually associated with different losses from failures”. This is similar to the discussion of the “two-state” assumption of RCM by Eisinger and Rakowsky (2000) and the criticism by Sherwin (2000) of system behaviour aggregation.

Todinov (2006) shows that if a system contains two components in series and the failure of one component precipitates the failure of the system, maximising the reliability of the whole system does not minimise the losses from failures of the system. Todinov expands the risk equation beyond the calculation of average losses to provide an evaluation of the potential losses from cumulative failures. A limit to potential losses can be set and the risk of exceeding that limit calculated at the component level. Condition-based maintenance policies can be assigned to components accordingly.

3.5.3 Condition-Based Maintenance

Condition-based maintenance (CBM) uses machine run-time data to determine the machinery fault/failure condition and uses this to schedule maintenance before the occurrence of anticipated failures (Vachtsevanos et al., 2006). The main advantage CBM has over other methodologies is that the reduced uncertainty allows maintenance to be planned properly in advance and at the best time (Yam et al., 2001). Applying CBM policies for all machine components however, will be costly as systems for monitoring the condition must be applied to each. Chen and Trivedi (2002) suggest using CBM policies when “the cost incurred by a device failure is greater than the cost of [CBM]”, but also note that some systems are subject to ‘hard’ failures, where deterioration is too fast for condition monitoring to be effective anyway. Vachtsevanos et al. recommend FMECA to “form a foundation for good CBM design”, because the systems with the greatest inherent risk deserve attention first.

Defining the ‘optimal’ time to perform maintenance tasks based on CBM can be complex, with many factors influencing any decision and, as such, there are many decision making optimisation models in CBM. Yam et al. (2001) suggest that after a fault has been detected, maintenance is performed to avoid “emergency breakdown”. By defining a maximum allowable threshold for fault development, early alarm systems can be used to forecast or schedule maintenance activities. Stopping equipment to conduct maintenance, if performed at the wrong time may result in significant losses. Koomsap et al. (2005) recommend that both maintenance and operational factors should be considered when aiming to minimise losses because servicing itself results in downtime. They develop an integrated control system that minimises average waiting times for machines where maintenance resources act as a constraint. Baek (2006) uses decision tree learning and historical data obtained using condition-based policies to schedule tasks to minimise the total maintenance cost over the lifetime of a machine.

Grall et al. (2002) provide a maintenance scheduling model which optimises both the costs of maintenance actions and the losses due to failures and breakdowns. Losses from failures are variable, so Grall et al. set a different maintenance policy and inspection interval depending on the condition of the system at inspection. This allows a less severe maintenance and inspection policy to be scheduled if the losses caused by these actions rise above some preset value. The more expensive maintenance and inspection tasks can then be carried out during periods of low demand. CBM can also be integrated into many other maintenance methodologies to give greater certainty in decision making. Jardine et al. (1998) use CBM to find the optimal replacement policy for equipment which minimises the risk of failure. Wang and Zhang (2008) use CBM policies to determine the remaining life of equipment, which has application for costing methodologies.

3.6 Prognostics and Health Management Technologies

Prognostics and health management (PHM) involves predicting the future behaviour of a system from the current operating state and scheduling the required maintenance activities (Vachtsevanos et al., 2006). CBM policies typically provide the condition of the machine, through monitoring the components in operation, using sensors to detect abnormal conditions. On detection of an abnormal condition, the presence of a fault must be isolated to the particular machine component and then the mode of failure classified (Vachtsevanos et al., 2006). This is typically termed fault diagnostics and the technologies and approaches used in the process depend on the machine components being monitored and the physical mode of degradation.

Hu et al. (2000) use fault trees to structure diagnostic knowledge for use in an integrated monitoring, diagnostic and decision system. Operators or experts use the fault trees to locate causes, which are then compared to the monitoring data and machine or process rules. Another popular method of fault diagnosis in machine tools is to monitor the vibration of machine components and measure any deviation from the ‘healthy’ condition. Identifying the failure signatures in vibration data is complicated by the multiple elements in a system which could be responsible for faulty behaviour and the periodicity over which these faulty elements act on the machine. Rehorn et al. (2006) use selective regional correlation as it focuses only on the specific part of the signal which is of interest, allowing the particular source of a fault to be identified.

Neural networks and expert systems have also been developed to locate machine faults. Expert systems use reasoning methods similar to human experts, but the acquisition of that knowledge is difficult. Neural networks can be used for simple machine processes, but struggle when applied to complex machine tools characterised by simultaneous processes and the possibility of new fault development (Starr et al., 2001). Starr et al. use a combination of both to overcome their respective disadvantages. Condition data are fed into a ‘meta system’ which acts as an interface between the neural network and the expert system (Figure 9).

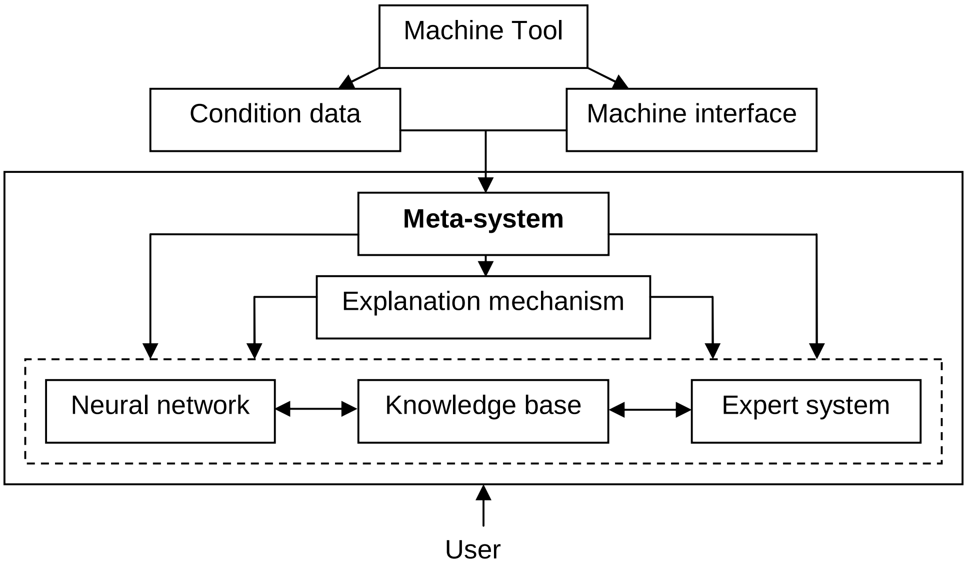


Figure 9: Fault diagnostics using expert systems and neural networks (Source: Star et al., 2001)

The neural network is used to diagnose faults first and the expert system is used when a new fault is encountered. The meta-system also trains the neural network to recognise this new type of fault.

Condition monitoring has been successfully developed by Artesis for use with machine tools. Their motor condition monitoring (MCM) products can be applied to any electrically driven motor allowing the health of the machine component to be measured. The 3 phases of the operating motor’s power supply are compared to a reference value of the normal condition which has been learned automatically by the device. The development of a fault causes the power supply to diverge from the normal condition which can be monitored and managed using computer software. This data can also be sent to remote locations via the internet, making remote monitoring and plant level performance monitoring much more effective.

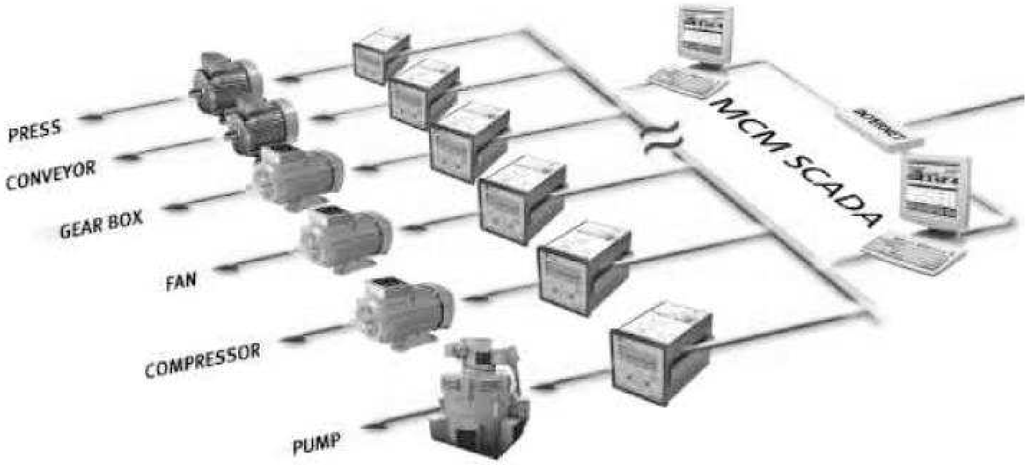


Figure 10: Motor condition monitoring (MCM) (Source: Artesis)

If unacceptable risk levels of future machine health can be determined or the point of component failure predicted, tremendous insight to service planners will be provided with which they can plan and optimise their activities. An intelligent maintenance system (IMS) is developed by Lee et al. (2006) which integrates many predictive algorithms into one 'toolbox' called Watchdog Agent^{TM}. Expert knowledge and data sharing between similar components can provide an input to improve the accuracy of behaviour modelling.

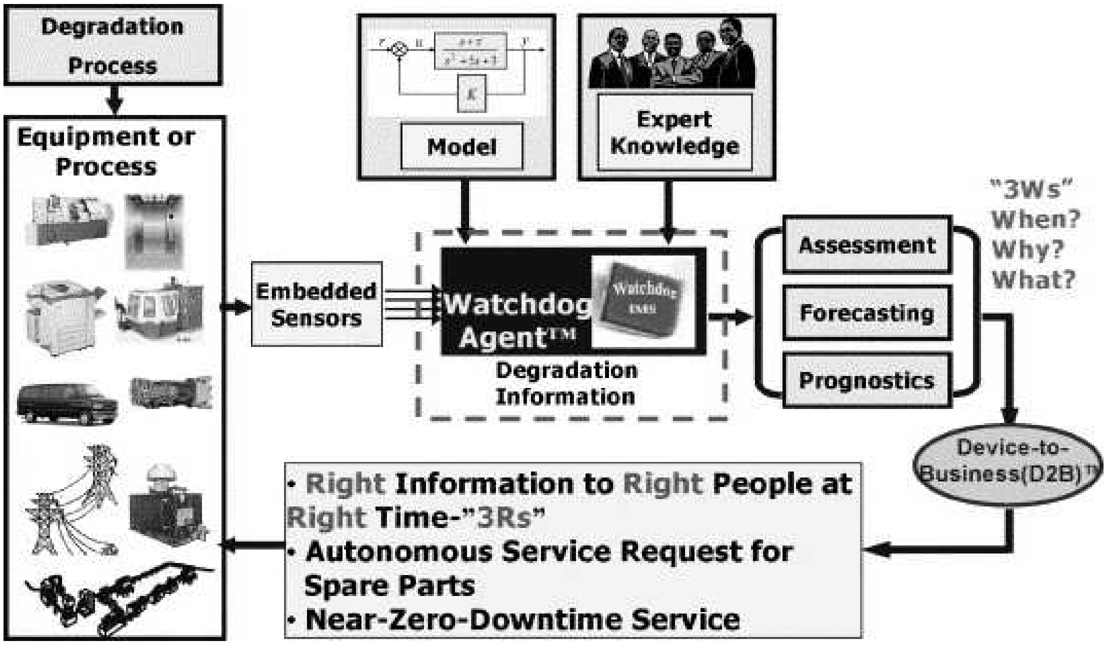


Figure 11: Watchdog Agent^{TM} Intelligent Maintenance System (IMS) (Source: Lee et al, 2006).

The system can also memorise machine behaviour and therefore learn to diagnose faults from particular pattern signatures. Lee et al. simulate the effectiveness of the system when used to schedule maintenance, including both production losses and maintenance costs in the model. A significant improvement is shown using the prognostic system over other maintenance scheduling methods including a simplified CBM approach.

Health monitoring itself produces large quantities of data that must be stored and compared to that of the machine performing under normal conditions. Martin (1993) comments that failure data itself is of interest to the manufacturer, as it allows feedback for improvements in design and greater accuracy in fault diagnosis. This feedback could be used to improve the relationship between manufacturer and customer, but issues of intellectual property, data acquisition and data storage must be addressed first.

3.7 Summary

Manufacturers are attempting to make the transition to service provider with the hope of increasing the competitiveness of their existing offerings through service differentiation and the establishment of long term customer relationships. A paradox is often encountered however, where the returns on investments to improve services by some manufacturers are poor compared to others who have made similar moves. There are many possible causes for this including a lack of perceived value, conflict over resources between maintenance and operations and ineffective service strategy.

Maintenance is a critical service to the performance of both the machine user and the entire supply chain. Recent approaches to operations and maintenance are taking a more holistic view of the two. Many commentators emphasise the lifecycle performance of the equipment in operation because maintenance has traditionally been undervalued as organisations opt for short term gains through maintenance cutbacks. The future performance of the machine is reduced, which can be predicted using lifecycle modelling. Value driven maintenance aims to demonstrate the value which maintenance provides to the organisation. This is achieved by matching maintenance and service strategies to the prevailing organisational strategy and business conditions.

CBM has many advantages over other maintenance approaches as decisions are made according to the physical condition of the machine, which reduces uncertainty and therefore lowers risk. CBM is more expensive than the simpler risk and reliability based approaches however, and the decisions concerning maintenance actions are more complex. CBM relies on the detection of faults and the monitoring of their development and therefore sensing and fault diagnostic strategies are required. These can be extended using PHM techniques, which forecast the future behaviour of the machine and use this information to optimise maintenance activities.

4. RESEARCH METHODOLOGY

The research problem is defined in this chapter and the aims, scope and objectives of the project are given. The scope is outlined which leads to a programme for research.

4.1 Research Problem

The difficulty of planning and executing maintenance effectively for machine tools stifles productivity and causes manufacturing inefficiency. Machine tool and service providers struggle to manage machine performance, which limits development in equipment services and maintenance is consequently undervalued. The IVHM programme and SHOAM tool developed by Boeing for use with aircraft are therefore highly desirable concepts for both industrial equipment providers and users alike. Capital intensive advanced machine tools may justify investment in technologies which provide a similar insight into machine health as IVHM provides for aircraft.

4.2 Project aims and Objectives

The aim of the research is to modify Boeing's SHOAM tool for use with an advanced machine tool so that the operational impact of failures on the quality of service from the machine can be evaluated.

The required objectives of the project are stated below:

1. Research typical operational scenarios featuring a machine that is required to perform according to a specified service level
2. Become familiar with Boeing's SHOAM tool through application and discussion with Boeing and SHOAM experts

3. Modify SHOAM to make it applicable to a machine tool as part of a manufacturing and supply system

The scope of the research extends to using the modified SHOAM model to show the impact of different maintenance techniques and condition-based technologies on the performance of the machine. The current approaches to maintenance of advanced machine tools and their operational environment must be investigated so that the adapted model has useful applicable.

4.3 Programme of Research

The stages of the research programme are broken down into work items and the objectives are met with the completion of particular work items. Figure 12 displays the research programme in block diagram form. Descriptions of each stage follow.

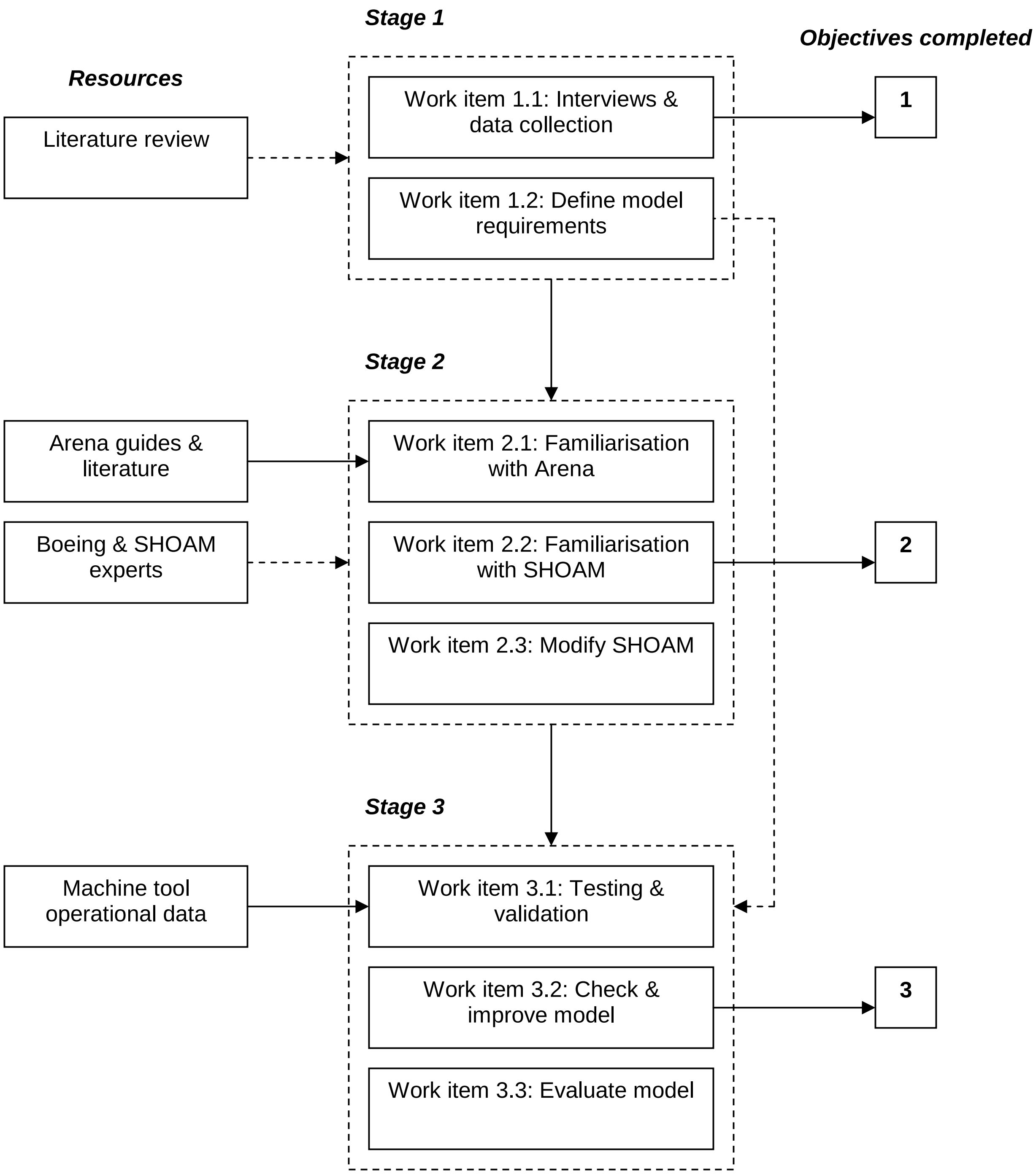


Figure 12: Programme of research

Stage 1: Data Collection and Model Requirements

The literature review reveals the current difficulties experienced by machine tool manufacturers attempting to make the transition to service provider. Different approaches to maintenance management, a key component of any machine tool service, are addressed using the literature and the currently available PHM technologies applicable for an advanced machine tool are also reviewed. To further focus the research for advanced machine tools, UK producers of specialised machines are interviewed to see how they currently maintain service levels and to investigate the operational environments in which these machines perform (work item **1.1**). The topics raised in the literature review are used to provide a framework for discussion, but the interview technique will remain informal to allow for variability between responses. A preliminary analysis of SHOAM will also be used to identify some of the data which will be required. Work item 1.1 and the literature review complete the first objective.

Work item **1.2** will use the results of the interviews and the literature review to define the requirements of the modified SHOAM tool. In this way, the operational environment of an advanced machine tool will be modelled more accurately and the value for manufacturers is ensured. In addition to the model requirements, operational data will be sought from advanced machine tool producers to provide the inputs to the modelling environment. There are many formats in which this data may be available; historical data such as failure rates and modes or component reliability data. Some partners of the University who produce machine tools for aerospace have expressed an interest in the project and will be approached for this data.

Stage 2: SHOAM Familiarisation and Modification

SHOAM is modelled in the Arena discrete event simulation environment. Work item **2.1** is a familiarisation with the Arena software package from Rockwell Automation, which is undertaken using the many tutorials and help files available with the software and other literature. When acquainted with the Arena modelling environment, a familiarisation with SHOAM follows using the literature available with the model and through application (work item **2.2**). Throughout this stage, Boeing and SHOAM experts provide guidance and consultation with the familiarisation effort where required, in order to quickly overcome obstacles to learning.

Modification of the SHOAM model may begin during work item 2.2, because the level of intimacy with SHOAM may be sufficient to begin modification before proficiency with the complete model is achieved. This is possible because of the expertise provided by Boeing which is available throughout this stage. Modification makes up work item **2.3** and follows, as much as possible, the requirements specified in Stage 1.

Stage 3: Testing and Evaluation

On completion of work item **2.3**, work item **3.1** tests and validates the model. First, the model will be validated by comparing the performance with the operational data obtained in stage 1. A sensitivity analysis then will be performed to test the features of the model and then the benefits of using CBM/PHM solutions tested for an advanced machine tool.

Deficiencies within the model, identified during testing, are used to improve the model performance (work item **3.2**). Work item 3.2 completes the final objective. Finally the model is evaluated with the requirements and the value it delivers (work item **3.3**).

4.4 Deliverables

The principle deliverable of the project is the modified SHOAM tool which may be used to analyse the benefits of CBM/PHM technologies and their impact on operational performance. The research and interviews in the earlier stages of the project will provide insight into the current state of machine tool servitization and the adoption of CBM/PHM.

5. INDUSTRY INTERVIEWS AND DATA COLLECTION

This chapter presents the results of the interviews with advanced machine tool users and manufacturers and the requirements of the model modifications are specified. The purpose of interviewing industry members is to identify how after sales services are currently being managed and to gather data on the operational environments of advanced machine tools. Issues found in the literature review can also be raised and will act as a guide for inquiry into maintenance management. This information is then used to specify the requirements which the modified SHOAM model must meet for it to be applicable for advanced machine tools. Empirical data will provide a comparison with the model for validation and to model a realistic environment.

5.1 Interview Method and Topics for Discussion

A preliminary examination of SHOAM and the literature review are used as a guide for the data collection and interviews. Reliability data and periods of maintainability are required for 9 subsystems in a machine tool. This data may be inferred from failure modes or rates. The intensity of the processing environment may be harsh for an advanced machine tool, so operational periods such as uptimes or shift lengths of machine use are required as is the impact of breakdowns. Information regarding the operation and management of both the machine and the manufacturing system will also be sought. This approach to data collection should ensure that the modified model reflects the current service and operational approaches for machine tools and will therefore be useful to equipment manufacturers and suppliers of product support.

As the variability in machine tool usage and the approaches to maintenance were anticipated to be high, a semi-structured interview approach was chosen, as it allows for divergence between responses. Semi-structured interviews have a framework for discussion, but questions are flexible and less formal than structured interviews. Descriptions of the main discussion topics are given in the appendix A. Advanced machine tool manufactures and service providers were identified in consultation with the Manufacturing Technologies Association (MTA). They are those which are most likely to supply specialised machine tools in which PHM technologies may be applied and include NCMT, Mazak, Electroimpact, Holroyd and Heller. Most of these companies supply machines for the aerospace industry, who are one of the largest consumers of complex and precision machine tools due to the demanding production requirements for aircraft.

5.2 Interview Findings

Some observations and results from the interviews and data collection are summarised under the respective topic headings used during interviewing.

5.2.1 Machine Reliability Data

To test and validate the model, reliability data from a machine tool was sought from those industry members interviewed. However due to many reasons, empirical data could not be obtained. A machine tool company who was a collaboratot to the research declined to cooperate towards the end of the project which caused further difficulties. Other machine tool companies who were interviewed such as Electroimpact, NCMT and Mazak could not release any data due to the sensitivity of reliability information to their customers operations. Other companies such as Holroyd and Cinetic Landis showed a lack of interest in developing services due to the highly user driven nature of the industry. Users specify the level of service they want and the machine providers will often meet their demands in order to win contracts. Some manufacturers were found not to collect empirical data on the reliability performance of their machines. This is due to the modular construction of many machines in which components from multiple sources are used, which makes reliability engineering difficult.

Commodity machine producers were also approached for reliability data; however these machines are often treated poorly by their users. Maintenance is often entirely neglected and machines simply run to breakdown. Sometimes this is done purposefully to provide a reason for late work to their customers. Also, the high variability between manufacturing environments in which these machines are operated renders any meaningful reliability data uninformative, as failure modes and rates vary considerably for any single component. This is similar to state of the aerospace industry before reliability engineering of aircraft components took place. The lower risks of machine tool downtime compared to aircraft however, and their modular constructions make further reliability studies seem expensive and time consuming to manufacturers.

5.2.2 Machine Operational Environment

Machine availability is often defined on a shift basis with typical shift length of 8 hours and manufacturers guarantee uptimes over the number of shifts required. Some advanced machine tools have an expected availability of 24 hours a day, 7 days a week, which is understandable given the high costs and overheads incurred using them. The uptimes guaranteed by manufacturers were found to range between 95 to 98%. Actual machine use rarely achieves a corresponding level however, as the production system management of machine users often cause idle periods for machines. PM also needs to be factored into availability and some manufacturers deduct planned maintenance time from the quoted machine performance.

There is a high variability between production environments which affects the machine performance depending on how the customer uses the machine and what metal is being processed. These factors cause uncertainty for service planners as both affect the reliability of machine components. Certain operations do not use all machine functions, as Mazak found when they experimented with CBM technologies. Some orientation features were not being utilised, which meant that these subsystems appeared to be very reliable, before CBM was employed.

Electroimpact machines used for wing assembly are often left without work due to an insufficient supply of parts and management conflict within the wing production facility. Work is scheduled to machines according to the priority of the job. The different stages of fabrication are managed as individual ‘business centres’, but share 10 machines causing conflict over machine availability. Holroyd machines are designed to run unmanned and so facilities with parts machine feeders aim to maintain a constant level of production. Heller machines often go through periods of production dropdown where once or twice a year industry reduces machine work load which precipitates a fall in utilisation. Service providers often take advantage of this period to schedule maintenance

5.2.3 Service Contract Type and Maturity Level

Due to the user driven nature of the industry, a large amount of flexibility in service offerings is demanded by machine users and so most manufacturers provide a range of services and customisable options allowing the customer to specify the level of service they require or can afford. Table 5.1 presents some of the typical service offerings from advanced machine tool providers and their positions according to the frameworks from Martin (1997) and Johansson and Olhager (2003). The contract used by Electroimpact for wing assembly is one of the more complex contracts found involving CBM, however the service duration is very short at only one year and machine performance is not the focus of the agreement.

Table 2: Service offerings of machine tool companies

Company	Service offering	Contract duration	Contract type (Martin, 1997)	Service maturity level (Johansson and Olhager, 2003)
Electroimpact	Fixed maintenance budget, scheduled maintenance, CBM	1 year	Performance	Med
NCMT	Monthly tasks & payment determined using historical cost data	2 years	Work package	Low-med
Holroyd	Installation and ramp up, training and technical advice offered based on condition data	1-2 years	Work package	Low-Med
Mazak	Guaranteed uptime, some CBM used, onsite engineers offered on request	1 year	Performance	Med
Heller	No parts included, whole lifecycle can be included, scheduled preventative maintenance	Up to 6 years	Work package	Low - Med

5.2.4 Service Strategy and Maintenance Management

Most manufacturers were found to be using a preventative maintenance (PM) schedule which was determined using historical experience of the machine components. For wing assembly, Electroimpact use a PM schedule which places each machine into a rota, where monthly inspections and minor work accompany a more intensive service, scheduled for every three months. Parts found in poor condition are replaced immediately to maintain machine function and a large amount of downtime is spent finding the causes of parts producing poor quality output. Spares are owned by the customer and stored onsite leaving Electroimpact to purchase spares as and when required. Costs are controlled using a fixed budget for maintenance and out of this comes a substantial amount of manpower and expertise, with up to 14 engineers onsite. Most companies offer to place an engineer onsite if the customer has purchased sufficient machines or requests one. Downtime and lost production are not covered in the Electroimpact service contract and incurred by the customer.

NCMT also have a contract offering scheduled PM similar to that used by Electroimpact. Inspections and replacement of machine consumables are carried out for components with a known reliability of 2000hrs and more rigorous service is scheduled again for components with reliabilities of 4-5000hrs. After inspections, a maintenance schedule and report is produced showing trends of components against future machine performance. The customer is contacted to decide whether and when the service to replace the components takes place. Most service providers estimate the average time to perform scheduled maintenance to be 3 to 5 days. NCMT also offer a care package in which historical data of maintenance cost is used to determine a monthly payment scheme. Machine consumables are ordered in according to a schedule although some buffer stock is held for rescheduling and NCMT hold a substantial amount of breakdown components due to the fast response demanded by some customers.

Holroyd offer a maintenance schedule which accommodates the customer’s shift pattern, but Holroyd do not guarantee that the machine will be ready on time to start work again. Advice on the component condition and remaining life is offered by Holroyd in a similar manner to NCMT. Engineers note the component condition during inspections and advise the customer on component life and machine performance. Mazak determine schedules through consultation with the customer. They have a widely distributed network of manufacturing plants and so use production stocks as replacements. Regional sales centres are also used to hold stocks of components as is a central warehouse in Belgium guaranteeing 24 hr breakdown response for parts. This performance however, depends on the reliability of couriers.

5.2.5 Relationship Management

The departmental management structure of Electroimpact's customers causes competition between the departments which share equipment. Maintenance costs are therefore often the first to be targeted for reduction by the customer's management which increases machine deterioration causing poor performance in the long term. This is a problem for Electroimpact who have to manage the performance of machines over the duration of the period. The maintenance schedule which they provide in the contract is often ignored by their customer's management, as completing wings is seen to be more important than maintaining a machine. As a result, machines scheduled for maintenance are often placed back onto the production line which reduces long term efficiency.

Confrontation with the customer is reduced by Electroimpact as their contract does not require them to compensate the customer for lost production time. NCMT however, do provide compensation for downtime, with an agreed value for losses to production. Their customers are required to perform daily checks on the machines and operate them according to machine specification, but when operators neglect these requirements, machine performance can deteriorate. Machine mistreatment and operator error are not compensated for by NCMT and are often cause of confrontation with their customers. Issues of a similar nature are experienced by many machine manufacturers and service providers. Condition monitoring and data issues were not found to be causing confrontation with machine users, but this is mainly due to the lack of monitoring and learning techniques used in industry.

5.2.6 Use of PHM/CBM

Most advanced machine tools have some form of built in fault diagnosis; however this is usually in the form of a machine code which informs the maintenance engineer of possible causes to an error which has already occurred. As already seen, maintenance engineers also use a form of condition monitoring and prognostics for components using the data obtained from inspections. Customers are then advised on the future performance of the machine which is used to optimise the maintenance schedule. For example some NCMT machines use condition monitoring on spindle bearings which is downloaded from the machine by the engineer.

The adoption of health monitoring and prognostic techniques, similar to those used for aircraft maintenance however, remains low overall. Some suppliers of machine oil will provide an analysis of oil samples taken from a used machine and determine possible problems. Bearing fragments found in the fluid for example, may indicate faulty bearing wear. Mazak use monitoring systems on a few of their advanced machines to record component run time data and schedule maintenance according. This provides a greater insight into the operational use of components in a machine. Advanced machine tools are used in different ways by different users, so components in similar machines undergo different levels of deterioration depending on the manner in which the machine is used. Monitoring usage tells Mazak how the machine is being operated and for how long, around which, maintenance is scheduled. This data is downloaded from a machine interface or streamed over the internet for remote monitoring. Mazak are also looking at using fault diagnosis and prognostics for key components such as spindles.

5.3 Specification of Model Requirements

The results from the interviews are used to produce the required model modifications to make SHOAM applicable for advanced machine tools.

5.3.1 Operational Environments

The modifications to SHOAM should allow maintenance planners and manufacturers to model the variability in operational environments which their machines will experience

- A priority based work schedule based on that used by Electroimpact will be used because it provides a realistic way of deciding between machine performance and job importance. This trade-off is made frequently by machine users given the perceived lower risk of future machine downtime compared to immediate productivity gains.
- Operations are based on a shift system with a minimum length of 8 hrs each. Numbers of shifts and shift length can then be varied to control utilisation.
- The ability to model operations in which certain machine components may not be used and variability between operational intensities will be included.
- The model must also be able to simulate the sensitivity of machine performance over longer term variations so that the machine lifecycle performance can be captured. This can include production ramp up periods and long term variations in manufacturing intensity.
- Advanced machine tools were found to by run in cells of many similar machines as well as individual machines. The sensitivity of multiple-machine cells to maintenance and operational variations may be different to that of a single machine which the model will analyse.

5.3.2 Variable Service Scenarios

As already seen, there are many different strategies for machine services and maintenance which the service designer will wish to model

- A planned maintenance approach with a variable schedule for activities. Examples from NCMT include an inspection and minor maintenance every 2000hrs and a longer service every 4000hrs.
- The model must allow the different approaches to managing spares to be compared and contrasted. These include a prognostic based spares ordering system and an onsite spares store. The response time to spares orders will vary with 24 hours used as an average.
- The ability to model the impact of having engineers onsite against offsite must be included
- The ability to use PHM techniques to schedule services in a timelier manner must also be available in the model to show any benefits of using these systems.

5.3.3 PHM System Specifications

One of the purposes of SHOAM is to simulate the benefits of machine performance to different PHM technologies. Given the apparent limited use of these systems in the machine tool industry, the model may be useful for demonstrating what, if any benefits using PHM technologies provide to manufacturers and service planners. The model can also provide feedback regarding which machine components need these systems the most.

5.3.4 Performance Measures

SHOAM uses Measures of Effectiveness (MOE) to indicate the performance of ‘benefactors’, such as equipment manufactures and maintenance providers. It is clear that some performance measures will depend on the service contract being offered. The measures of interest to machine users include:

- Availability (also productivity)

- Quality of output
- Waiting times for jobs
- Machine utilisation (depending on the service contract)

Lifecycle costs and the service performance are critical for those manufacturers wishing to expand their services. For maintenance, the key measures include largely the lifecycle costs, which must be measured over periods up to 5 years. Included in this will be:

- Resource usage such as labour hours and spares
- Downtime (time in maintenance)
- Costs of CBM/PHM technologies

6. SHOAM FAMILIARISATION AND MODIFICATION

This chapter describes the main modifications to the SHOAM concept tool which were necessary to make it applicable for an advanced machine tool. Many intricate modifications are not described below, as these are largely concerned with the operation of the model itself and are of little relevance to the research findings.

6.1 Modification Method

SHOAM is a large model built using the Arena software package to simulate the aging of aircraft in a service environment and therefore contains many elements which have no application for a machine tool. In order to modify the model effectively within the time period, Boeing and SHOAM experts were consulted to provide insight where complexity or a lack of information impeded understanding. Modifying SHOAM directly proved difficult given the complexity of the model and the inter-dependence between different model areas. A new model is constructed using elements from SHOAM, but with modification so that the new system meets the requirements set out in the previous chapter. This approach to building the model is faster than direct modification, as a preliminary filtering of the unnecessary SHOAM elements is not needed. Only those elements which add value for advanced machine tool manufacturers are included with modifications. Most of these are described below and for a detailed description of the model, see appendix B.

6.2 Job Priority Scheduling

It was discovered in the previous chapter that machine tool maintainers regularly have to contend with a machine user’s operations for access to the machine. This is due to the short term necessity of finishing some jobs which are given a higher priority than the immediate maintenance of the machine. To capture this, a system is created that assigns every new production order with a priority ranging between one to three. Priorities affect the behaviour of the model in different ways and the effect on each area is explained under the corresponding heading below.

The immediate effect on job scheduling is that machines will wait in a ‘pool’ or queue until an order arrives. Priority one orders are the most important and these are assigned to waiting machines first. Priority three is the lowest priority and these jobs are scheduled last. The distribution of job priorities can also be used to reflect different manufacturing scenarios. A cellular design, for example could assign priorities using a triangular distribution with an adjustable mode allowing the variability in assigned priorities to be adjusted (Figure 13).

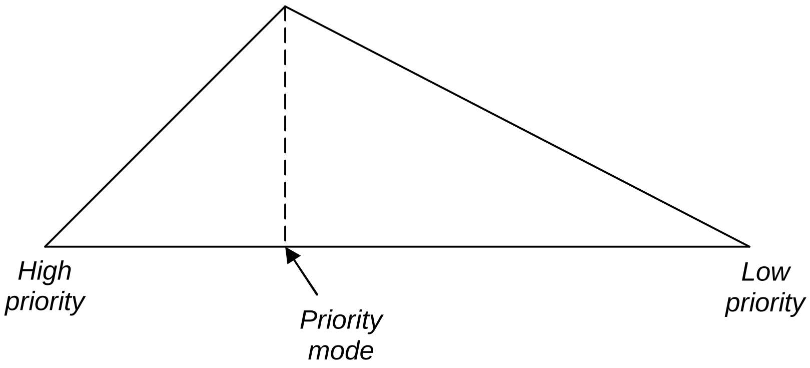


Figure 13: Priority mode distribution

A lower mode will result in a higher proportion of priority one jobs which effectively increases the intensity of the manufacturing environment. Alternatively, if a uniform distribution is used, the model behaviour will roughly reflect a production line, as apposed to a manufacturing cell, with job priority representing the job ‘progression’ along the line.

6.3 Machine Design

Aircraft in SHOAM are modelled as having 9 different subsystems, each characterised by a set of reliability data and maintenance times. Each system is then aged and fails according to the distribution assigned. This setup is also used to characterise a machine tool in the modified model. As discussed in the previous chapter, meaningful reliability data could not be obtained so instead 9 subsystems which are typical of machine tools are designed. The mean time between failures (MTBF) of each subsystem is inferred from the best data obtained during interviews and the characteristic distribution from discussion with machine researchers in the university. Details of these subsystems are available in appendix C as is more information on the modified model to capture the behaviour of a machine tool. Examples are given in Table 3. Lognormal distributions are used to characterise the repair time of a subsystem as it reflects typical process time carried out by humans (Kelton, 2007).

Table 3: Example subsystems

System	Description	Reliability distribution	Mean time between failure	Mean time to repair
Spindle	Provides main rotational force on tool head	Exponential	6000 hrs	16 hrs
Oil filters	Maintains oil purity	Exponential	2000 hrs	2 hrs
X-axis motion system	Controls position of tool head	Exponential	4000 hrs	6 hrs

6.4 Operational Environment

The aircraft in SHOAM age during a flight and can either fail and return home, or can complete their ‘missions’. This is modified as industrial equipment breaks down without changing location substantially. The model environment is also modified to allow greater variability in operational intensity and more flexibility over the aging process. Aircraft during flight are simulated as aging only according to the duration of the flight. The level of intensity of a machine tool’s processing environment will detriment the machine in different ways, such as when different metals are processed, and therefore simulating the impact of different operational intensities is essential for maintenance planners. Different aging processes can therefore be set for different job priorities. A priority one job environment, for example, could work or age the machine twice as hard as a priority two environment.

The probability that certain machine functions will not be utilised (§5.3.1) has been included as a separate module which can be attached or removed within the modelling environment. It essentially ‘heals’ certain subsystems after an operation before checking if any machine components have broken down. This may be useful for advanced machine tools which perform many functions, as Mazak discovered when experimenting with CBM technologies. It also allows far greater control over the manufacturing environment, because rather than all subsystems aging by the operation duration, different environments can be modelled to age certain systems differently over the lifecycle of the machine.

6.5 CBM/PHM

Subsystem faults develop during flights in SHOAM and if a fault occurs planes enter maintenance as soon as they land. Prognostics are modelled by setting a prognostic ‘horizon’ to indicate the point at which a failure can be detected. In RCB, this is often referred to as the ‘potential failure’ interval and is characterised by the P-F curve (Moubray, 1997). A typical P-F curve is shown in Figure 14, where P is the point when monitoring systems can detect a machine fault and F is the fail point of the component. SHOAM deducts the time between P and F from the subsystem failure point, effectively reducing the MTBF of the subsystem by the P-F interval.

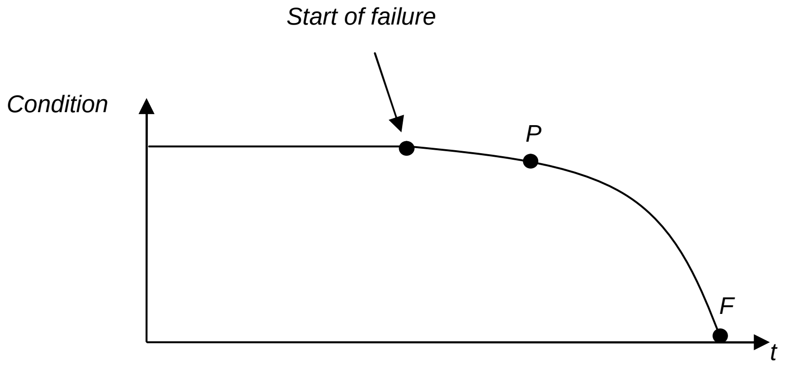


Figure 14: Typical P-F curve (source: Moubray, 1997)

The aircraft enters maintenance immediately on detection of a fault (or reaching point P) instead of flying again and risking failure. The risk of aircraft failure however, is substantially greater than that of a machine tool as machine tool operation and failure rarely impacts human health. A different approach to prognostics is therefore used to allow the analyst to differentiate between fault detection and maintenance action. This flexibility is also practiced for machine tools and other industrial equipment as CBM, where engineers collect data from a machine which then returns to production whilst the data analysis takes place (§5.2.6). For more information on these changes, see appendix C.

Confidence in any prognosis will depend on the accuracy of the monitoring and diagnostic systems being employed. Accuracy may also be a function of the P-F interval length and the time at which the fault was detected. Figure 15 illustrates this by showing that detection accuracy (top distributions) increases as the fault develops (a1, a2, a3) and more information about the fault obtained from the monitoring systems. The longer the P-F interval then, the greater the probability is for detection. This is represented by characterising the P-F interval by a reliability distribution itself. A normal distribution is selected with the standard deviation representing the inherent system accuracy. As the machine tool ages the probability that any faults are detected accurately increases.

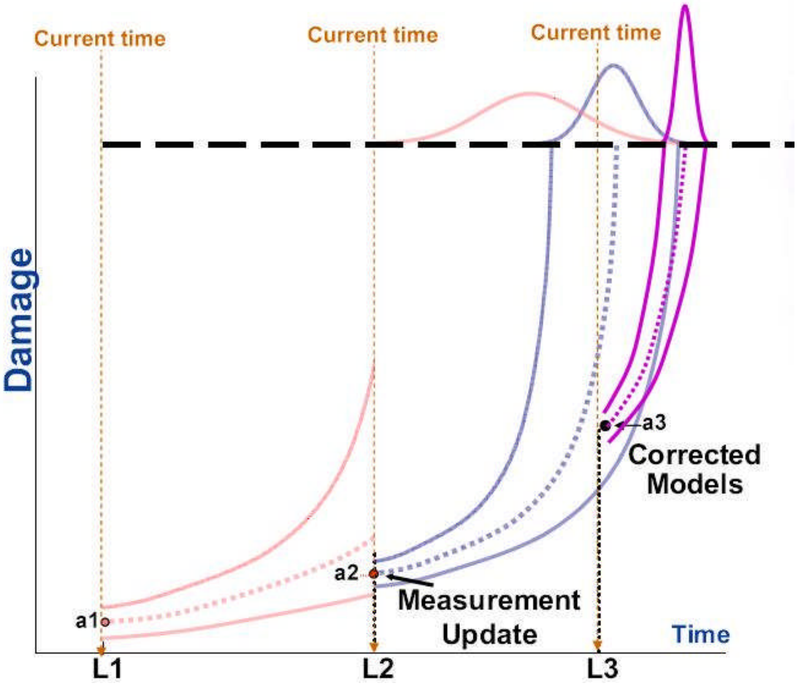


Figure 15: Monitoring accuracy (source: Impact Technologies)

Knowledge and learning abilities are now common features in the development of machine tool fault diagnostic and prognostic systems (§3.6). This is simulated by using the *knowledge* variable from SHOAM and using it to improve the P-F interval. The *knowledge* variable itself is used in SHOAM to show improvement in maintenance planning by reducing the time for maintenance tasks by a percentage. For the machine tool model, *knowledge* increases the P-F interval length and decreases the standard deviation; if a fault is detected during operation accurately. This increases maintenance response and improves the accuracy of detection systems.

6.6 Quality

Quality is not measured in the SHOAM model, but is for advanced machine tools as a large proportion are used in the aerospace industry. Three subsystems in machine tools which impact quality of the output substantially are those used to control the coordinates of the tool in the work envelope. Poor quality is modelled by introducing a random variable which causes a poor quality product as these systems reach the end of their lives. This only affects the very end of the subsystem life and is not a function over the entire life of the component. This reflects the wear-out phase of the 'bathtub curve' (Figure 16), which characterises the failure rate *λ* of many engineering components and where failures increase towards the end of life (Dhillon, 2007).

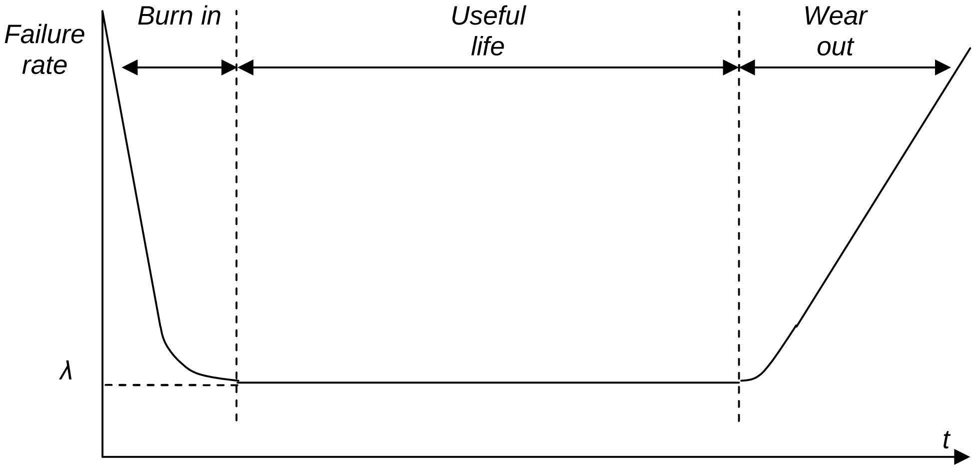


Figure 16: The bathtub curve

The observation by Todinov (2006), that the different consequences of failure affect risk, is also captured because maximising overall machine reliability may not minimise the risk of poor quality. Components can also fail without producing any poor quality work and quality can be improved using PHM systems.

6.7 Maintenance & Resources

Changes were made to maintenance to incorporate job priority and the reaction to fault diagnosis. Scheduled maintenance is often neglected by machine users if important jobs or rush orders are present. In the model, priority one is used to represent these important jobs, so when a scheduled maintenance period is reached, the number of priority one jobs is compared to the machines available and if a shortage is found, the scheduled maintenance period is skipped. It is therefore possible to run a machine into a breakdown, as is occasionally practiced in industry (§5.2.5). Machines with PHM systems onboard can also skip their scheduled maintenance if priority one jobs are present, but the use of prognostics should make this a safer option.

PHM systems are also changed to model the behaviour for machine tools. SHOAM uses health monitoring during a flight to reserve maintenance resources before the aircraft completes the flight. Prognostics are changed to allow the analyst to differentiate between fault detection and action. Spares can be ordered and maintenance resources reserved whilst the machine continues in operation until specified to leave. This reflects machine tool CBM again, as data analysis is often performed whilst the machine continues with production. This is done using a new variable; *flag,* which is introduced to trigger the time from point P on the P-F curve where the machine is sent to maintenance (Figure 17).

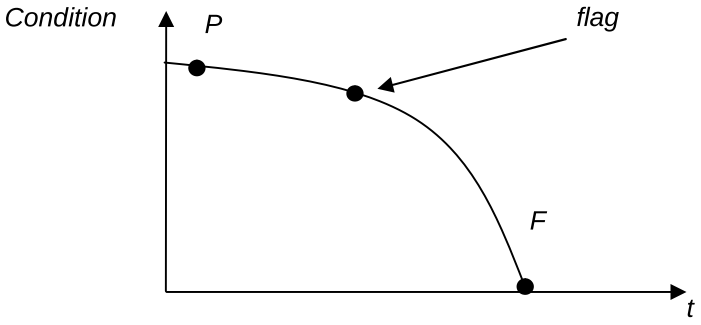


Figure 17: Maintenance flag

There are clearly tradeoffs involved when setting the *flag* position which may improve or detriment the performance of a machine. If the flag is set very late after a fault is detected, maintenance resources will be reserved for that fault whilst the machine continues with its operation. It could fail or develop another fault however, and therefore require a longer period in maintenance and risk breakdown. If the flag is set very early, the machine will enter maintenance early despite usable life in the machine components. The length of the P-F interval, delivery times and the reliability of the components must all be considered when setting the flag and therefore presents a strategic decision for the maintenance planner which can be optimised using simulation. This also prevents forcing a two-state response to fault detection, noted by Eisinger and Rakowsky, (2000) to cause inefficiency.

Spares in SHOAM are ordered using PHM systems or when the plane is in maintenance. The option of using a scheduled approach for ordering spares is also introduced whereby a minimum level of spares is specified, which are replenished to this level intermittently, allowing a ‘parts store’ to be modelled as part of a service. This can also be set up to model a just-in-time approach to parts if the part delivery time is known and the minimum level set accordingly.

Changes to the way spares are allocated means that measuring the cost of the spares ‘store’ is more accurate, as is the unavailability of maintenance resources. Parts are now reserved immediately when requested, but remain in the parts store until the repair is performed. Reserving spares early therefore incurs a premium, as the parts will be unavailable for other machine repairs, but a holding cost may still be applied, making lifecycle costs for spares easier to calculate. The option of modelling the availability of engineers on-site against off-site is also introduced, where a delay is incurred to model the response time of an engineer to a break down.

6.8 Performance Measurement

Changes to the way SHOAM calculates availability and utilisation provide a more accurate reflection of machine availability. Given the difficulty of extracting data for individual entities in the Arena simulating environment, SHOAM uses a ‘snap-shot’ of the number of machines in maintenance at a particular interval and computes the number of aircraft available at that time. A sampling method is used instead in which all machines pass through a module which records the time each machine spent in maintenance. After 10 records have been collected, the average of all machines is calculated. This is also done for utilisation and provides a running estimate of the average performance of the production system. The performance of machines over the lifecycle period has been modified from SHOAM to provide a breakdown of performance into 6 month intervals. This makes the impact of maintenance and services easier to visualise over longer durations.

7. MODEL TESTING AND DISCUSSION

This chapter presents the design and results of the model testing. A discussion follows where the utility for machine tool services and performance is evaluated and the limits of the model identified.

7.1 Testing Method

Reliability data could not be obtained for a machine tool and as such, model validation cannot take place. A sensitivity analysis is performed to test the model features and experiments using the best available data from the interviews are conducted to illustrate the capability of the model for evaluating the impact of reduced downtime and the benefits of CBM/PHM technologies. An example of one experimental service evaluation, based on a ten machine cell similar to that used in wing manufacture, is given below and further examples can be found in appendix E for comparison. In the ten machine cell test, different designs of service contracts offered by machine tool manufacturers are simulated using multiple experimental runs of the model and evaluated over a 5 year lifecycle. The benefits of using CBM/PHM systems will also be compared and the result is the test matrix in Table 4.

Table 4: Service contract test matrix

Service contract	Preventative maintenance schedule	Engineer onsite	Parts store	PHM
1	✓	✗	✗	✗
2	✓	✓	✗	✗
3	✓	✓	✓	✗
4	✗	✗	✗	✓

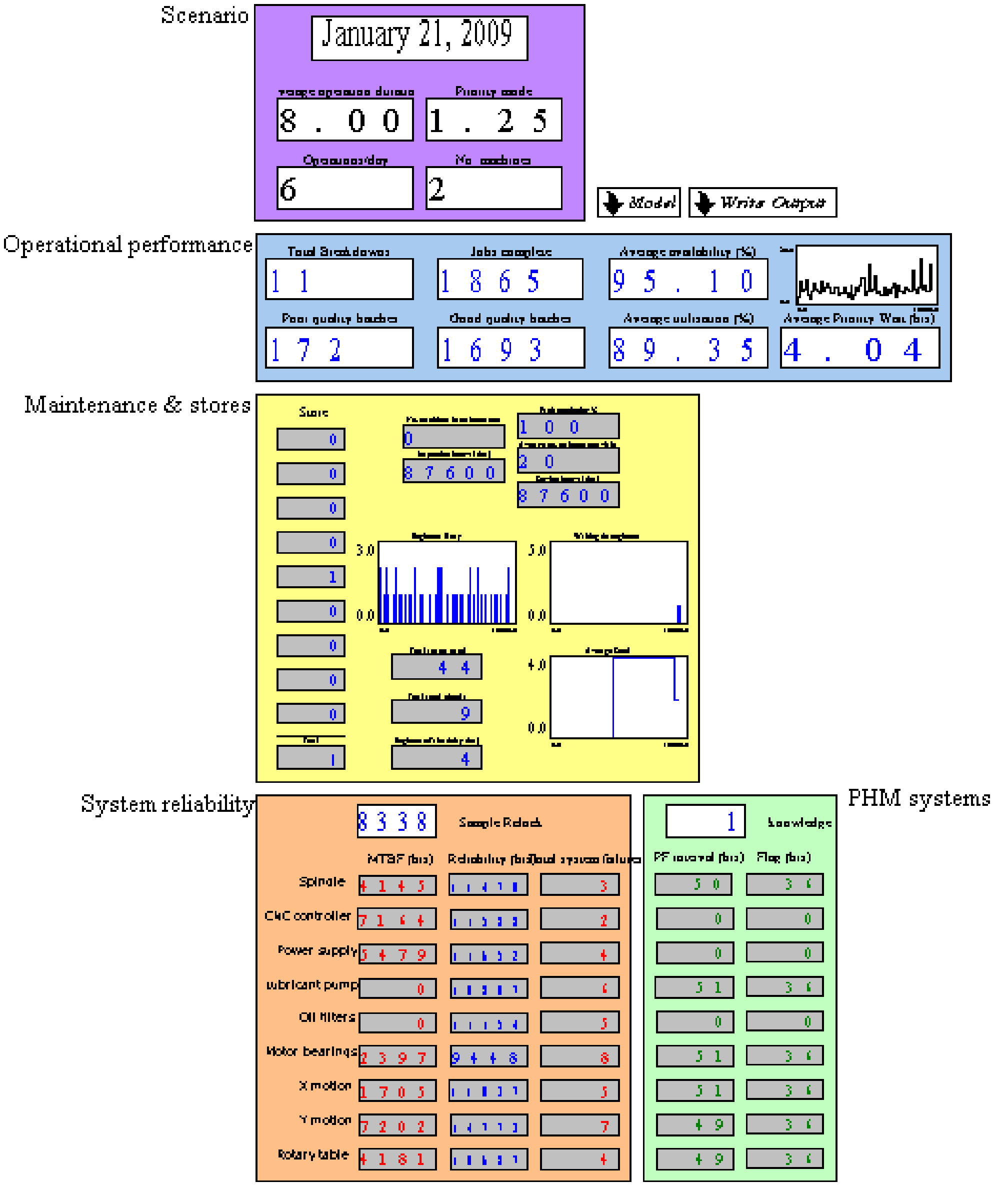
The machine used for the test is based on the information obtained for an NCMT machine and the corresponding preventative maintenance schedule is therefore also applied. A single shift inspection and repair of systems every three months is supported by a longer three shift service every six months. A two shift scheduling system is used, with each shift averaging around nine hours to simulate a harsher production environment compared to the typical 8 hour shift. Artesis motor condition monitoring systems are used to simulate condition monitoring and are therefore only applied to the six subsystems which are motorised. Each of these units costs £2000 and it therefore costs £12000 to monitor a complete machine.

7.2 Testing Results

The results of the sensitivity analysis are available in appendix E. Shown below are the model behaviour in terms of inputs and outputs and the results of the example service comparison given above.

7.2.1 Model Inputs and Outputs

Data is entered into a spreadsheet which provides the input to the model. This includes the machine design characteristics, the operational scenario and the service strategy. The data which can be put into the input sheet to design a service scenario is included in appendix D. Some data must be changed in the model itself, including the schedules for maintenance engineers and the delivery intervals for spares schedules. There are three formats for simulation results. An interface in the model (Figure 18) provides live information whilst the simulation is in progress. Built-in plots in the interface display average stock levels and resource utilisation, giving a short-term view of changes in performance. Another format for results is a report which is automatically generated by the Arena software package at the end of a completed simulation. A further format for results is an output spreadsheet which has been created to record ten performance statistics at six month intervals and records the total failures for each subsystem at the end of the simulation. Each of these three formats is most useful for analysing changes in performance over different time intervals.



January 21, 2009

Average operation duration: 8.00
Priority mode: 1.25
Operations/day: 6
No. machines: 2

Total Breakdowns: 11
Jobs complete: 1865
Average availability (%): 95.10
Poor quality batches: 172
Good quality batches: 1693
Average utilisation (%): 89.35
Average Priority Wait (hrs): 4.04

Store: 0, 0, 0, 0, 1, 0, 0, 0, 0
Total: 1

[illegible]: 0
[illegible]: 87600
[illegible]: 100
[illegible]: 20
[illegible]: 87600
[illegible]: 44
[illegible]: 9
[illegible]: 4

8338 Sample Reliab

1 knowledge

	MTBF (hrs)	Reliability (hrs)	Total system failures	PF interval (hrs)	Flag (hrs)
Spindle	4145	[illegible]	3	50	36
CNC controller	7164	[illegible]	2	0	0
Power supply	5479	[illegible]	4	0	0
Lubricant pump	0	[illegible]	6	51	36
Oil filters	0	[illegible]	5	0	0
Motor bearings	2397	9448	8	51	36
X motion	1705	[illegible]	5	51	36
Y motion	7202	[illegible]	7	49	36
Rotary table	4181	[illegible]	4	49	36

Figure 18: New model interface

7.2.2 Service Comparison Results

The first three contracts do not improve the operational reliability of the machine itself, but aim to get the machine working again as soon as possible. Breakdowns therefore do not change dramatically between each of the first 3 contracts and it is the service which is responsible for improved manufacturing performance. Using CBM/PHM, breakdowns are reduced by 300% as maintenance is performed before failure occurs. Figure 19 shows the improvements to availability and quality with each service contract.

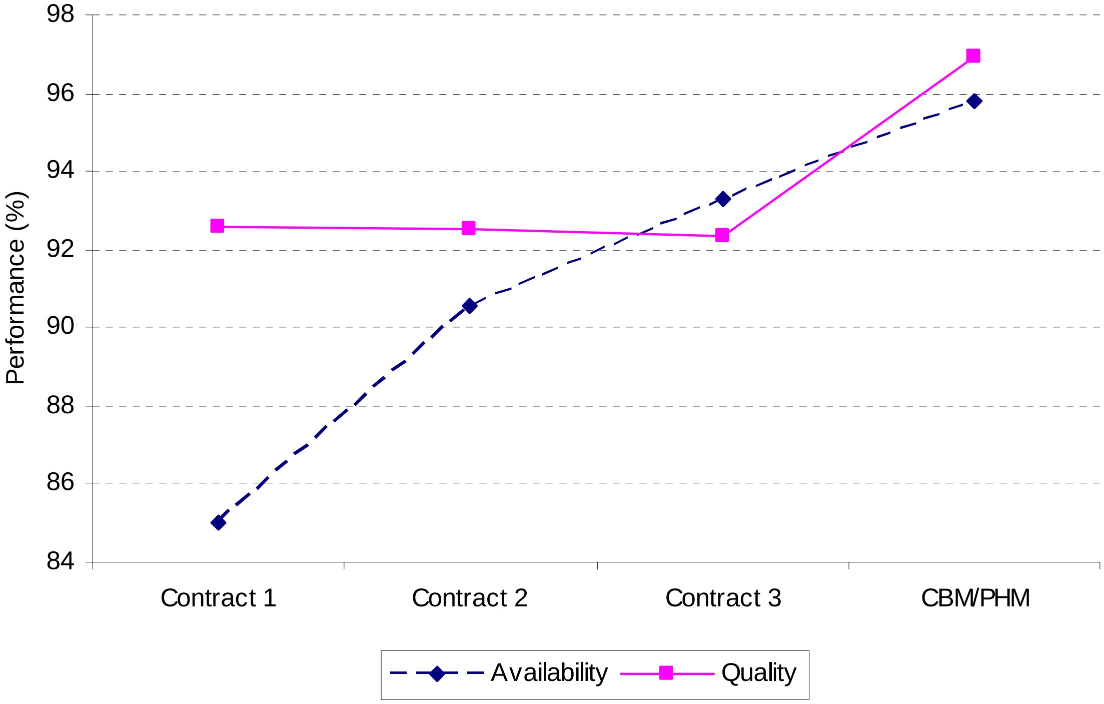


Figure 19: Cell manufacturing performance under each service contract

The improvements to availability are realised in improved manufacturing output. Figure 20 shows improvements in annual productivity with each expansion of the service. Output which passes the quality requirements is also shown and the benefits of using CBM systems on quality output are clearly demonstrated. Productive output improves by just over 1%, or around 950 hrs of machine time. This is also dependent on utilisation, which reaches a maximum of 87%.

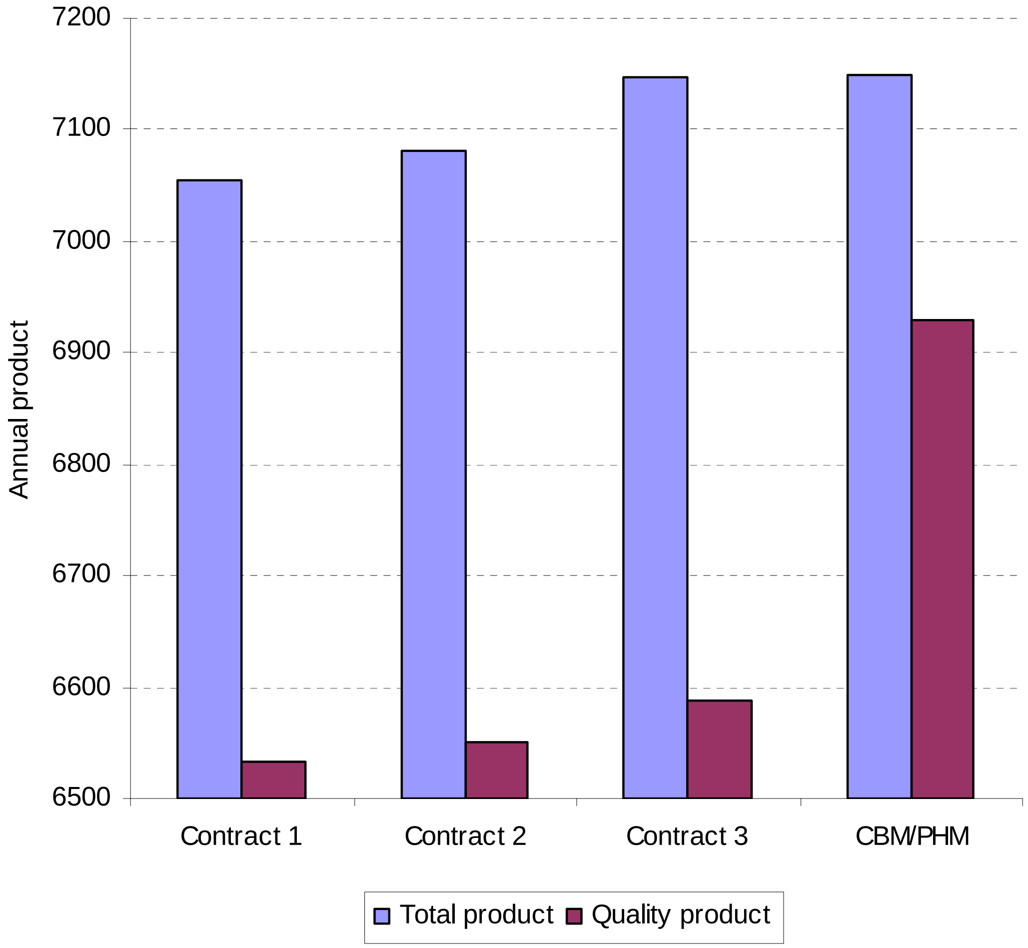


Figure 20: Cell productivity under each service contract

The waiting times for priority jobs are shown in Figure 21, indicating the reliability of the manufacturing cell to meet orders on time. This is significant for supply chain performance.

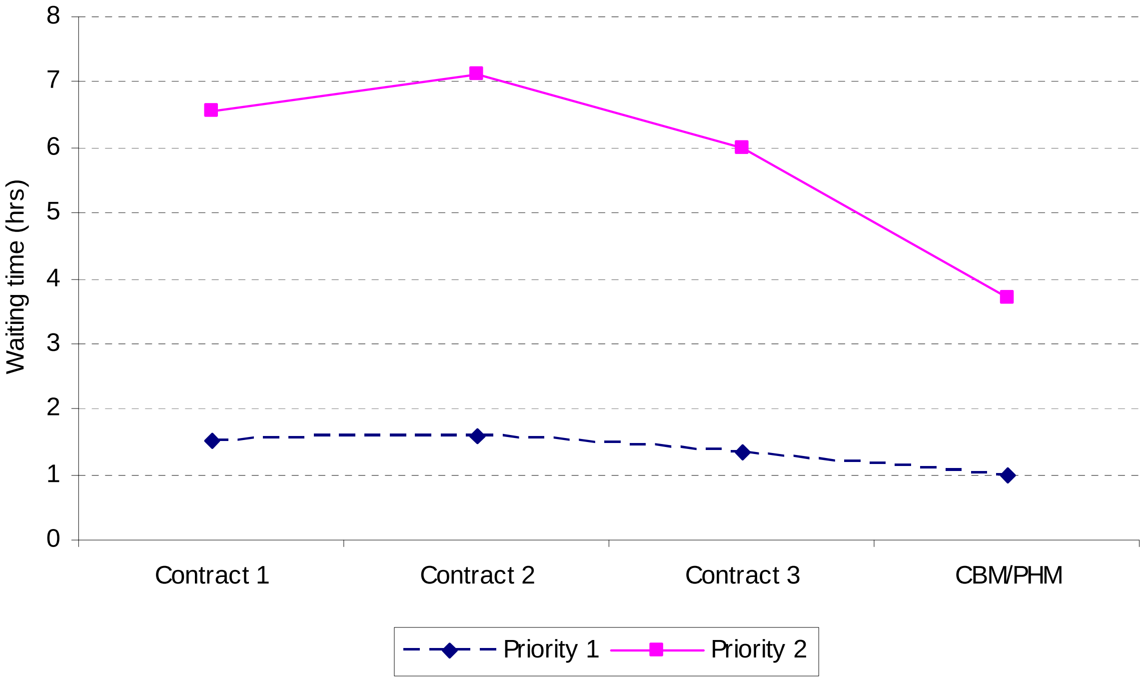


Figure 21: Waiting times for priority jobs in each service contract

Using these results, manufacturers can clearly demonstrate the value that their services provide and may guarantee a specified performance with increased certainty that this level of service will be met.

For machine maintainers, cost will be a factor in determining if the service should be expanded. The SHOAM tool effectively demonstrates lifecycle performance, but assessing costs using the model is more difficult. Modelling the spare parts store is particularly difficult because complete subsystems are rarely held onsite by machine tool service providers and repairs do not typically replace entire subsystems. Components also vary considerably in cost with spindles found to reach up to £20,000, but cartridge loading spindles can be changed for a significantly reduced cost. Electroimpact estimate that around 59% of the cost of a machine is held on the shelf for their 10 machine facility, which is used to model a full part store in this analysis. The particular machines used in this test typically cost £250,000, but some advanced machine tools were found to cost up to £8m. The parts store also rarely remains full, so the average number of spares in the store over the five years is used to determine the final holding cost. Typical technicians cost £28,000 per year and the costs of downtime are determined using the machine cost. Figure 22 shows the change in the lifecycle cost of each service contract with contract 1 as 100%.

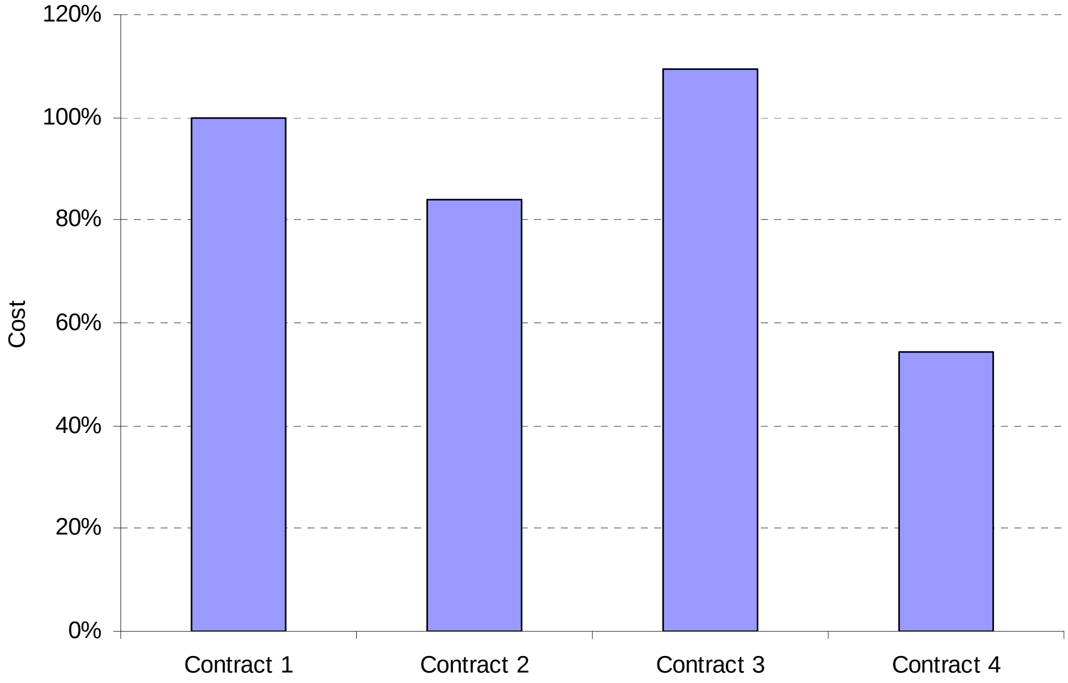


Figure 22: Lifecycle cost

The main driver of maintenance effectiveness is downtime, which is shown in Figure 23. The improved service throughput with each contract results from the increased availability of maintenance resources including spares and engineers, which reduces the waiting times for broken machines. Despite a longer downtime period than contract 3, contract 4 has an improved availability. The use of CBM means that maintenance is performed according to machine condition, which eliminates unnecessary servicing and therefore the machine downtime is minimised over the lifecycle of the contract. This is shown in Figure 23 as a reduced number of maintenance visits. Using CBM/PHM systems also reduces the time being repaired, because faults have been already been diagnosed.

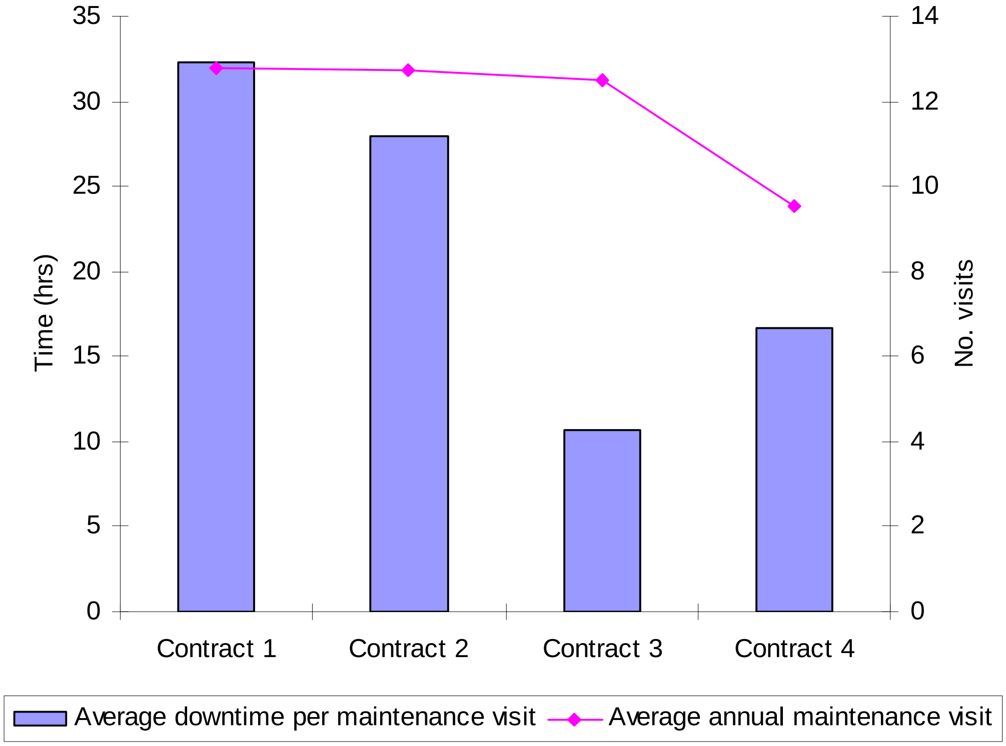


Figure 23: Average downtime and maintenance visits

The test reveals that reducing machine tool downtime is being achieved effectively by the services which machine tool manufacturers provide, but this does not necessarily minimise cost. Holding an engineer onsite only marginally reduces downtime, but the lifecycle cost is also reduced. Holding spare parts considerably reduces the downtime, but to the detriment of lifecycle costs. This may be the reason why this type of service is only found in intensive manufacturing environments where there are more machines or more expensive machines over which the costs of the parts store are spread. Indeed, economies of scale can be seen between single and three cell tests in appendix E. Using CBM greatly improves operational reliability through reduced breakdowns and also by increasing the quality of output by allowing faults which do not cause subsystem failures to be recognised and reduced. CBM also eliminates unnecessary maintenance which improves availability. PHM reduces the time in maintenance significantly, although not as much as the spare parts store.

7.3 Model Evaluation and Discussion

The value which each service delivers to the customer can clearly be demonstrated in the model. The difficulty of demonstrating the value of a particular service is one of the main causes of the servitization paradox experienced by manufacturers and noted by Gebauer et al. (2005).The benefits delivered by CBM/PHM solutions over the lifecycle of the machine are also demonstrated and these can be compared to the expense of implementing these systems for a machine. Even if PHM is not used, employing CBM systems can significantly increase performance through the elimination of unnecessary maintenance, improved operational reliability and quality.

The maintenance flag increases the flexibility of CBM/PHM system management and allows the behaviour seen in the machine tool industry to be modelled, in which machines continue operating despite the detection of a system fault. The increased risks of keeping a machine in operation whilst maintenance is prepared can be evaluated using the model before implementing for a machine. The response to CBM/PHM information can therefore be optimised according to the designer's constraints; be they manufacturing system performance, cost or service environment. Services can therefore be matched to the organisational and business conditions, which Haarman (2005) uses in a VDM methodology, again to show the value of maintenance services for an organisation.

Including quality in the model introduces another risk seen in industry to be modelled, as poor quality for aerospace is a failure, even if the particular subsystem may still be operational. Management of quality is therefore essential for advanced machine tools. The manufacturing environment also effects quality performance and risk can be reduced through simulation. Indeed, uncertainty and risk can be managed more effectively through simulation, which should help manufacturers develop more effective long term service strategies .

Feedback to a machine designer is also provided, because machine performance can be matched to the anticipated operational environment. Designing services and machine cells in concert could be used for plant level designs, where process plant reliability is optimised during the design phase (Goel et al, 2003). Limiting a machine tool to a single set of subsystems however, may be too restrictive. Unless each subsystem is an LRU as defined by Wessels, (2003) then systems will undoubtedly comprise numbers of components and a risk analysis of the subsystem will be necessary. This could also be true for PHM systems, as it is unlikely that one P-F interval is sufficient to describe the behaviour of an entire subsystem.

Given the lack of accurate data for machine tool reliability, many of the model features, such as the impact of different manufacturing environments could not be used. Without accurate reliability data, only the model capabilities are being demonstrated here and the model must first be validated in order to make full use of these capabilities. This will require substantial cooperation from an advanced machine tool manufacturer, as data from commodity machine producers could not be used in this type of analysis. Failure modes and rates seen in these machines can vary considerably for any single component due to the variability in manufacturing environments and the user neglect of the machines. It may only be capital intensive manufacturing environments then, where downtime cannot be afforded and where far more failure data is collected, that a model such as this can be used.

8. CONCLUSION

8.1 Summary of Findings

Machine tool manufacturers in the UK have responded to market turbulence and competition from low labour cost economies by increasing the technological complexity of their machines to target niche markets and by focusing on the services which maintain them. The transition to service provider however, has been problematic for many equipment providers, such that the success of some companies in contrast to the failure of others, has been described as a paradox. The causes are complex and involve the sensitive relationship between service provider and equipment user, the difficulty of demonstrating the value of services in the manufacturing sector and the uncertainty involved in making long term commitments.

A model is created to allow the operation of a machine tool in a service arrangement to be simulated. The SHOAM tool, developed by The Boeing Company, which performs a similar function for aircraft, is used and modified which improves the model scope. The operational environments of advanced machine tools are researched using interviews of industry members and literature, the results of which define the requirements of the new model. The interviews reveal the low maturity of machine tool services, with services offered on machines for a premium. The industry is highly user driven, with customers specifying the services they require and manufacturers agreeing to supply them. One of the causes of this low maturity result from the fierce competition in the industry which gives manufacturers relatively low bargaining power compared to users. Another is the neglect of maintenance by machine users, who are therefore responsible for a large proportion of machine downtime. Consequently, performance based contracts cannot be guaranteed. Compounded with this, the high variability in machine tool operational environments and the modular construction of the machines makes component failures highly variable and reliability engineering costly. They also reveal the lack of adoption of health management technologies, which have shown potential for improving maintenance and service response for aerospace and automotive applications.

The SHOAM tool, modified to build the model, is used to analyse aircraft, but the risks of machine tool failure are lower than that of an aircraft and consequently, many SHOAM modifications allow greater flexibility in the response to system health information. This allows the behaviour seen in industry to be modelled more effectively. More control over the operational environment is also introduced, which allows the different manufacturing conditions and levels of uncertainty in which machine tools operate to be modelled. Typical services that are present in the machine tool industry are also included so that the benefits of health monitoring systems can be compared to existing service strategies.

The model demonstrates the sensitivity of machine tool performance to different service and maintenance strategies, which can then be optimised over the lifecycle of the machine or service contract. This allows risks and uncertainty to be reduced and an effective service strategy planned, which could help overcome some of the causes to the service paradox experienced by equipment manufacturers. Demonstrating the value delivered by equipment services is another cause and the model allows the benefits of a service strategy to be clearly demonstrated.

CBM/PHM systems show great potential for improving the performance of machines and reducing lifecycle costs. CBM reduces unnecessary maintenance and can increase operational reliability substantially. Quality can also be managed more effectively, which is critical for advanced machine tools in aerospace. PHM systems allow similar reductions in machine downtime to the more capital intensive services currently used for advanced machines, but a significantly reduced lifecycle cost.

8.2 Research Limits

The greatest limit of the model was the lack of quality data for machine tool reliability. This prevented validation of the model and so only the model capabilities could be analysed. This was largely due to the nature of the data itself, which is highly sensitive to the customers of advanced machine tool manufacturers. Commodity machine data was not consistent enough to be used either. The variability between modes and rates would make any result from a model such as this unrealistic and the risk of using such results would therefore increase substantially. The method of interviewing may also be responsible for the lack of quality data. Phone interviews proved inefficient and a more direct, face-to-face approach may have been more useful, although the interest of the some manufactures in the development of services was found to be low.

There are potentially a great many improvements to the model which could be made depending on the application. Modelling logistics in greater detail is one example. Not all machine tool manufacturers use a centralised parts distributor and the flexibility to model a decentralised approach might be of interest. More data and knowledge of how the model will be used in practice should be sought however, before changes such as these are made. Although SHOAM does not currently model costs, it has great potential in doing so and a more efficient way of modelling repairs would therefore be useful for analysis.

8.3 Further Work

The model must be validated using a real operational setting with the corresponding machine reliability data so that its effectiveness can be evaluated. A list of model failures should follow immediately which can be used for future improvements. These may only be cosmetic; requiring just minor modification of measures and variables, however if more detail, such as increased subsystem decomposition is required, then more fundamental changes to the model will be necessary. It will be interesting to see how the problem of subsystem decomposition is addressed in the Arena modelling environment, although it is understood that another programme; PICAM, is in development which aims to provide the inputs to SHOAM.

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APPENDIX A: SEMI-STRUCTURED INTERVIEW TOPICS

A.1 Machine Operational Environment

Given the costs of acquiring advanced machine tools it is anticipated that utilisation will be a common concern for machine users. Information regarding typical operational durations is therefore required to provide an insight into the value of machine availability. This information is also useful for designing efficient services both for the machine users and service providers. A preliminary examination of SHOAM reveals that reliability data for machine tool subsystems will be needed. SHOAM models an aircraft as a set of 9 subsystems, each characterised by sets of reliability data. There are three key reliability measures need for each subsystem and these are listed below:

1. Mean time between failure (MTBF) & distribution
2. Mean time between unscheduled maintenance (maintenance which does not cause critical breakdown)
3. Mean time to repair (MTTR) & distribution

It may also be possible to infer MTBFs and the characteristic distribution from historical data or past performance measures.

Topics:

- Brief description of machine purpose and tasks being performed
- How long is the machine required to be operational per day?
- What is a typical cycle time of a single job?
- How many jobs are performed per day?
- How are jobs scheduled and controlled?
- How many similar machines are in use at the same time?

- Is the machine part of a manufacturing cell or production line?
- How are parts delivered to the machine?
- What happens to parts after processing?
- What happens to the job and production system if the machine breaks down?

A.2 Service Contract Type & Maturity Level

This subject is included to provide a benchmark between the different service offerings. The services included in the contract, how they are paid for and their duration may be used to place the company into one of the frameworks from the literature.

- What is offered/guaranteed – service level/warranty?
- Under what conditions are services offered – i.e. types/numbers of machines etc?
- Period of service contract
- Does the customer purchase the machine and the services are included for a premium?
- Does the customer purchase the services the machine function provides i.e. rent the machine?
- Which service type generates most profit/business?
- Most popular types of contract and growth trends
- How are the benefits shown to the customer?

A.3 Service Strategy and Management

This subject is where the most variability in responses is anticipated, as there are many ways to manage maintenance, as seen from the literature review. Particular attention is therefore given to suppliers of product services and not in-house maintenance. The key areas of focus will be on the management of maintenance activities, particularly regarding the interface between operations and machine performance. Measures of effectiveness (MOEs) which are used in SHOAM to analyse performance will also be obtained and are expected to vary depending on the particular service contract being offered.

- How are the tasks which need to be performed on a machine identified?
- How maintenance activities are planned and scheduled?
- How does production and operations impact the service strategy?
- How are service costs calculated?
- How is performance measured?

A.4 Implementation and Confidentiality

The problems with implementation and execution of service contracts and issues such as data sharing, privacy and responsibility will be raised here.

- Problems with implementation and execution
- Data sharing with customer

A.5 Maintenance Methodologies

The technical side of maintenance will be raised here. The success of a PHM offering is the effective use of health monitoring and prognostic systems. The use and proliferation of monitoring technologies and prognostic techniques currently employed in industry will also be surveyed. The use of this data for learning/knowledge can also increase service effectiveness

- How the service level is ensured
- Delivery of services including spares/installation/replacement
- Use of CBM and PHM

- Scheduling of maintenance activities and integration with CBM
- What happens to the collected data? E.g. use for learning process

APPENDIX B: MODEL DESCRIPTION

B.1 Model Overview

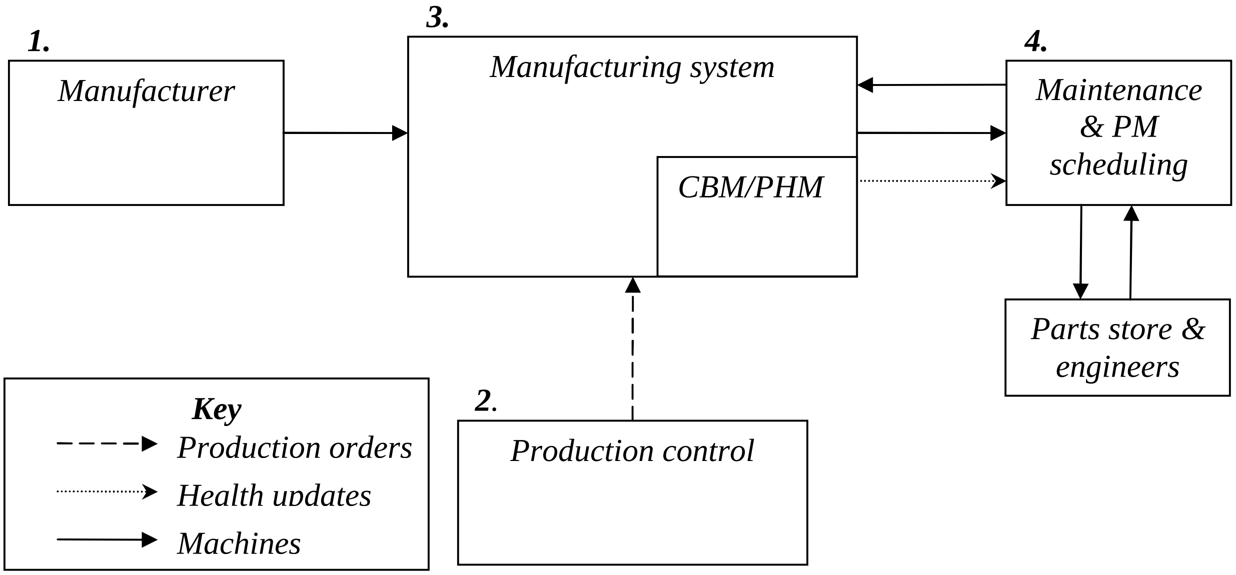

Figure 24: Model overview

1. *Manufacturer* is where the machines are designed and created. The reliability of each machine and the machine cell size is also specified. This is similar to the Original Equipment Manufacturer benefactor in SHOAM.

2. *Production control* generates and introduces production orders, or jobs, into the manufacturing system. It is used to generate the manufacturing scenario in which the machine tool and service arrangement can be simulated. The SHOAM counterpart to Production control is the Flight Planning benefactor.

3. The *Manufacturing system* ages the machines according to the operational environment specified in *Production control*. Machines are introduced and assigned to operations or

orders, which then age the machine. It can then go to maintenance if scheduled or undergoes a breakdown. Fixed and repaired machines are reintroduced into the manufacturing system from maintenance to continue work. CBM/PHM systems if used send repeated health updates to maintenance with which maintenance resources are ordered accordingly. SHOAM counterparts include a mix of Hold Aircraft and Assign Flights, Fix or Fly and Flights. All these functions will be internal to a machine cell in a manufacturing environment and *Manufacturing system* models a machine cell.

4. *Maintenance and PM scheduling* repairs machines and reintroduces them into the manufacturing system. Preventative maintenance is also scheduled here if used. *Parts store and engineers*, although displayed separately to *Maintenance and PM scheduling* in Figure 24, is actually contained within it. Here, parts are held in stock and ordered in according to a stock schedule or at the request of PHM systems. The SHOAM counterpart is clearly the Maintenance Operations benefactor.

Both the *Manufacturer* and *Production control* are used to transfer data from the input sheet into the model. They are mostly legacy systems of SHOAM, but with modification to include the new modelling behaviour. The *Production system*, *CBM/PHM* and *Parts store* are almost entirely different to SHOAM. Maintenance and PM scheduling is a mix of SHOAM legacy and new systems. In the description of the model below, machines are described as ‘moving’ around the model because the Arena user interface animates each event as a movement. Machines or any other entities however, do not actually move anywhere in the model. A movement then, indicates a new event.

B.2 Manufacturer & Machine Design

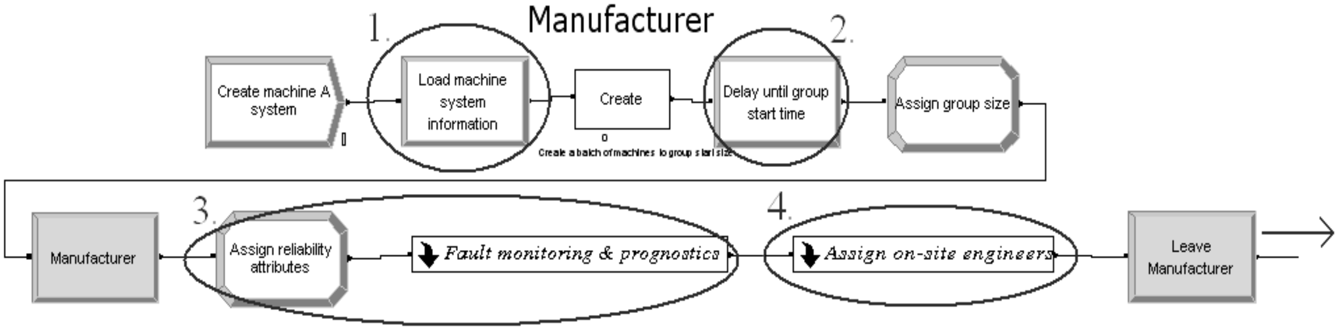

Figure 25: Manufacturer logic

1. The machine cell specification, which is defined in the input sheet, is loaded into the Arena model environment. The cells size and start time, percentage of machines with PHM systems, the learning capabilities of those systems and the engineer resources available to the cell are introduced here. The machine specification is then duplicated to make up the machines in the cell.
2. The machines are then delayed for the duration of the cell start time, which is specified in the input sheet. This can be used to model the installation time for machines or simply be used to allow production orders to be accumulated before the machines are introduced into the cell.
3. The *Rclock* attribute and number of subsystems are assigned here. *Rclock* accumulates the time which the machine has been in operation. When it reaches the fail point of the subsystem, the machine breaks down. To repair the machine, the subsystem MTBF is added to the fail point so that *Rclock* can begin to accumulate again. After *Rclock* is assigned, the *Fault monitoring & prognostics* sub module assigns the reliability and prognostic characteristics of each machine subsystem.

4. If different machines have different numbers of engineers on-site, then this is specified in the *Assign on-site engineers* sub module. The maintenance schedule of each machine is also specified here.

B.2.1 Assign Fault Monitoring & Prognostics Sub Module

In the *fault monitoring and prognostics* sub module, the *critical fail points* and the prognostic capabilities of each subsystem are assigned.

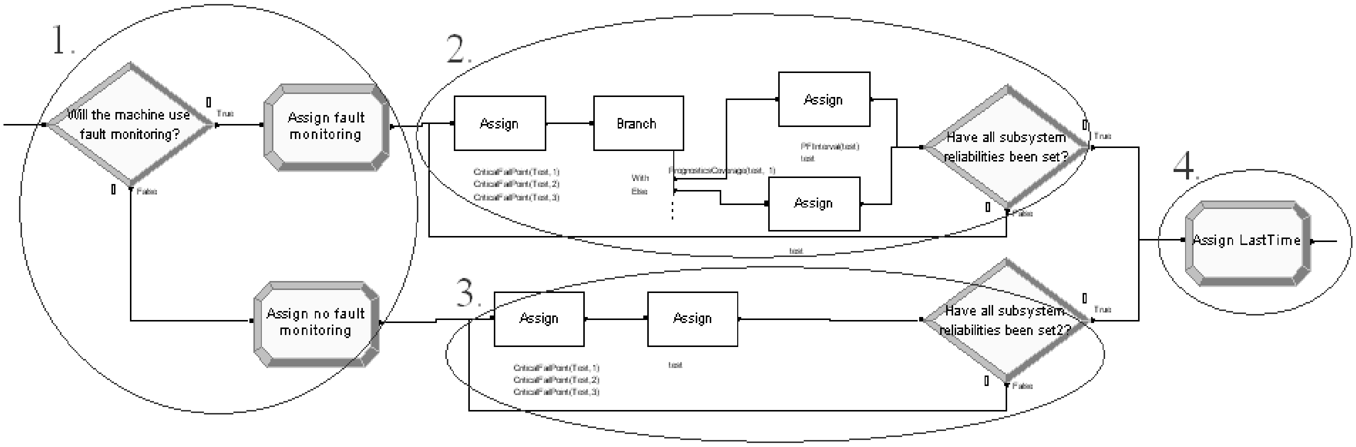

Figure 26: Fault monitoring & prognostics assignment logic

1. First, a decision module distributes the number of machines with PHM systems according to the PHM% value specified in the input sheet. If the machine has PHM systems on board, the machine takes the top path to 2. If no PHM systems are used, the bottom path is taken to 3.
2. The *critical fail point* attributes of each subsystem and the subsystem prognostic capabilities are now set. Each subsystem has 3 *critical fail point* attributes and there are typically 9 subsystems in a machine. A *Test* attribute is incremented each time the subsystem reliability and prognostic characteristics are set signifying that the next subsystem is going to be specified. When *Test* reaches 10, then the model knows that

all subsystem characteristics have been assigned and the machine proceeds to 4. First, the 3 *critical fail point*s of the subsystem are set.

Critical fail point 1 is the actual fail point of the sub system. When the *Rclock* attribute reaches the value in *critical fail point 1*, the subsystem and machine breakdown. To repair the subsystem, MTBFs are added to *critical fail point 1* until it is above *Rclock* again.

The number of times an MTBF is added to *critical fail point 1* is recorded in the *critical fail point 2* attribute of the subsystem, which represents the number of repairs required for the subsystem.

Critical fail point 3 is used when creating a health update message during fault diagnostics. Instead of adding MTBFs to *critical fail point 1*, they are added to *critical fail point 3*, leaving the first fail point in tact so that the machine can continue working normally. The number of times an MTBF is added to *critical fail point 3* is recorded in *critical fail point 2* as a negative value, representing that the faults were discovered using PHM systems. *Critical fail point 3* is later assigned to the subsystem *critical fail point 1*, when the machine is repaired.

After the *critical fail point*s have been assigned, a decision block decides if the subsystem has PHM systems by checking the *prognostic coverage* specified in the input sheet. Prognostic coverage determines the probability that a catastrophic failure can be prevented using PHM systems. The *Test* attribute is incremented for the next subsystem.

3. If no PHM capabilities are to be assigned to the machine, then only the *critical fail points* are set for the 9 subsystems, and the machine proceeds to 4.
4. Finally, *Test* is reset to 1 and the *Last Time* attribute, which is used for statistical gathering is set to the current simulation time.

B.3 Production Control

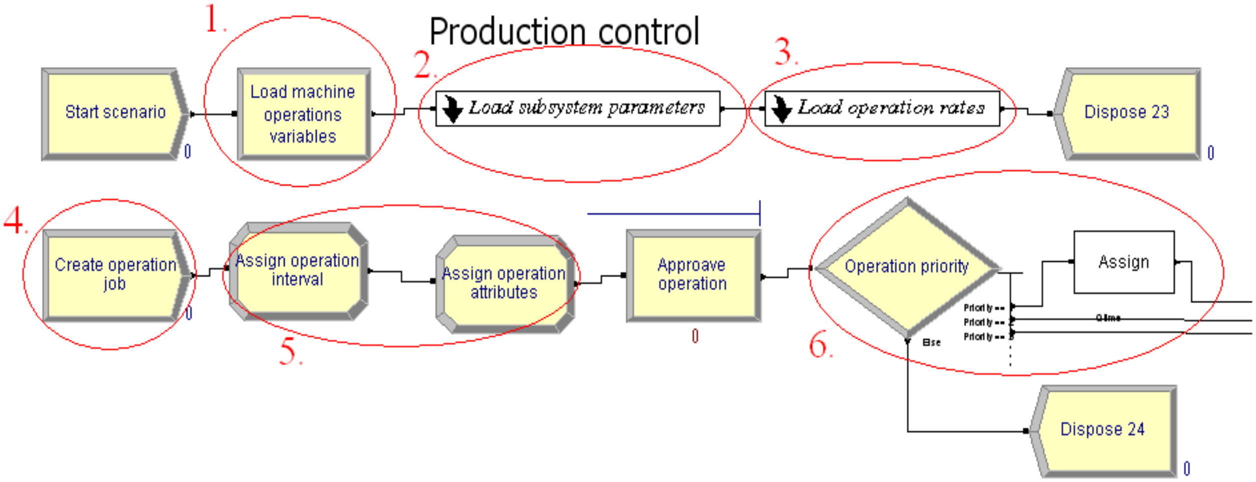

Figure 27: Production control logic

Production control generates the manufacturing scenario, including the operation durations, long term business cycles and the job priority control system. Production control is generally a function of the customer, but can be used to simulate the performance of a machine tool service arrangement under different manufacturing conditions.

1. First, a scenario entity is created which is used to load the operation variables into the model from the input sheet, which includes the operation durations, setup and shut down times and the service life of the machine in operational hours.

2. The subsystem variables are then loaded into the model from the input sheet. These include all the tables such as MTBFs and MTTRs of the subsystems, the subsystem spares management and the scheduled maintenance and engineers.
3. The scenario entity is then used to schedule the business cycle scenario, if it is used. In the *Load operation rates* sub module, the normal production load of jobs per day is loaded from the input sheet, which controls the number of production jobs generated per day in 4. This rate is continued until the business cycle is ready to start, which is defined in the input sheet. The business cycle production load is then loaded into the model, which alters the job orders per day of 4 and this lasts for the duration of the business cycle. The normal load rates are then returned and the scenario entity is disposed of.
4. Here, the production jobs or orders are generated. The production job rates, which were specified in 3, are used to control the number of jobs generated per day in 4. When the rate changes, then so too will the number of production orders sent to manufacturing. This can be used to control the level of machine utilisation, in concert with the operation durations and priority modes.
5. The operation durations, which can be used to simulate a single shift or a single job are then loaded. Each order is subject to a variability, which introduces uncertainty into the modelling environment. The priority mode, which controls the distribution of job priorities, is also assigned to the production order here.
6. There are 3 exits to *Production control*, one for each job priority. This decision module ensures that each job takes the correct path to the *Manufacturing system*. The assign block in 6 is used to gather statistics on priority one jobs, such as the time which these orders wait for a machine. The orders or jobs then continue to their respective match modules in the M*anufacturing system*, where they wait to be assigned to a machine.

B.4 Manufacturing System

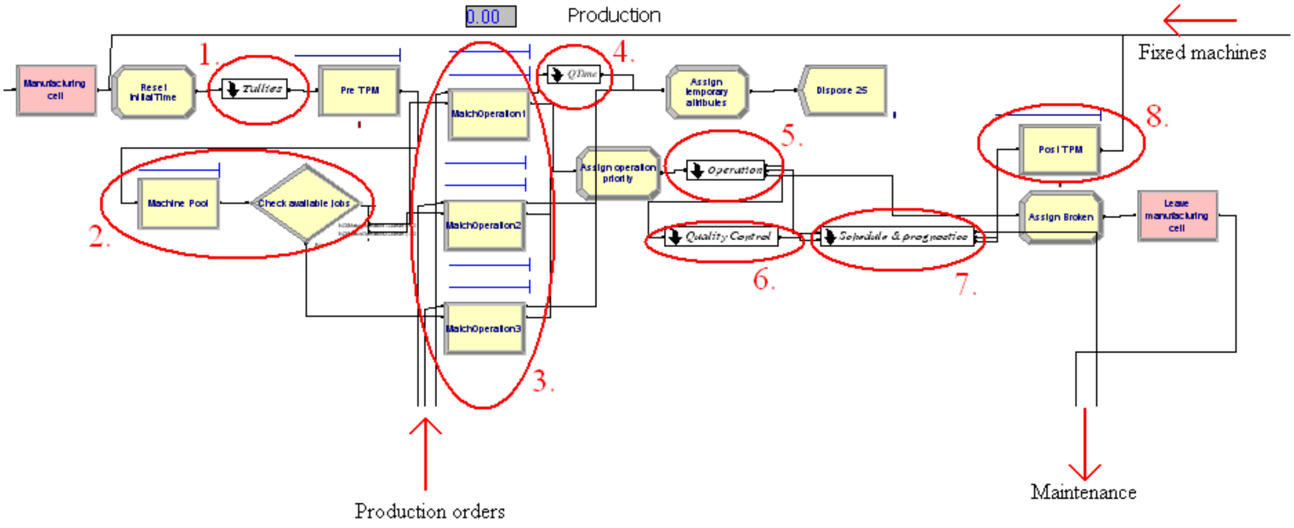

Figure 28: Manufacturing system logic

Machines enter from the left from either the manufacturer, as fixed machines from maintenance, or as machines which have completed an operation and are healthy.

1. Machines enter the first sub module *Tallies. Tallies* records the performance statistics for 10 machines, including availability, utilisation and maintenance visits. An average is then taken and displayed on the interface. After *Tallies*, the machines enter the process *Pre TPM*, where any pre maintenance checks are carried out. The time for this a function of the TPM value from the input sheet.
2. The machine then enters the machine pool, where it is held and waits with other machines until assigned to a job. When a job is available, a decision module assigns it to highest priority job waiting.
3. Production orders enter via the upward pointing arrow. Each will have a priority and will wait in its respective match module until a machine is available. When a machine is assigned to a job, they leave the match module, the machine continuing to 5 and the production order continuing to 4.

4. Qtime measures the time which priority one orders had to wait for an available machine. After this is recorded, the operational environment of the job is recorded temporarily and the order is disposed of.
5. The machines leave the match module and are the production environment is assigned from the temporary values recorded in 4. After this they enter the *Operation* sub module where the operation takes place. During operation, the machines are aged and can breakdown, in which case they exit the operation module and leave via the downward pointing arrow in Figure 28 to maintenance. If not they proceed to 6. Health messages are also generated in the *Operation* module and enter into 7.
6. After finishing their operation, the output of the machine is checked in the *Quality control* sub module. The machines then proceed to 7.
7. The health messages generated during operation and the machines after the quality check both enter the *Scheduling & prognostics* sub module. Here, decisions based on the machine health, the maintenance schedule and the waiting production orders determine whether the machine should go to maintenance (and exit via the downward pointing arrow) or should return to production and go to 8.
8. If the machine is going back into production some maintenance checks are carried and the machine returns to 1.

B.4.1 Operation Sub Module

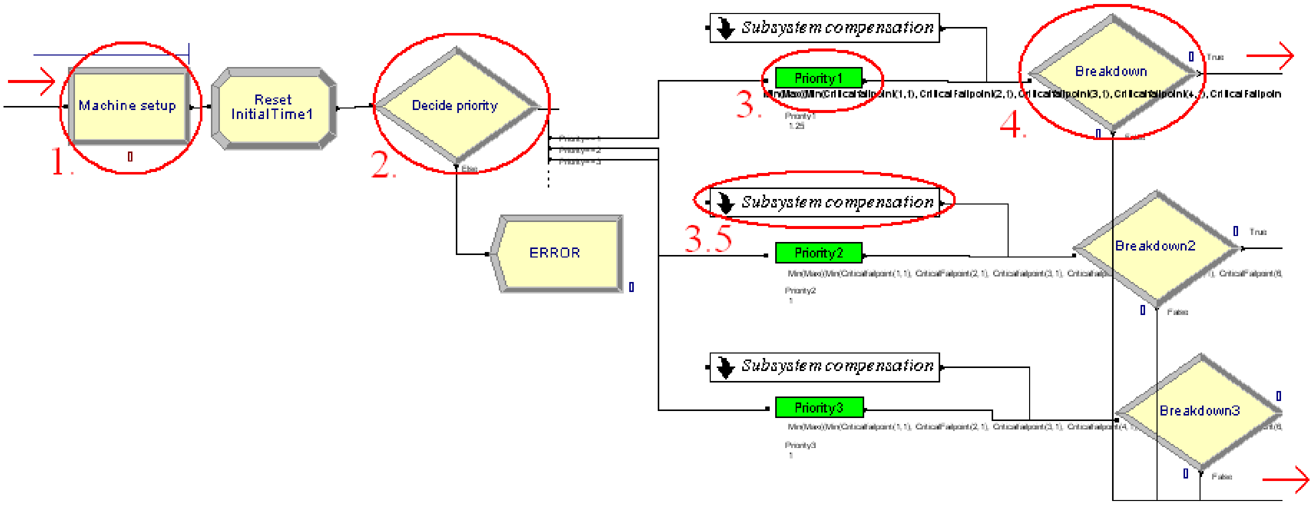

Figure 29: Operation sub module logic part 1

1. Machines enter the machine setup module, where any setup operations take place. The time for the setup module comes from the input sheet and an *operator* resource is required.
2. After setup, the decision module decides which priority the job is and sends it to the corresponding environment module in 3.
3. The *environment module* is a legacy of SHOAM and is programmed to increase the *Rclock* of each machine by the value determined by the expression entered in the module. In this case, the expression takes either the shortest remaining life (critical failpoint – *Rclock*), 0 (in case all sub systems have failed), or the operation duration. So if the shortest remaining life is less than the operation duration, then *Rclock* will increase by this amount and vice versa if operation duration is less than the shortest remaining life.
4. The decision module then decides if the machine failed during that operation. It compares the time the machine was in the *environment module* to the length of the

operation duration. It is clear from 3, that if the time the machine was in the *environment module* is less than the operation duration, then the shortest life was not long enough to complete the operation and the machine has broken down. If the time the machine was in the *environment module* is equal to the operation duration, then the machine must have completed the operation and remains healthy. If healthy, the machine progresses to 5 via the top arrow in Figure 29. If it has broken down, it goes down from the decision module via the arrow in Figure 29 to 8.

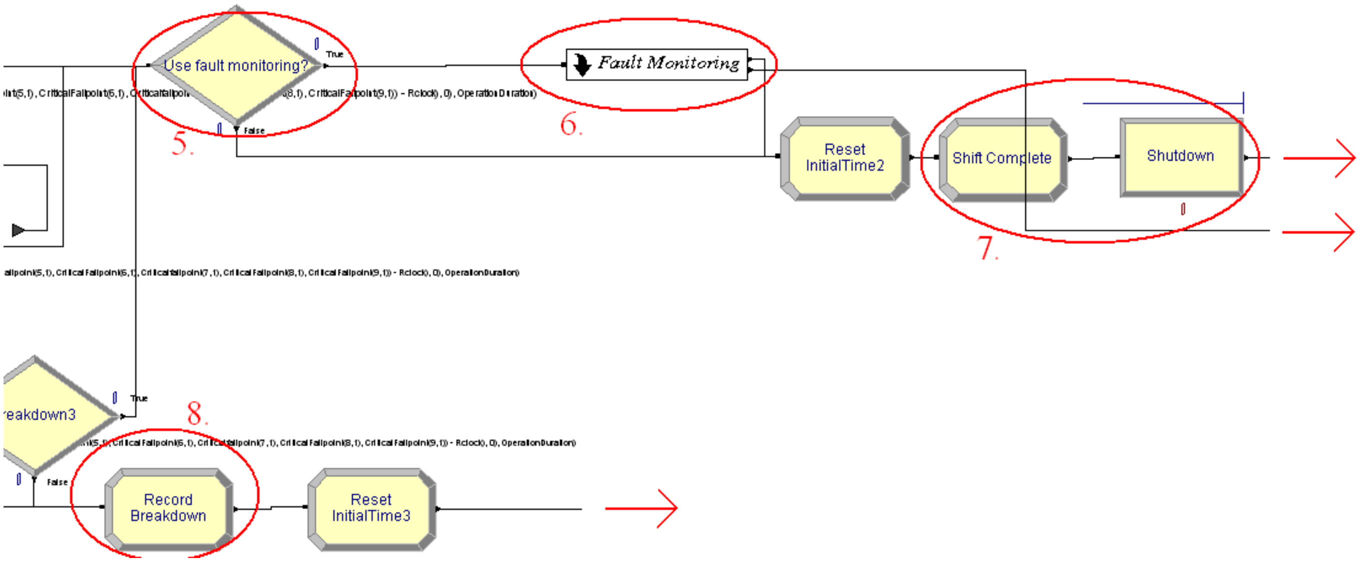

Figure 30: Operation logic part 2

5. Healthy machines are then checked for their fault diagnosing capabilities. If so they enter the *Fault monitoring* sub module 6.
6. The *Fault monitoring* sub module generates a health update on the machine which is then sent to *Scheduling and Prognostics* via the centre arrow in Figure 30.
7. The final tasks of the operation include recording the completion of the successful operation and then shutting the machine down. *Shut down* process is similar to the

Setup. After the completion of this process, the machine leaves via the top arrow in Figure 30.

8. Machines which have broken down are recorded as unsuccessful jobs and leave via the bottom arrow in Figure 30.

3.5 The *Subsystem compensation* module replaces the *environment* module 3 and allows the probability of not using a subsystem during operation. Although it sounds unlikely, this was found to be occurring by manufacturers when they applied CBM technologies to certain machine components. The module must be attached before the model is run.

B.4.2 Fault Monitoring Sub Module

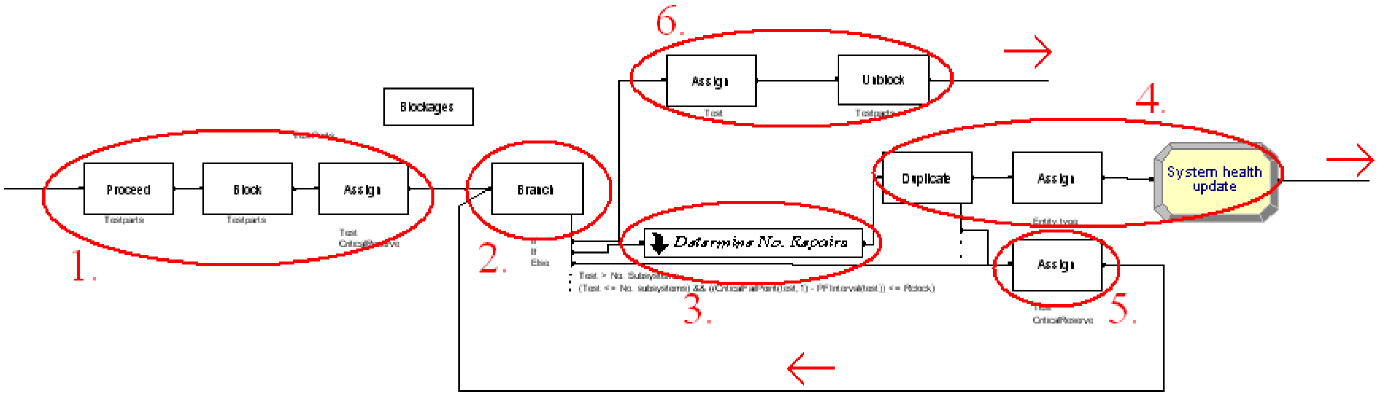

Figure 31: Fault monitoring logic

Much of the *fault monitoring* module design is a legacy of SHOAM

1. As machines enter the fault monitoring module, they are blocked so that only one is tested at any one time. An attribute *Test* is applied which determines which subsystem is being tested at that time. *Test* can therefore vary from 1 to 9.
2. The health of each subsystem is tested for faults independently. This branch module determines if all the subsystems on the machine have been tested by seeing if the *Test* is equal to 10. *Test* is incremented when the subsystem test has been completed.

When *Test* reaches 10, then all subsystems have been tested and the machine leaves via 6. This module also decides if the subsystem has developed a fault. *Rclock* is compared to the P-F interval, and if it is found to be within this region, then a fault has occurred and the subsystem will require maintenance soon. It leaves via the module and enters the *Determine no. repairs module* 3. If a fault has not occurred, then the machine goes to 5.

3. The *Determine no. repairs* first records the critical fail point of the sub system into the attribute *critical fail point 3* so that this attribute can be changed without affecting the actual fail point of the system. MTBFs are then added to *critical fail point 3* until its ‘health’ is above the P-F interval i.e. to return the subsystem health back up to beyond the P-F interval. The number of times this has to happen is recorded in *critical fail point 2*. This number is negative to indicate that the faults were detected using PHM techniques.
4. After the number of repairs recorded in *critical fail points 2 and 3*, the machine is duplicated and one is turned into a health message, the other returns for the next test. The *Test* attribute of the machine that is used as a message is still set to the machine subsystem which was tested, so in effect, a message is sent for each subsystem which has developed a fault. These messages exit the module via the far right arrow, after the display picture is changed to a red report.
5. The duplicated machine from 4 and any subsystems which do not have faults have their *Test* attribute incremented ready for the next subsystem test and go via the arrow pointing to the left in Figure 31, back to the decision module at 2.
6. After all subsystems in the machine have been tested, the module is unblocked to allow the next machine to be tested.

B.4.3 Subsystem Compensation Sub Module

Figure 32 shows the subsystem compensation module.

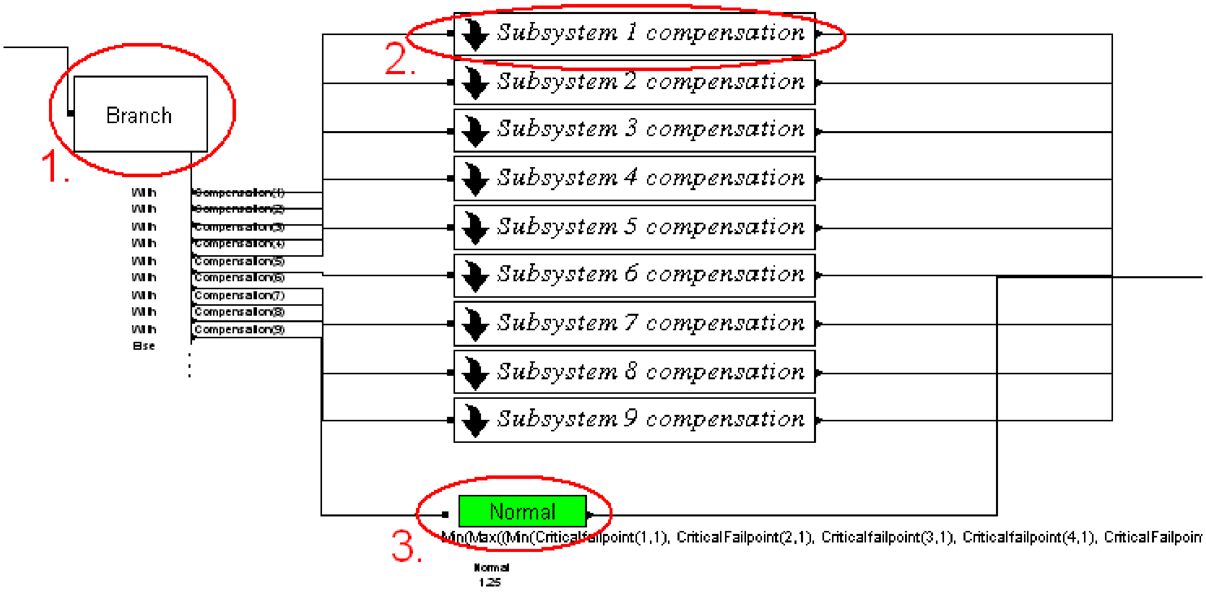

Figure 32: Subsystem compensation sub module

1. A branch module uses the probabilities specified in the compensation table in the input sheet to distribute the subsystems during simulation.
2. Each machine then enters another *subsystem compensation* module, which ages all subsystems in the machine, and then 'heals' or compensates the subsystem which is not being aged. The aging process is also changed so that the subsystem which is not being aged does not affect the duration of the aging of the remaining subsystems
3. The probability that all subsystems will be aged is also included and used if the compensation table is left blank. This is simply the normal aging process.

B.4.4 Quality Control Sub Module

Figure 33: Quality control sub module

In quality control, the output of machines is tested for good or bad quality. The three quality systems on the machine decrease in quality performance as they reach the end of life. This is similar to the wear out phase seen in the bath tub curve which characterises the lifecycle reliability of many engineering components (Dhillon, 2007). The quality test in the module takes the smallest remaining life of all the quality systems and sees if it is within 5% of the remaining sub module life. If so, a random variable determines if poor quality is produced. This increases as the remaining life decreases. Poor quality and good quality are recorded and displayed in the interface. The machine then proceeds to *Scheduling and prognostics*.

B.4.5 Scheduling and Prognostics Sub Module

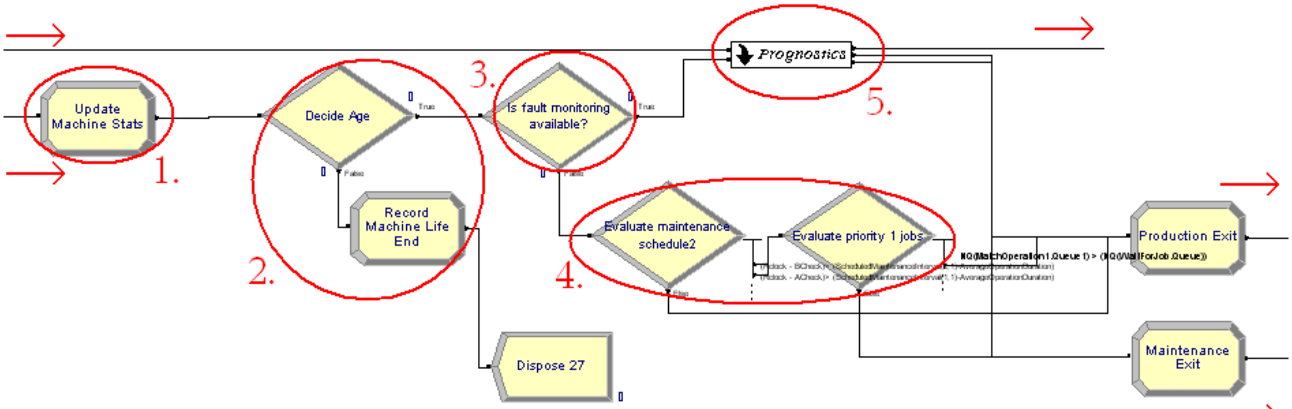

Figure 34: Scheduling and prognostics logic

1. Machines enter the module via the bottom arrow on the left of Figure 34. Some statistics of the machine are recorded here such as availability, utilisation and uptime.
2. This decision module sees if the machine has reached the end of its life. *Rclock* is compared to the maximum operational life from the input sheet. If the machine has reached this point, it is recorded as such and disposed of.
3. If the machine has life left in it, a decision module determines if PHM systems are installed on the machine. If so, the machine enters the *Prognostics* sub module 5. If not, the machine goes down to 4.
4. If the machine does not have PHM systems on board, the maintenance schedule for the machine is evaluated. The time the machine has until the next scheduled maintenance period is compared to the operation duration. If the operation duration is longer than the remaining time, then the number of priority one jobs waiting are first evaluated before sending the machine off to maintenance. If the number of priority one jobs waiting are more than the number of machines which are available, the machine is sent back into production despite being scheduled for maintenance. It exits via the centre arrow on the right of Figure 34. Otherwise it goes to maintenance via the bottom arrow. If the operation duration is shorter than the time until the next scheduled maintenance period, the machine exits the sub module via the centre arrow on the right hand side of Figure 34 and goes back to production.
5. In prognostics, the machines enter from 3 and decisions are made over whether to send them back to maintenance or to send them back into production. Machines going to maintenance exit via the bottom arrow on the right of Figure 34 whereas machines going to production exit via the centre arrow. The health messages, which arrive from the top arrow on the left, are compared against those already in maintenance to see if maintenance has already started ordering spares for the subsystem.

B.4.6 Prognostics Sub Module

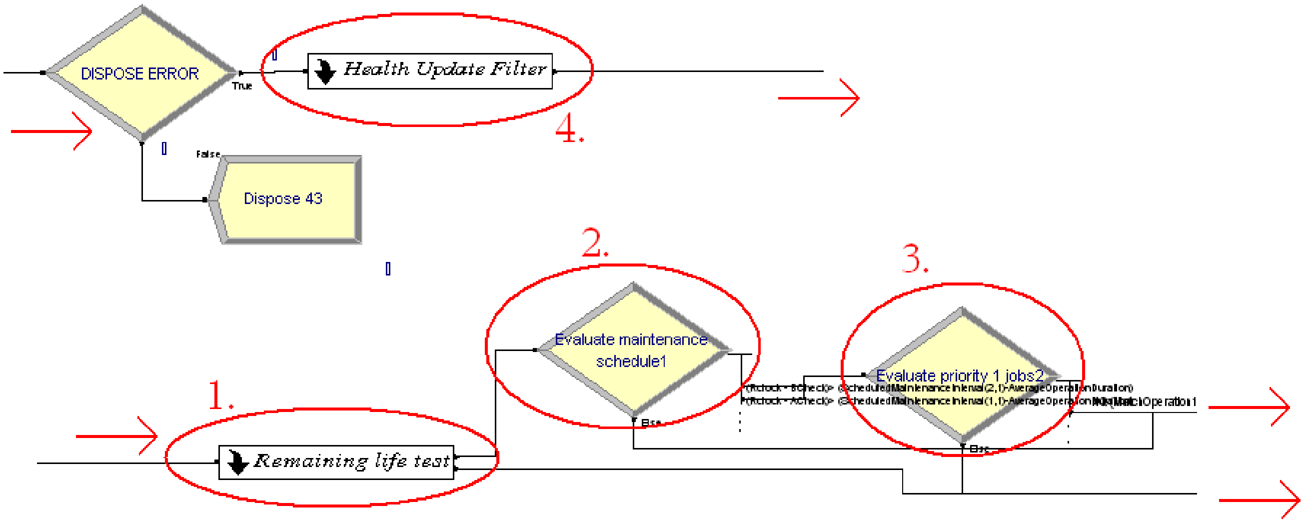

Figure 35: Prognostics logic

1. The machines enter via the bottom arrow on the left of Figure 35 and go into the *Remaining life test* sub module. Here, *Rclock* is compared to the maintenance flag of each subsystem, which is set in the input sheet. If the *Rclock* is greater than the maintenance flag, then the machine is sent to maintenance via the bottom arrow on the right in Figure 35. If *Rclock* is less than the maintenance flag, then the machine tool is evaluated for scheduled maintenance.
2. The machine maintenance schedule is evaluated in a similar manner to that conducted in the *Scheduling and prognostics* sub module. The time the machine has until the next scheduled maintenance period is compared to the operation duration. If the operation duration is longer than the remaining time, the machine is scheduled for maintenance and goes to 3. If the operation duration is shorter than the time until the next scheduled maintenance period, the machine exits the sub module via the centre arrow on the right hand side of Figure 34 and goes back to production.

3. The number of priority one jobs waiting are evaluated before sending the machine for the scheduled maintenance. If the number of priority one jobs waiting for machines are more than the number of machines which are available, the machine is sent back into production despite being scheduled for maintenance. It exits via the centre arrow on the right of Figure 34. Otherwise it goes to maintenance via the bottom arrow.
4. Health messages, which have come from the *Operation* sub module, are evaluated to see if maintenance is already processing orders for that machine subsystem. If so, the message is deleted. If not, the message goes to maintenance.

B.5 Maintenance

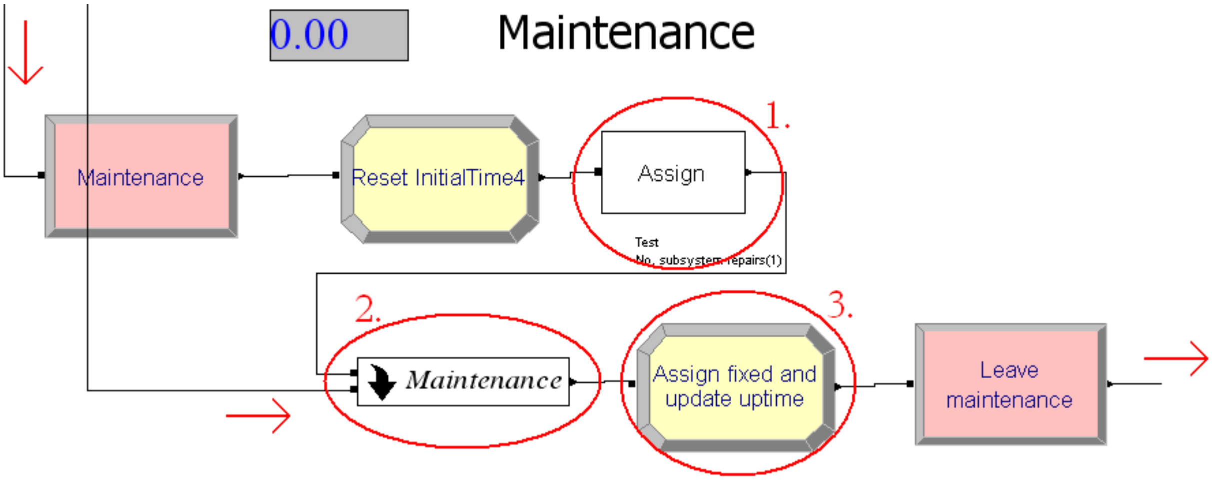

Figure 36: Maintenance

1. Machines enter maintenance via the top left arrow in Figure 36. Machines which have broken down during operation are red, whereas machines which have been sent to maintenance before breakdown are blue. The *Test* attribute is set to 1, ready for the first subsystem test. The number of subsystem repairs are also reset, as they are either determined in maintenance or from health messages.

2. The fault messages enter the *Maintenance* sub module via the bottom arrow on the left of Figure 36 and machines continue from 1. In *Maintenance*, machines are repaired and spares are stored. There are 3 sub modules within *Maintenance* and include *No. repairs*, *Parts planning and repairs*, and *Scheduled maintenance*.
3. After being repaired, machines have their uptime statistics updated and the picture is changed back into a blue healthy machine.

B.5.1 No. Repairs Sub Module

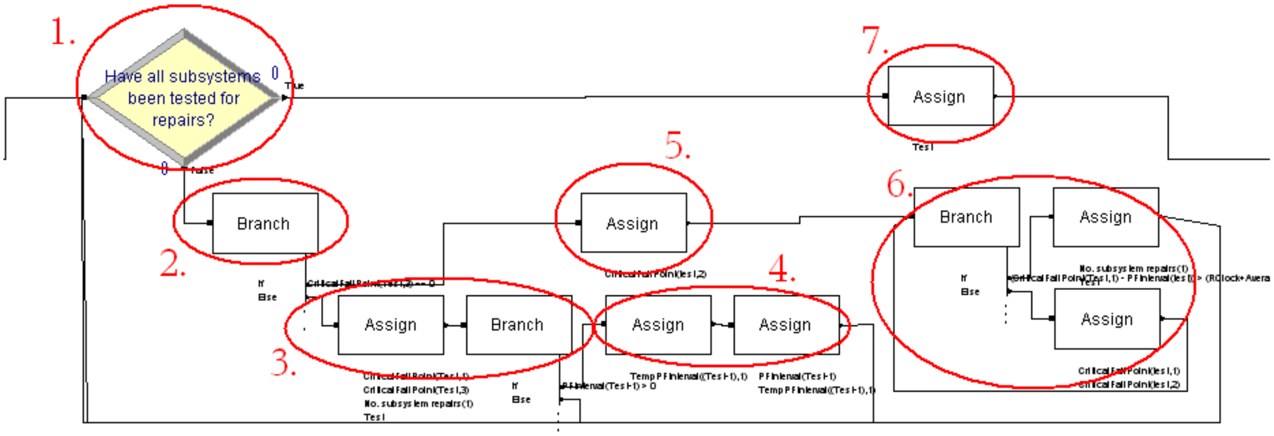

Figure 37: No. Repairs logic

The *No. repairs* sub module is where the machine is actually repaired. A lot of the design is legacy of SHOAM, but with some modification.

1. Machines enter from the left of Figure 37 and exit on the right. When they enter, the first decision module recognises that no machine subsystems have been tested yet. The *Test* attribute is used again and is incremented for each machine subsystem that is being tested. When *Test* is greater than the number of subsystems, this decision module recognises that all subsystems on the machine have been tested, and the machine goes to 7.

2. When all subsystems have not been tested, the machine enters a branch block, which decides if any faults on the machine were detected in operation. If so, the *Critical fail point 3* attribute, will have a value in it which was defined in the *Fault monitoring* sub module in *Operation*. The machine is then sent to 3. If the *critical fail point 3* attribute has no value in it, then the subsystem must be checked to see if faults have occurred and the machine goes to 5.
3. The value in *critical fail point 3* is the value of the next MTBF of the subsystem and was assigned in the *fault monitoring* sub module. This is assigned to *critical fail point 1* of the subsystem as the new fail point and the machine subsystem is repaired. The value in *critical fail point 2* was also assigned during *fault monitoring* and is a record of the number of times the MTBF had to be added to *critical fail point 3* to get the subsystem healthy again. This value is assigned to the *No. subsystem repairs* attribute and is used later to assign spares. The *Test* attribute is also incremented so that the next subsystem may be tested. The next branch block looks to see if the P-F interval of the subsystem is greater than 0 if so, this means that the fault was recorded using PHM systems and the machine goes to 4. If not, the machine goes back to 1 for the next subsystem test.
4. The failures were successfully recorded during fault monitoring and this data is used for the PHM learning capabilities. A new P-F interval is assigned which is slightly longer than before, depending on the *learning coefficient*, defined in the input sheet. The standard deviation of the P-F interval is also reduced by a factor of the *learning coefficient*, which increases the accuracy of the P-F interval estimate. The machine then returns to 1 to have the next subsystem checked.
5. If faults were not detected using the PHM systems a fault has been detected and *critical fail point 2*, is incremented by one.

6. Similar to the method used for *critical fail point 3*, the subsystem *critical fail point 1* has MTBFs added to its health is above that needed to return to work. The subsystem has been repaired. Each time an MTBF is added to *critical fail point 1*, *critical failpoint 2* is incremented, recording the need for another repair. When the value of *critical fail point 1* is above that which is required to continue working, the number of subsystem repairs is recorded and the *Test* attribute is incremented ready for the next test.
7. When all subsystems have been tested, the *Test* attribute is reset to 1 and the machine exist the submodule.

B.5.2 Parts, Planning and Repairs Sub Module

The *Parts, planning and repairs* sub module is large and has been divided up into several parts leading from the left, where machines and messages enter, to the right, where they exit. It should be noted that machines have already been repaired in the *No. repairs* module. Here, there the maintenance delay and the spares consumption are modelled.

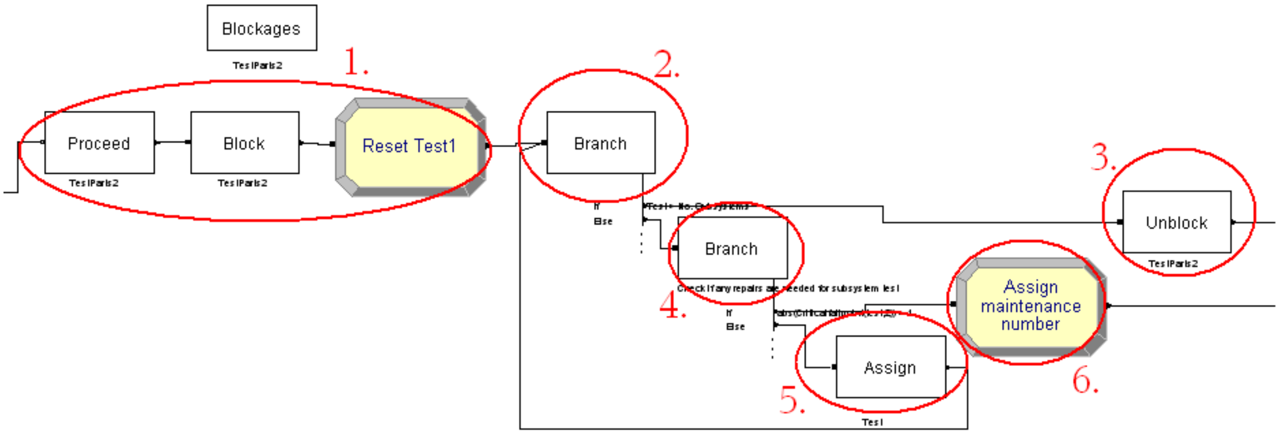

Figure 38: Parts, planning and repairs logic part 1

1. Machines enter having been through the *No. repairs* module. Each machine is blocked on entry so that only one machine is treated at any one time. This does not mean that

machines go through a delay until maintenance is cleared, because blockages in arena use a global variable to make up the time difference. Resources permitting then, multiple machines can be maintained at once. After a machine is released from the block, the *Test* value is reset to one for the first subsystem test.

2. The branch block decides if all machine subsystems have been tested by comparing the *Test* attribute, which is incremented as subsystems are tested, with the number of subsystems in the machine. If all subsystems have been tested, the machine exits via 3. If not, the machine goes to 4.
3. When all subsystems have been tested, the next machine which is ready for maintenance is unblocked in 1. The original proceeds to 17, to wait for all the subsystem repairs to be carried out.
4. If a subsystem requires maintenance, the absolute value of the *Critical fail point 2* attribute, which records the number of subsystem repairs required for that subsystem, will have a value which is greater than 1. The absolute value is taken because the number of repairs stored in *critical fail point 2* will be negative if the failure was detected in the *fault monitoring* module. If the subsystem requires maintenance, this branch block duplicates the machine, sending one machine to 6, the other to 5. In effect, a new machine is generated for each subsystem which requires repairs. These are combined later with original machine at 17. If the subsystem does not require maintenance, it is not duplicated and continues to 5.
5. The *Test* attribute for the subsystem is incremented ready for the next subsystem test and the machine returns to 2.
6. The subsystem requires maintenance and so has a unique maintenance number attached to it so that it can be distinguished from all the other repairs which may be going on. The machine then continues to 7.

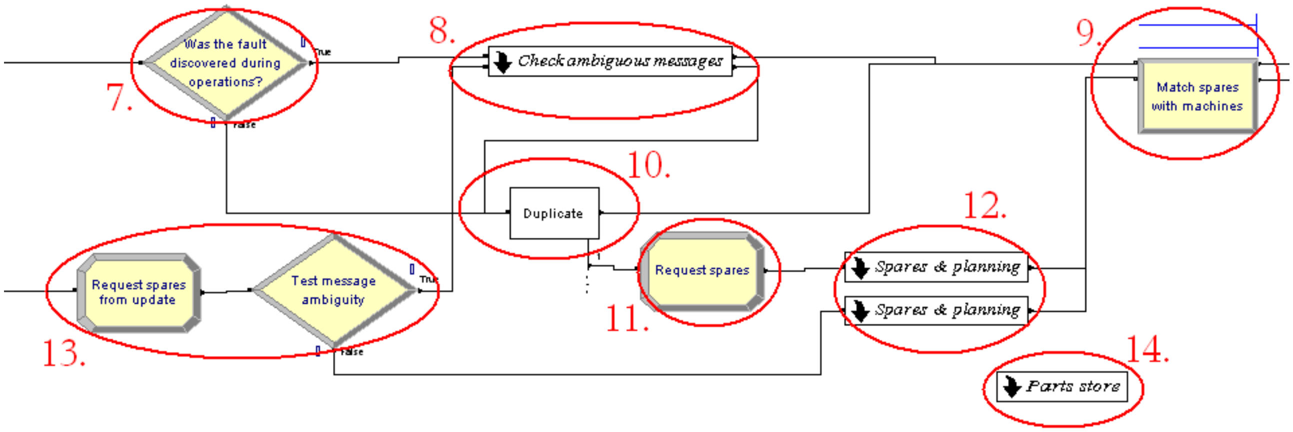

Figure 39: Parts, planning and repairs logic part 2

7. The decision model sees if the fault was discovered using fault monitoring by looking at the *critical fail point 2* again. If so, then the message will have been sent ahead of the machine and will be either waiting for it with spares ready, in the process of ordering spares in which case the machine will have to wait, or the message will be ambiguous and cannot. If the *critical fail point 2* holds a negative value, then the machine proceeds to 8. If not, it goes to 10.
8. Fault messages which are ambiguous will not be used to order spares, so the machine will have to wait for them to arrive. In the *Check ambiguous messages* module, the fault messages which are ambiguous will be waiting for the machine to enter maintenance. The machine is matched to the right message and the message is deleted. The machine is then treated as if no fault forwarding messages existed and proceeds to 10. Machines whose messages were not ambiguous proceed to 9.
9. Machines wait for the spares and messages to arrive. Once matched, they proceed to 15. The messages proceed to 16.
10. Faults which were not detected using prognostics arrive from 7 or 8 and must have their spares collected here in maintenance. The machine is duplicated with one being

used to collect parts, the other goes to 9 and waits with the other machines for the parts to arrive.

11. The duplicated machines or ambiguous messages from 8 are turned into a yellow report picture signifying that the spares collection has not been done using PHM systems. The messages then proceed to 12.
12. Here spares are ordered and managed. If spares are available, they are reserved on the shelf in the *Parts store* and the message proceeds to 9 where the machine is waiting. If no spares are available, the message is used to order spares and wait for them to arrive. The delay is the delivery time for that subsystem, which is specified in the input sheet. The spare arrives at the *Parts store* and is reserved on the shelf. The minimum parts delay which is specified in the input sheet is the time it takes to get the spare from the shelf to the machine. The message then proceeds to 9 where the machine is waiting. If fault was detected using PHM systems, it is assumed that the fault will already have been diagnosed. If not, then a delay is incurred in 12 to model the fault diagnostic period. The duration of this period is defined in the input sheet.
13. Messages enter via the bottom left of Figure 39. First the message is tested for ambiguity. The probability that a message is ambiguous is specified in the input sheet for each subsystem. If the message is ambiguous it proceeds to 8 and waits for the machine. If not, it proceeds straight to 12 to reserve the spares the machine will require.
14. In the *Parts store* sub module, spare parts are held for each subsystem. Statistics on the spares are kept and displayed on the interface including the average stocks available and the total spares consumed. A scheduling system also orders in parts according to the minimum level of spares specified in the input sheet. Every time this occurs, it records this as a stock check and displays it in the interface.

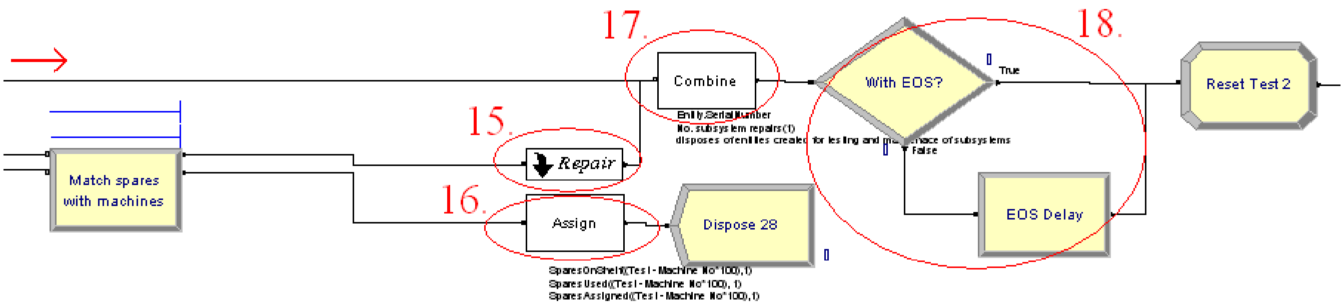

Figure 40: Parts, planning and repairs logic part 3

15. Once machines are matched successfully with their spares, they are repaired. Here, Engineer resources are used according to the required number specified in the input sheet for that subsystem and undergo a delay according to the MTTR of the subsystem, also specified in the input sheet. Once repaired, they proceed to 17.
16. The messages which have the spares reserved for the machines now relinquish the reserve and a spare is deducted from the shelf. This allows the whole time which the spare has been waiting in the store to be modelled accurately, if the parts are ordered ahead. The messages are then disposed of.
17. Every time a subsystem fault was detected, the machine was duplicated so that the subsystem could be used for repairs and to order spares. Now all the duplicates are combined with the original machine, which was waiting here. Once combined, the machine proceeds to 18.
18. Machines which have engineers on site do not need to wait for the engineers to respond to the breakdowns as they are already there. If the machine does not have an engineer on site, it must undergo a delay, which represents the response time of engineers to breakdowns. Once Engineer response has been modelled, the machine

exits the *Parts, planning and repairs* sub module and continues to the *Scheduled maintenance* sub module

B.5.3 Scheduled Maintenance Sub Module

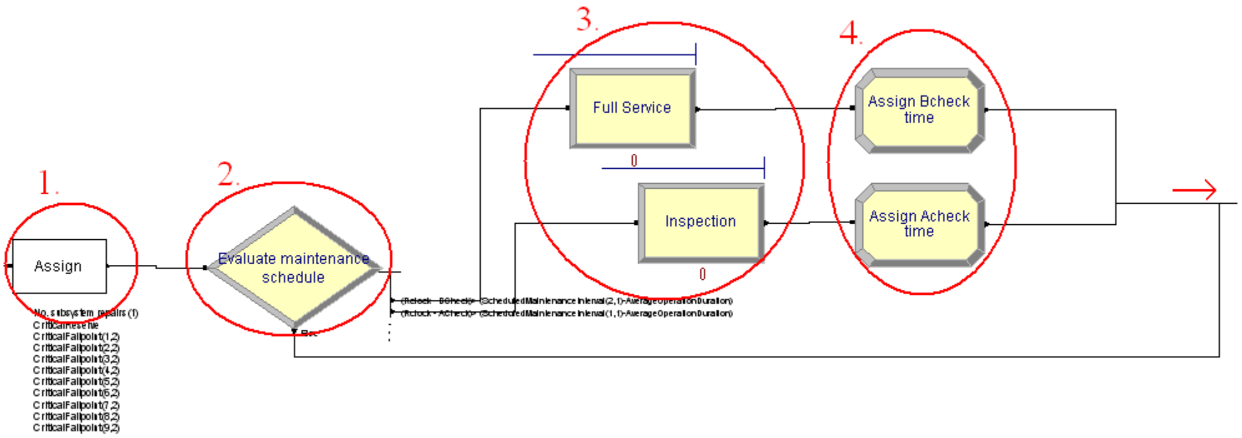

Figure 41: Scheduled maintenance logic

1. After machines have left the *Parts, planning and repairs* sub module and enter the *Scheduled maintenance* sub module, the *critical fail point 2* attribute for each subsystem of the machine is reset. *Critical fail point 2* records the number of repairs which were required for that subsystem and the default value is 1.The number of subsystem repairs and critical reserve attributes are also reset to their default values.
2. The maintenance schedule is then evaluated to see if the repairs, which the machine just underwent, are to be modelled as part of a scheduled maintenance period or not. If the time until the next scheduled maintenance period is less than the operation duration, then the machine goes into the scheduled maintenance. If not the machine exits maintenance via the arrow on the right of Figure 41 and continues back to production.
3. Depending on which maintenance period the machine is in, it goes to either a full service or just the inspection. The machine also undergoes a delay which is

representative of the scheduled maintenance action that is taking place. This delay is specified in the input sheet. The machine then proceeds to 4.

4. Here, the next maintenance schedule for this particular action is assigned. The machine then exits via the arrow on the left of Figure 41 and returns to the manufacturing system.

APPENDIX C: SUBSYSTEM SPECIFICATION

C.1 Subsystem Design

It was expected that the reliability characteristics of machine tool subsystems could be sampled from actual data of advanced machine tool failure modes and rates. This has not been possible however, so example subsystems are determined instead from information from interviews with machine manufacturers and other academic resources. The machine reliability characteristics may not be realistic which prevents effective validation; but this should not affect the usefulness of the model itself for analysing machine performance and services, as the benefits from CBM/PHM and different service designs on the performance of a machine can still be evaluated. The data for specific machines can be entered into the model by manufacturers from historical or reliability data where available.

Typical subsystems found in many metal cutting machine tools are selected, which are described in Table 5, as are the reliability and maintenance characteristics of each. The three subsystem characteristics include the characteristic reliability distribution, mean time between failures (*MTBF*) and mean time to repair (*MTTR*). NCMT perform a basic maintenance and inspection of components with known reliabilities of around 2000 hrs which includes oil filters and some consumables such as lubricant. This service takes around a day. A more thorough maintenance and service is performed every 6 months on components which have reliabilities ranging between 4000 to 5000hrs and includes the motion components and the spindle condition is checked again. This type of service can take up to three days. This data may be used as to estimate the MTBFs of components and some variability is included to introduce uncertainty. The reliability distribution however, cannot be inferred and a suitable substitute is determined in discussion with machine researchers at the university.

Table 5: Nine machine tool subsystem

Subsystem	Description	Reliability distribution	MTBF (hrs)	MTTR (hrs)
Spindle	Provides main rotational force on either the work piece or the tool	Exponential	6000	16
Power supply	External source of power to machine components including the controller and motors	Uniform	5000	4
CNC controller	Controls the machine functions via a computer	Uniform	5000	4
Lubrication system	Maintains lubricating fluid	Lognormal	3000	3
Oil filters	Maintain the purity of the machine oil	Lognormal	2000	1
Motor bearings	Ensure smooth rotation of motors and absorb some of the loads generated during process	Exponential	4000	16
X motion system Y motion system	Control the motion of the tool in the work envelope and therefore impact the quality of the finished product	Exponential	4000	6
Rotary table	Rotates the work piece in an axis and also impacts the product quality.	Uniform	4000	6

C.2 Removal of Type II Failures

SHOAM characterises the failure of each subsystem by two failure modes. Each flight is divided into two halves. Failure mode type I affects the first half of the flight, and type II failure modes only affect the second half of the flight. If the aircraft fails during the first half of the flight, it returns to the original location and the flight is considered as a failure. If it makes it past the first half of a flight, then the aircraft will always complete the second half and the flight is considered a success. It makes no difference if a subsystem fails via the type II failure mode during the first half or the second and only maintenance resources will be required. Prognostics are therefore only used on type I failure modes since it is only these which can affect the operational performance of an aircraft. Indeed, a plane may fly repeatedly in SHOAM having all subsystems failed via the type II failure mode. The modification to a machine tool means removing the two ‘halves’ of an operation and reducing it to one. It also means removing the second failure mode as this is an unsatisfactory way of characterising failures. Only type I failure modes remain, characterised by the MTBF in Table 5

C.3 Improvement in Modelling PHM Systems

The reduction to just a single operation instead of two halves allows more variability for manufacturing environments, as the duration of each operation may now model a complete shift or a single operation. The response of prognostics and health management systems to these changes can also be simulated as they will alter the system behaviour for the duration of the shift or operation and not just the first half. In order to allow this however, fundamental changes to the way fault forwarding and PHM are modelled had to be made. Fault forwarding in SHOAM can only be used to order spares and maintenance during a single flight. The benefits of using these systems mean that the maintenance resources can be ordered ahead of the aircraft landing, and the reduced waiting time is that of the aircraft completing the flight. In the modified model, operation durations may be much shorter, for example only an hour. The benefits of using PHM systems will be entirely reduced then, if spares can only be ordered before the machine completes a single job as only one hour will be saved. If spares take 24 hours to arrive, any benefit of using fault forwarding is almost entirely wiped out.

To introduce greater flexibility the *maintenance flag* is introduced allowing spares to be ordered ahead whilst the machine continues to perform operations (see §6.7). If an operation happens to be only one hour long and a fault is detected during that operation, spares and maintenance can be ordered using fault forwarding, whilst the machine continues with more operations. This also reflects machine tool CBM more, because diagnosing the remaining life of a machine tool component is often done separately to the machine using data collected from the machine interface and the results sent to the customer with which they make decisions over when the best time to perform maintenance will be.

APPENDIX D: INPUT SHEET DATA

The data which can be used to design a complete model simulation is entered in the model input sheet and a list is given below. Not all fields need to be used and the amount depends on the level of detail that the analyst wishes to model.

Key information:
(All times are in specified as hours)
Cell start size: The number of machines in the cell at the beginning of the simulation
Cell start time: ‘Delay time’ for machine delivery
PHM%: Percentage of machines in the cell which have PHM systems
Knowledge coefficient: learning capabilities of fault diagnostics
Parts delay: Time locate and retrieve part from the parts store
% with EOS: % of machines in cell with engineer available on site
Engineer response time: Time for engineers to respond to breakdowns
Max number of operations: Maximum number generated by production control
Average operation duration: Can also be used for shifts lengths etc
Setup time: Time taken to setup machine
TPM: Total productive maintenance activities
Service life: Maximum life in operational hours
Normal load: Mean operations generated per day
Business cycle: Mean operations generated per day during business cycle period
Business cycle duration: Length of business cycle period
Priority mode: Controls distribution of job priority assignments
Scheduled maintenance interval: interval between scheduled maintenance activities
Scheduled maintenance time: Time for each maintenance activity
Engineers for scheduled maintenance: No. engineers required for each maintenance activity

Subsystem Spares and Maintenance Flag:
Engineers for subsystem repairs: No. engineers required to repair the subsystem
Starting spares: No spares for subsystem in parts store at beginning of simulation
Minimum spares level: Minimum no. of spares to hold when using scheduled spares management
Flag: The time that the machine will continue in operation after a fault is detected

Compensation (%): The probability that the subsystem will not be used during an operation. The column must not total over 100% and if all fields are 0 then all subsystems will be aged the same.

Subsystem Tables:
(Distribution, key and P values correspond to Arena distribution table)
MTTR: Mean time to repair subsystem
MTBF: Mean time between subsystem failure
P-F interval: ‘Point-of-failure’ interval is the time between fault detection and failure
Prognostic coverage: The percentage of machines with PHM systems for this subsystem. Defines the probability that the prognostic systems will be able to prevent catastrophic failure
Delivery time for parts: Variability in delivery times for subsystem part
Message ambiguity: The probability that a message will be ambiguous
Diagnostic Time: Time to diagnose sub system fault if PHM are not used

APPENDIX E: SERVICE EVALUATION & SENSITIVITY ANALYSIS

The use of the model to evaluate service contracts for machine tools in service arrangements is then given. More of the features in the model are then tested and the sensitivity analysed.

E.1 Single Machine Cell

For comparison with the 10 machine cell in chapter 7, a single machine cell and a three machine cell are compared against the four service contracts defined in Table 4. Figure 42 shows the reduction in machine tool downtime under each service contract for a single machine cell. The figure shows the time each machine spends in maintenance when a breakdown occurs.

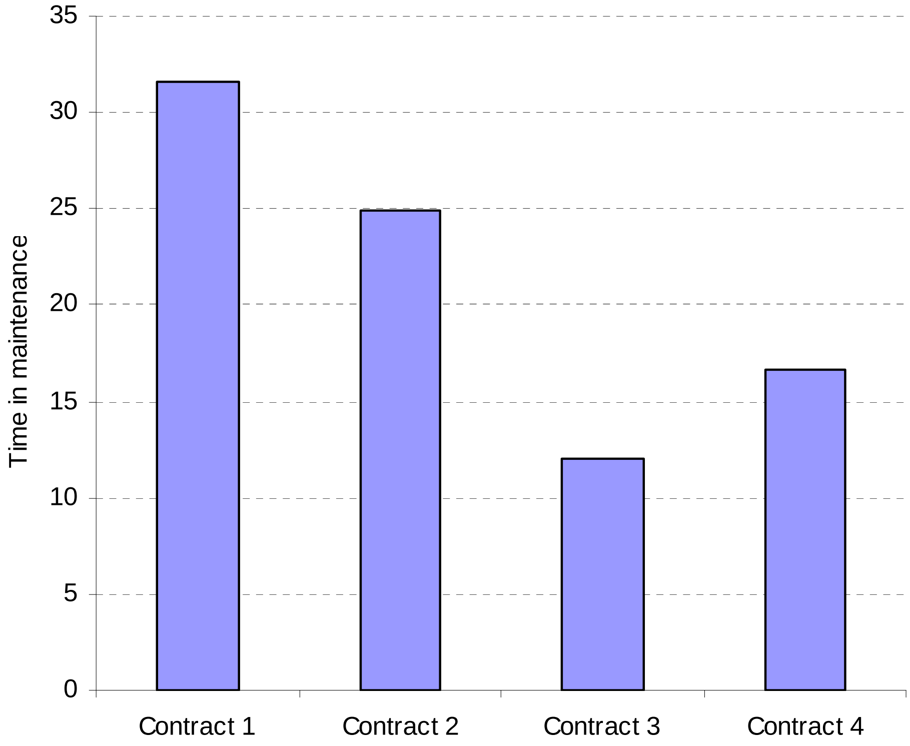

Figure 42: Single machine cell downtime

Figure 43 shows the improvements to availability realised by the reduction to machine tool downtime. Despite the increased machine downtime over contract 3, contract 4 uses CBM which means that unnecessary maintenance is minimised and the total time in maintenance over the lifecycle of the machine is reduced. This results in improved availability of the machine seen in Figure 43.

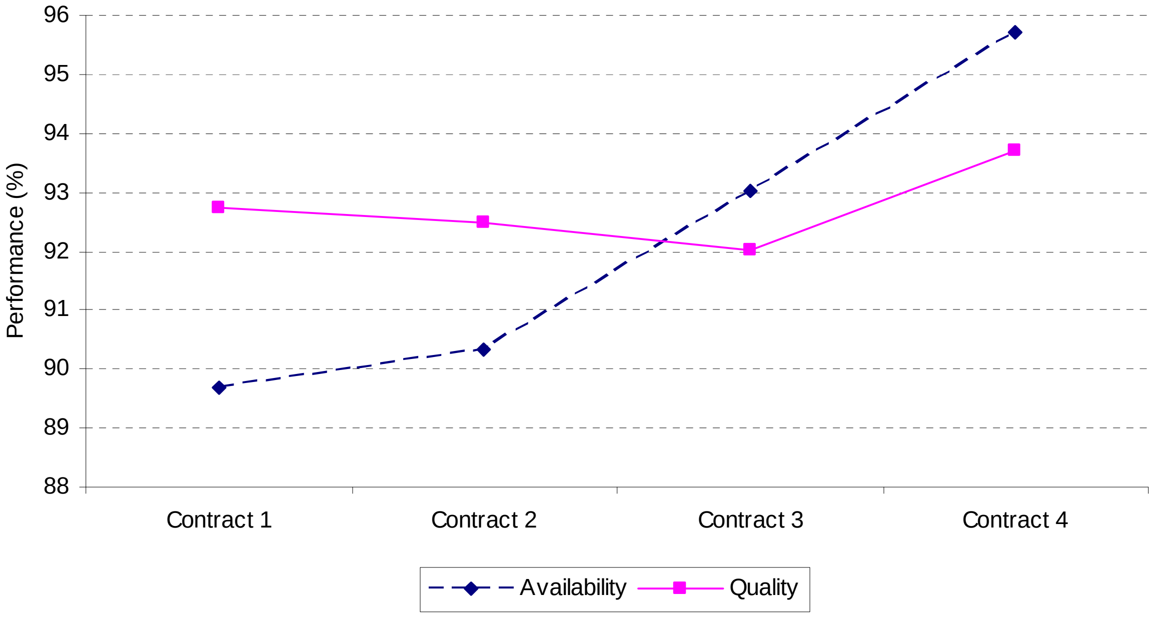

Figure 43: Single cell availability and quality

Figure 44 shows the annual output of the machine under each service contract. As was seen in chapter 7, the improvement in output is not spectacular. The utilisation of the machine reaches only 84%, which is the reason why improved output does not correspond with the improved availability.

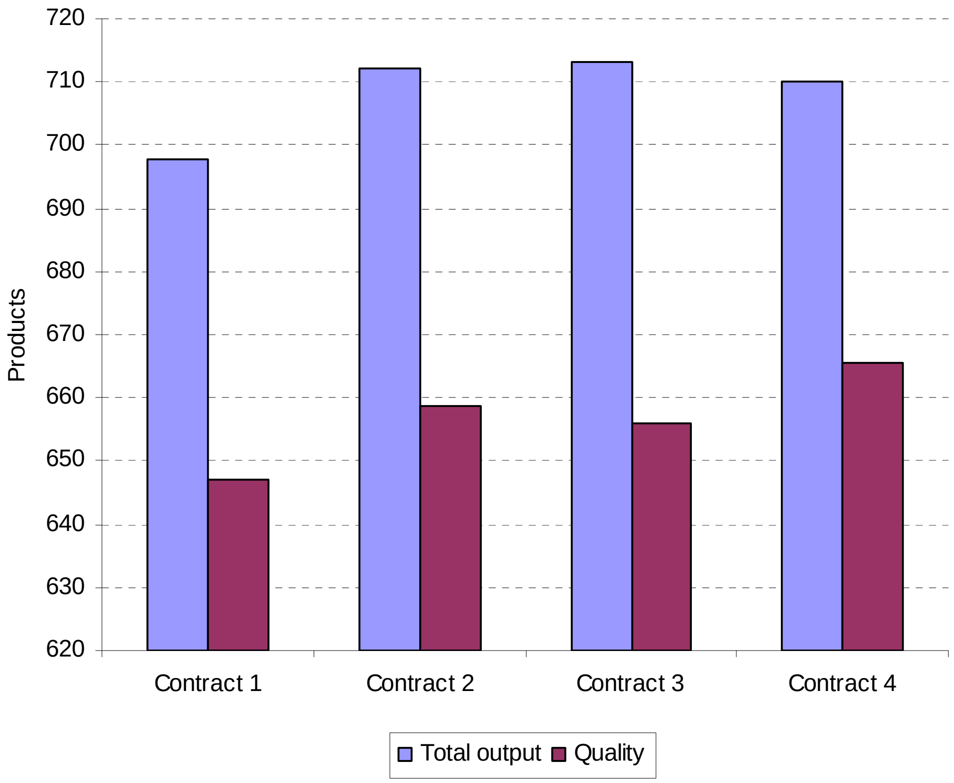

Figure 44: Single cell productivity

Figure 45 shows the cost of each contract for each of the services provided. There are clearly economies of scale between the single cell scenario and the ten machine scenario from Chapter 7. The spares store in the ten machine scenario means that the cost of maintenance resources such as spares and engineers are distributed among the ten machines.

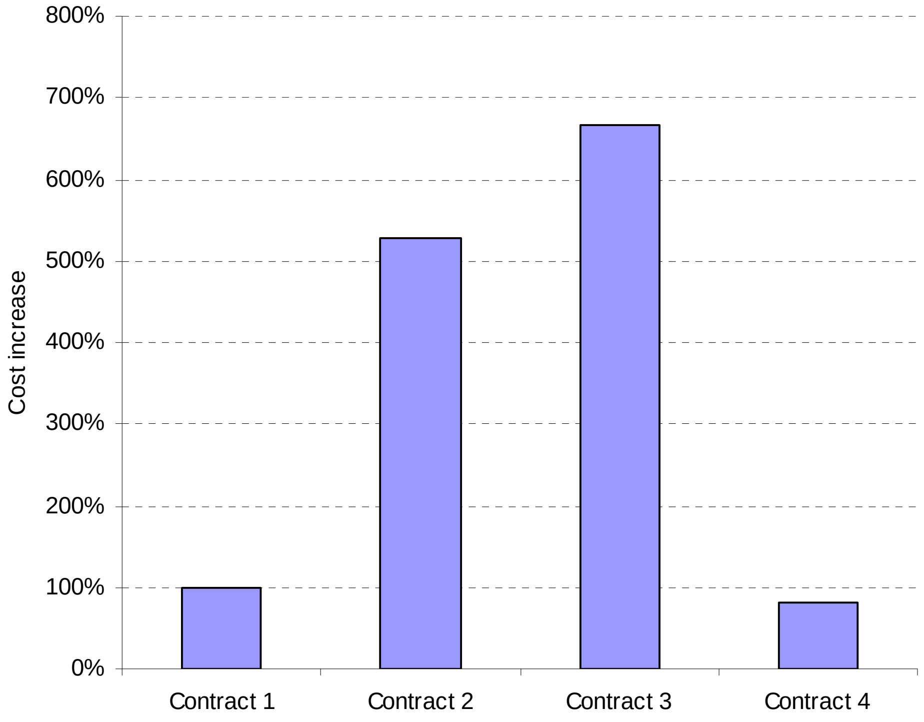

Figure 45: Single cell lifecycle cost

E.2 Three Machine Cell

The three machine cell performs similar to the single machine, but with reduced costs for contracts 3 and 4 due to the economies of scale.

Table 6: Three machine cell test results for each contract

Contract	**Availability**	**Quality**	**Annual no. breakdowns**	**Annual productivity (jobs)**	**Average machine downtime (hrs)**	**Lifecycle costs**
1	89%	92%	63	2052	30	100%
2	91%	92%	64	2079	29	178%
3	96%	92%	61	2098	7	333%
4	96%	94%	19	2145	12	77%

E.3 Sensitivity Analysis

Some of the other modelling features which have not been used in the service analysis, but which can be add value for service planners, are given below. A single machine is used for testing and each result is a separate experimental run of the model. Figure 46 below for example, demonstrates 11 different experiments with only one variable being altered.

E.4 P-F Interval

The P-F interval is the time at which a fault or potential failure is detected before the failure occurs. As Figure 46 demonstrates, the earlier that a fault can be detected, then the greater the probability that a breakdown can be prevented.

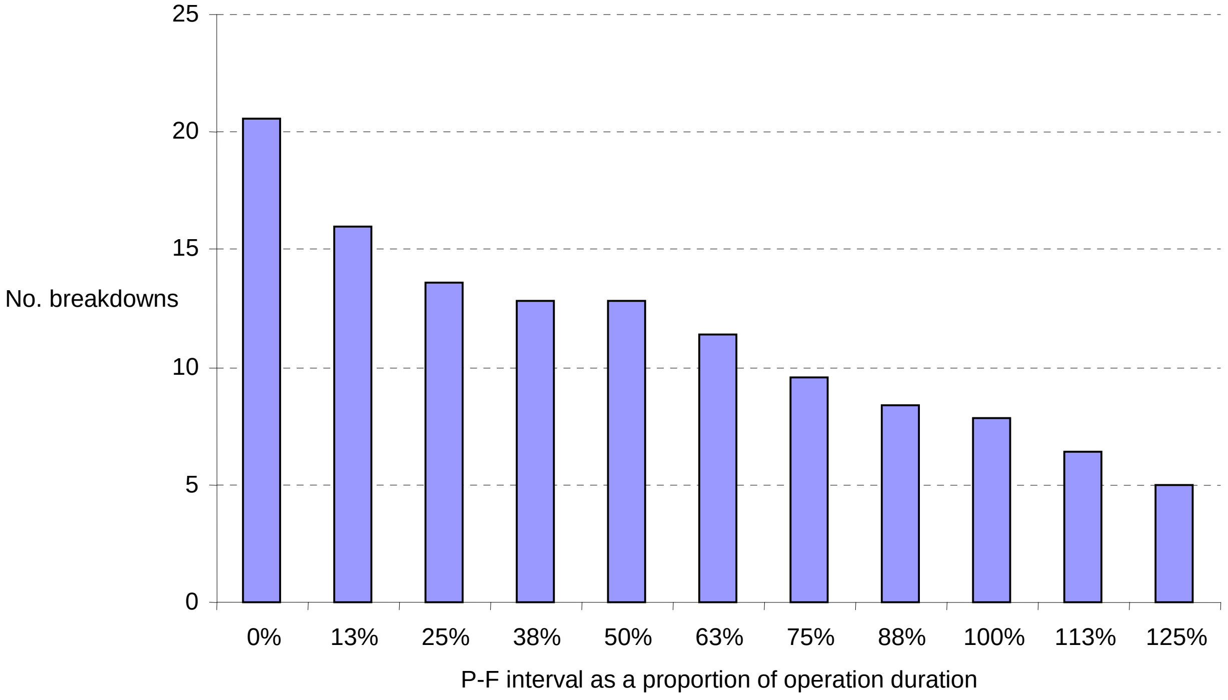

Figure 46: Impact of extending the P-F interval on breakdowns

Figure 46 shows the P-F interval as a proportion of the operation duration, because catastrophic failures (breakdowns) can only occur during an operation. The figure also shows that due to the inherent uncertainty in component reliability, breakdowns can rarely be fully prevented.

E.5 Maintenance Flag

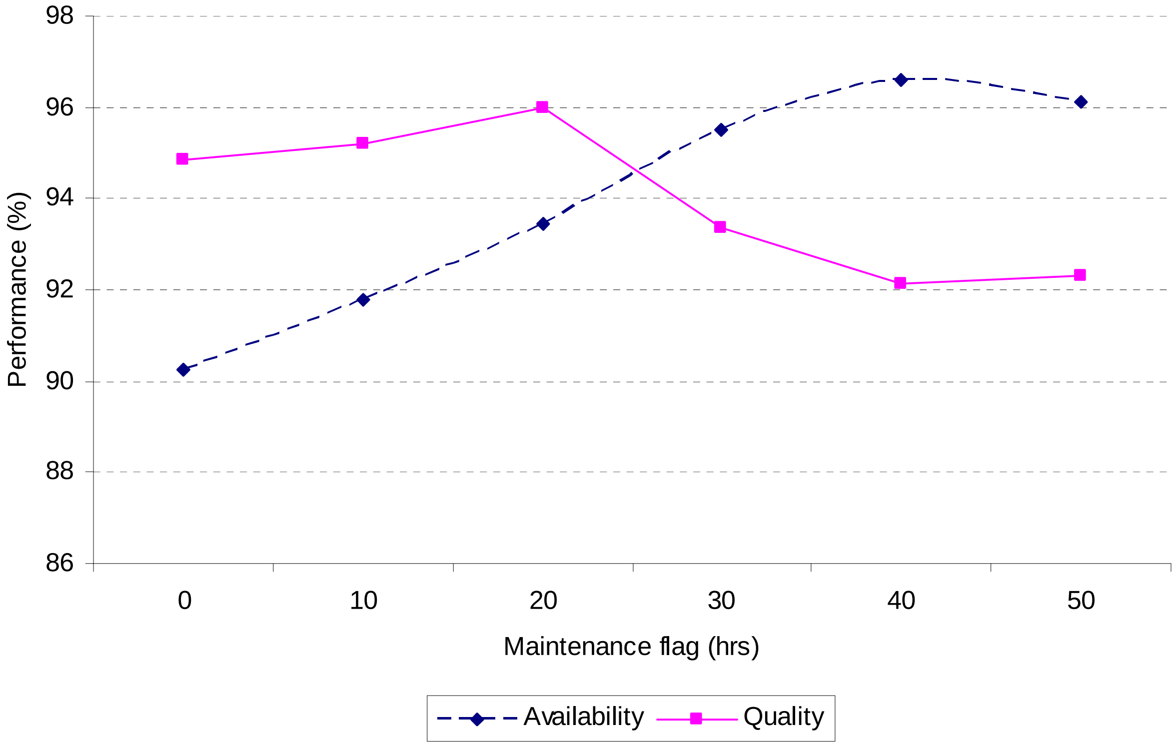

Figure 47: Maintenance flag

When a fault is detected during a flight in SHOAM the plane enters maintenance as soon as it completes the flight. This is changed for industrial equipment to allow the analyst to decide the optimal time to perform maintenance. The maintenance flag is introduced to allow a differentiation between the detection of a failure and the maintenance action. Upon detection of a fault, spares and resources are ordered from maintenance whilst the machine continues in operation for the duration of time specified by the maintenance flag. Figure 47 shows the impact of the maintenance flag on the manufacturing performance in terms of quality and availability. The longer the maintenance flag is set, the longer the machine spends in operation. This increases availability, but after a certain point, reduces quality performance as the faults interfere with the operation of the machine and the risk of breakdown goes up. Depending on the effectiveness of the machine desired, the analyst can optimise the maintenance flag. Another effect of the flag is the impact on spares levels. If the flag is set very late, spares are ordered early which increases inventory costs.

E.6 Message Ambiguity

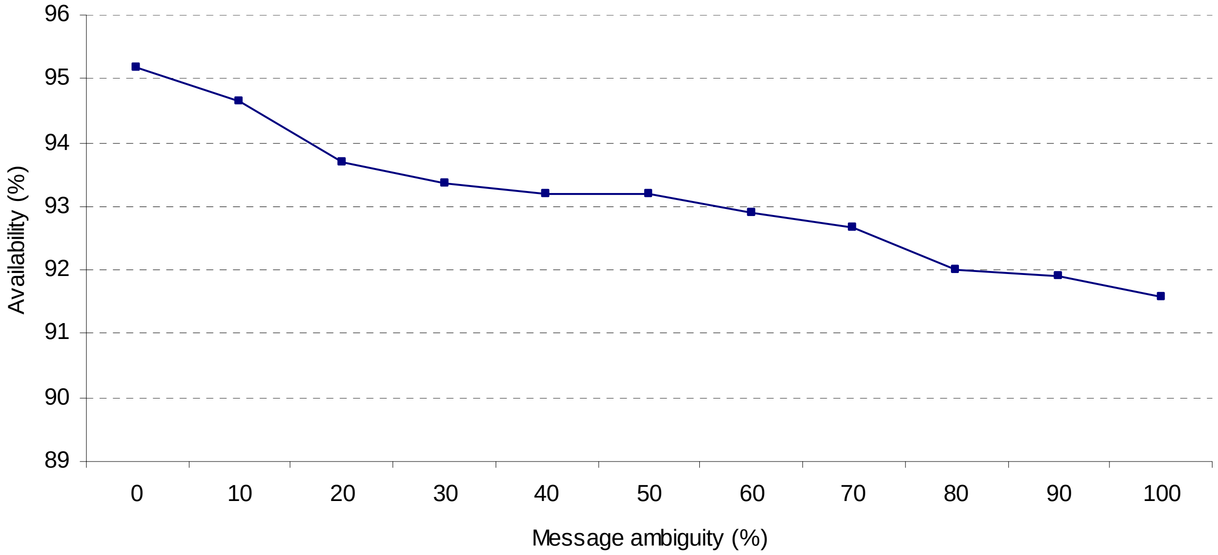

Figure 48: Impact of message ambiguity on availability

Another feature from SHOAM is the ability to analyse the impact of fault detection system efficiency. If a fault detection system sends an ambiguous fault message, the procedure of analysing the fault and ordering parts must take place in maintenance, which reduces the availability of the machine (Figure 48) due to the increased downtime (Figure 49). A modification from SHOAM is the inclusion of a diagnosis period, in which a delay is incurred in maintenance if a fault requires diagnosing. It is assumed that fault messages which are not ambiguous will already have a diagnosis of the fault and this delay period is not applied. Ambiguous messages and ordinary breakdowns will incur this delay period which is specified for each subsystem in the diagnostic time table in the input sheet. A lognormal distribution is chosen as it is assumed that an engineer will perform the diagnosis.

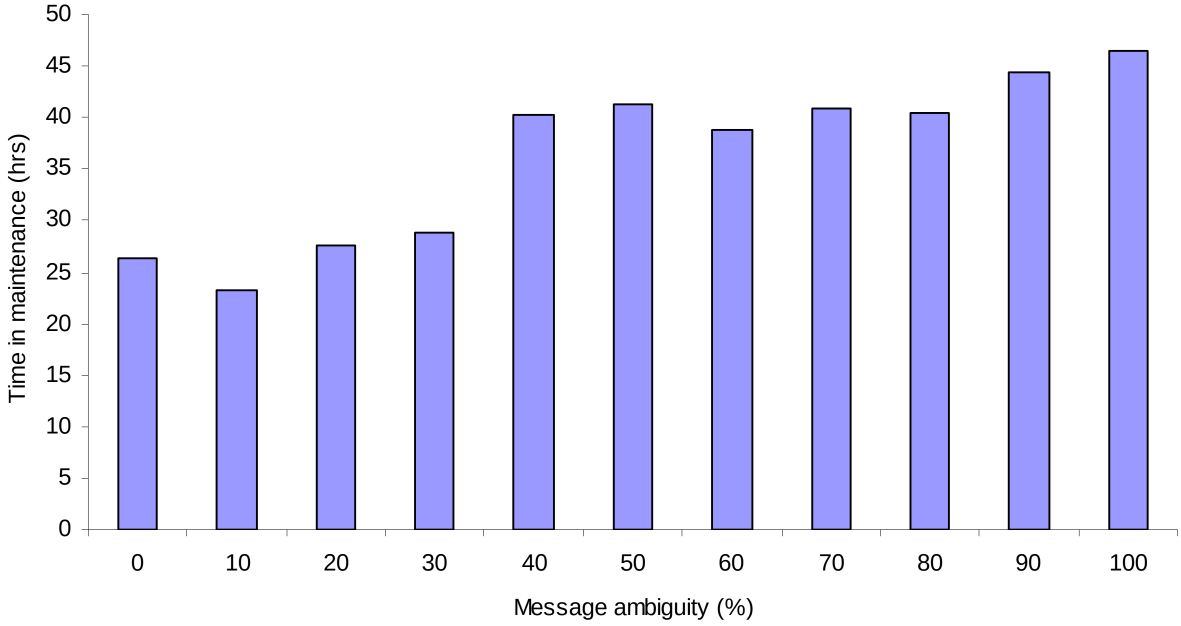

Figure 49: Impact of message ambiguity on average downtime

E.7 Subsystem Monitoring

Given the expense of CBM/PHM systems, manufacturers will want to maximise the benefits gained from any investment and to minimise the risks involved. The model can be used to analyse the benefits of monitoring particular subsystems so that the lifecycle costs are minimised. Figure 50 shows the improvements in operational reliability (the number of successful operations with no breakdown) over the lifecycle of a machine by monitoring each subsystem. The improvements with each subsystem can be compared to the subsystem MTBF and distribution, allowing those components of the highest risk to be managed more effectively. Most improvement is achieved by monitoring the rotary table, which has the same average MTBF as the X and Y motion systems, but a different reliability distribution.

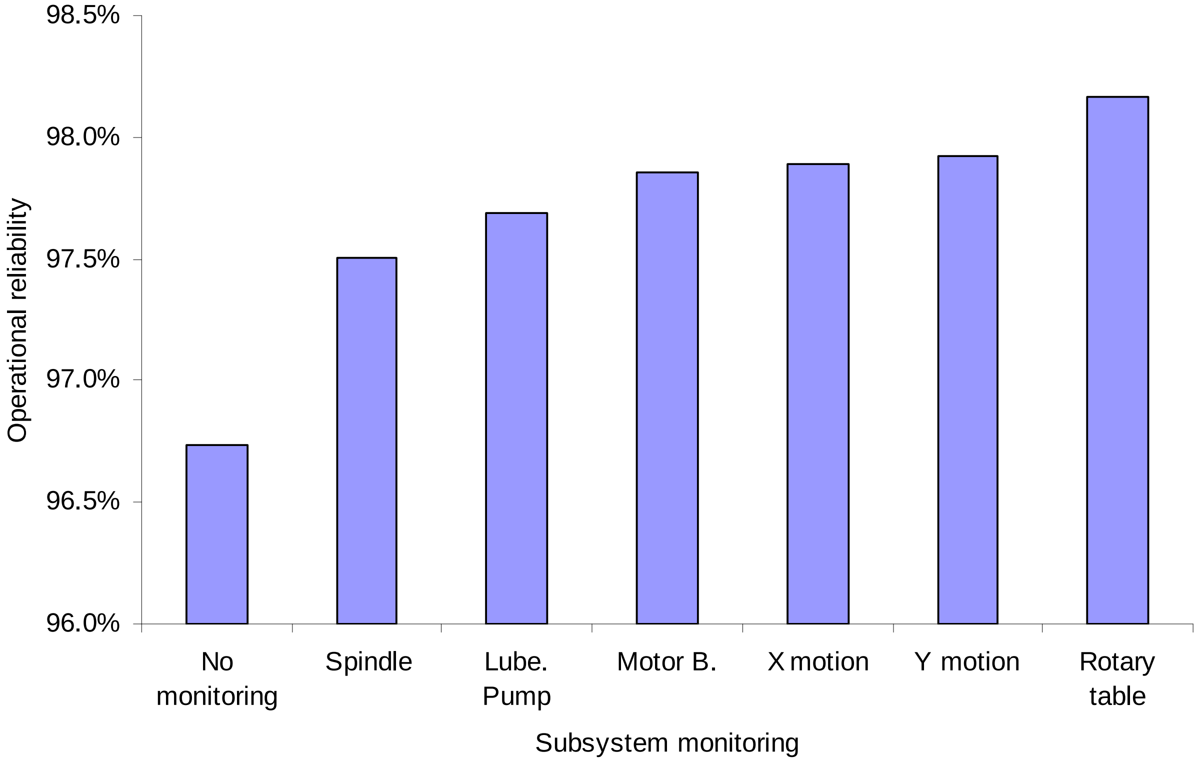

Figure 50: Impact of monitoring different subsystems on operational reliability

E.8 Subsystem Compensation

The subsystem compensation modules are added to allow greater control over the manufacturing environments in which the machines are used. All subsystems in SHOAM age according to the duration of the flight. Machine tool subsystems however, can age differently, depending on the material being processed, the geometric shape of the work piece etc. The compensation module can therefore be used to simulate this uncertainty by distributing operational harshness among the subsystems. Figure 51 shows the predictable result of reducing the aging process of one subsystem on the total failures of that system. The compensation table in the input sheet specifies the distribution of the aging process in the environment. If the table is left blank, all subsystems are aged by the operation duration.

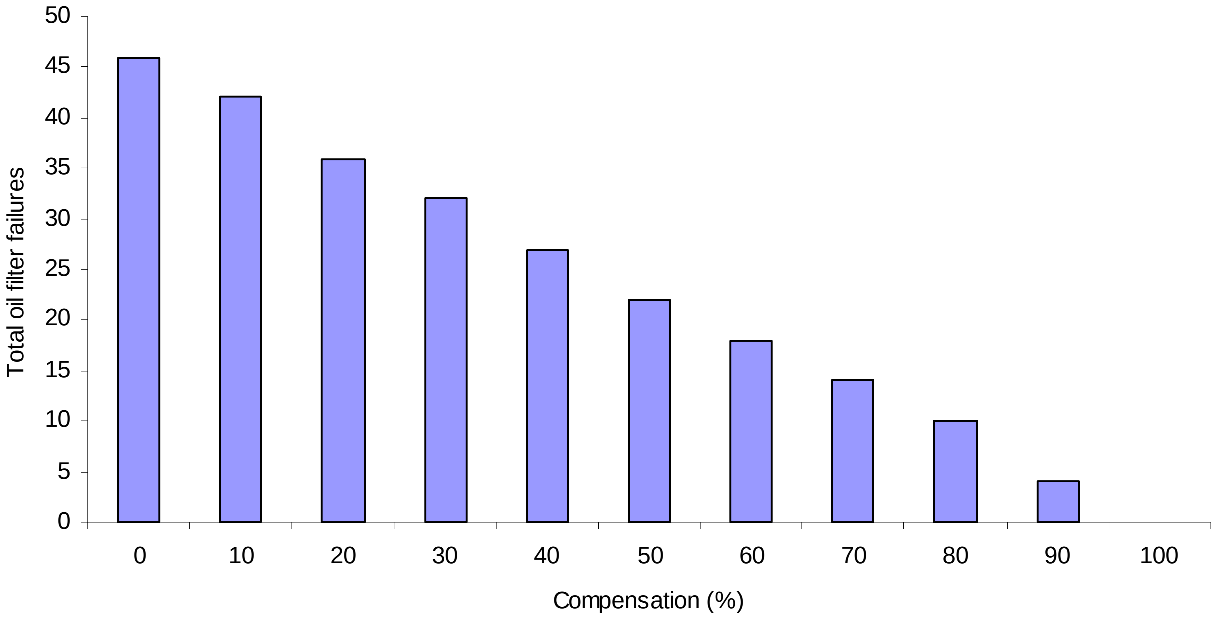

Figure 51: Oil filter compensation

E.9 Long Term Scenario

Simulating long term business cycles or production cycles are necessary for accurate analysis and optimisation of lifecycle performance and for reducing the risk in lifecycle contracts. Figure 52 shows a long term cycle in which production orders increase or 'ramp up' after the first year and drop down after the third. This may be used to model the installation of machines at a new facility. This increases the demand on maintenance resources after the first year as is shown by the increased consumption of spares. Utilisation of the machine continues to go up after the third year because back orders which accumulated during the ramp up phase must be cleared. Figure 52 also demonstrates one of the modified output formats, which provides a breakdown of the lifecycle performance into six month intervals.

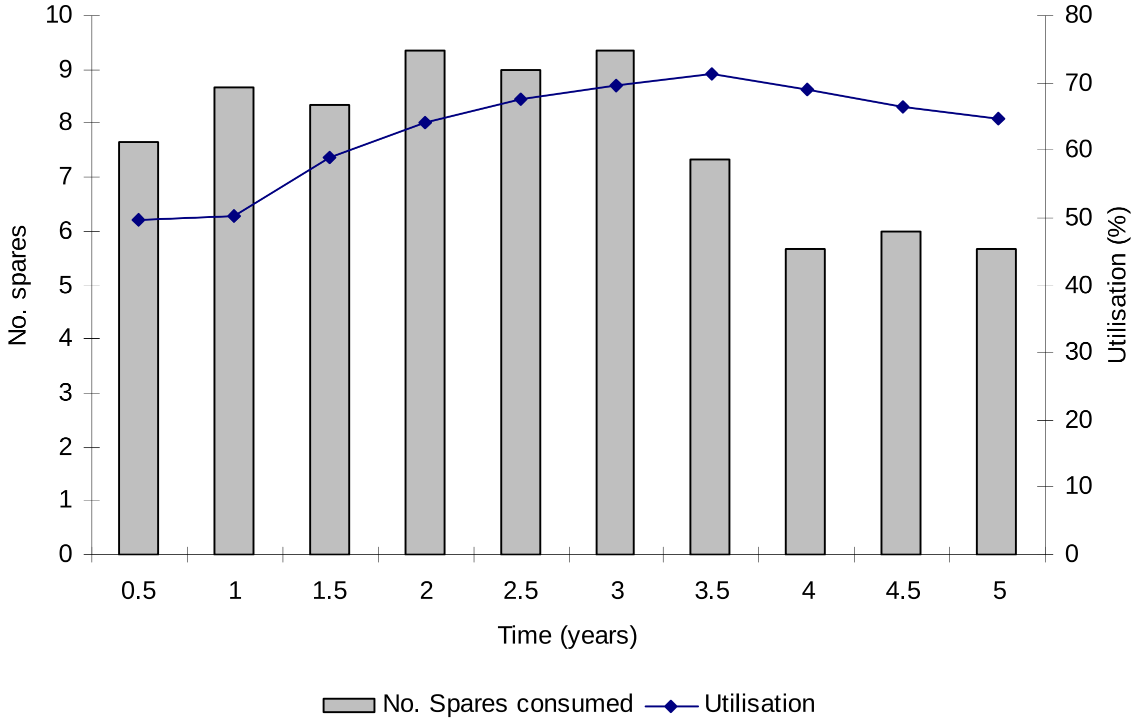

Figure 52: Production ramp up scenario

E.10 Parts Store

In SHOAM, spares can be ordered using PHM systems or when the plane enters maintenance. This is modified to allow spares to be ordered early and held in a store, which is one service offered by machine suppliers. The minimum level of spares held in the store is specified in the input sheet and the spares levels affect many elements in the model. Figure 53 shows the impact of increasing the spares levels on machine availability. Holding more spares means reducing the downtime spent in maintenance waiting for them to be delivered.

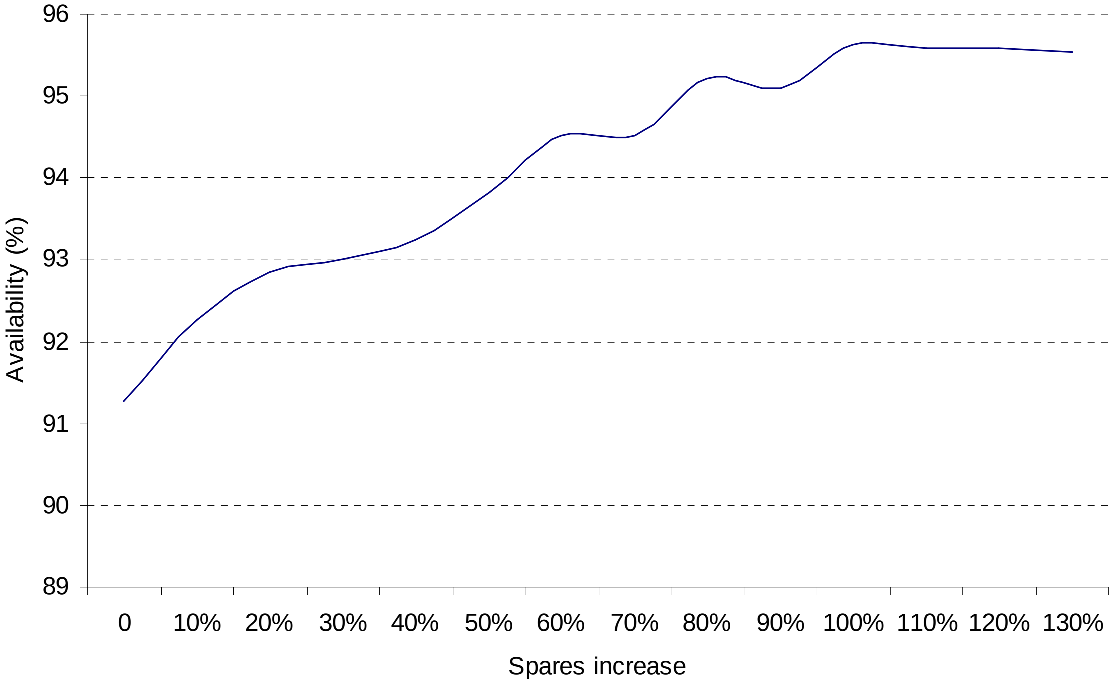

Figure 53: Impact of spares levels on availability

Holding more spares will push up inventory costs, but if the contract specifies the service provider to pay for downtime, then the reduced time in maintenance (Figure 54) may compensate for this increased cost. Some parts will also cost more than others and the analyst can measure the benefits of holding a particular part before purchasing it.

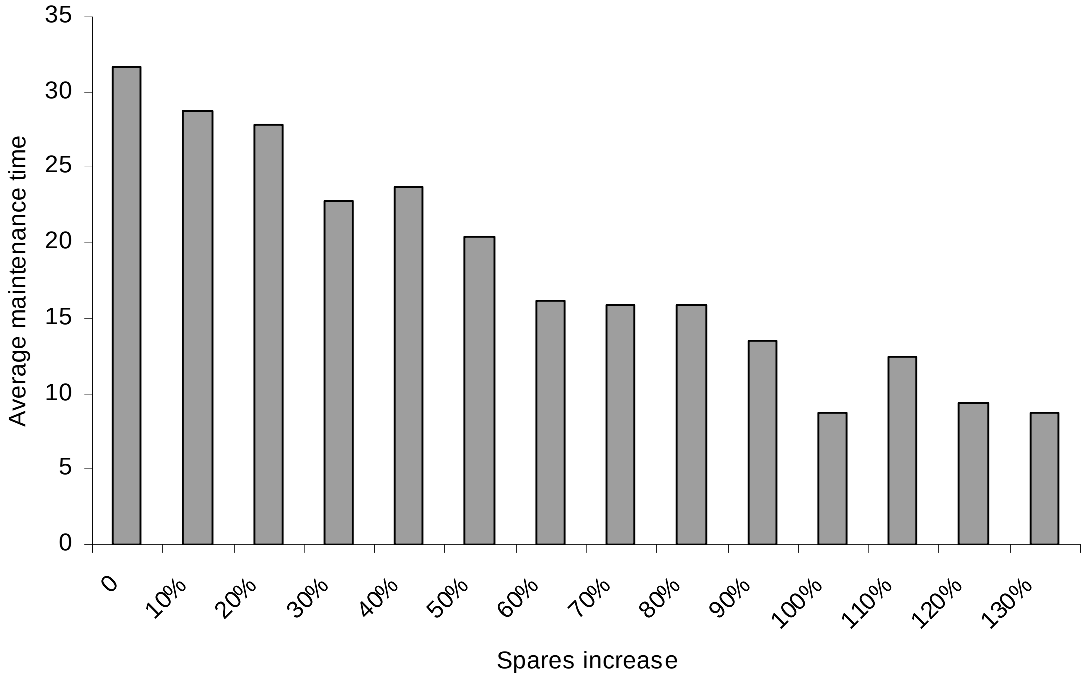

Figure 54: Impact of spares levels on downtime